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Low-Cost
Solar Array Project

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Proceedings of the Low-Cost Solar Array Wafering Workshop

(8-10 June, 1981, The Pointe, Phoenix, Arizona)

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Through an Agreement with
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by
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California Institute of Technology
Pasadena, California

(JPL PUBLICATION 82-9)

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The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

ABSTRACT

The Low-Cost Solar Array Wafering Workshop was held on June 8-10, 1981, at The Pointe, Phoenix, Arizona, under the sponsorship of the Low-Cost Solar Array Project (since then renamed the Flat-Plate Array Project) of the Jet Propulsion Laboratory. The Workshop consisted of seven sessions covering all aspects of ingot wafering, including fixed- and free-abrasive sawing, materials, mechanisms, characterization, innovative concepts and economics. Twenty-seven papers were presented.

Keywords:

Coolants
Crystals
Abrasive
Damage
Diamond
Wafering
Slicing
Sawing
ID
Slurry
Fixed-abrasive
Multiple-blade
Lubricants
Silicon

PREFACE

The Workshop on ingot wafering was held on June 8-10, 1981 at The Pointe, Phoenix, Arizona, under the sponsorship of the Low-Cost Solar Array Project* of the Jet Propulsion Laboratory.

The objectives of the Workshop were to clarify and define the state of the art in silicon wafering, to solicit and explore innovative ideas in wafering, and to stimulate a productive exchange of technology within the slicing community. The approach was to hold an intensive Workshop with invited and submitted papers on the various aspects of ingot wafering, to invite acknowledged experts in the field who would lend perspective to the subject as well as their technical expertise, and to provide an atmosphere that would give ample opportunity for discussion.

The Workshop consisted of seven sessions covering all aspects of ingot wafering, including fixed- and free-abrasive sawing, wire, ID, and multiblade sawing, materials, mechanisms, characterization, innovative concepts and economics.

These Proceedings contain the texts of the presentations made at the Workshop as submitted by their authors to the Committee at the beginning of the Workshop. Thus they may vary from the actual presentations in the technical sessions. The discussions following each presentation were tape-recorded at the conference, and have been edited for clarity and continuity.

It is hoped that this Proceedings volume will be useful both as a record of the Workshop and as a source book on the subject of ingot wafering.

It is published by the Jet Propulsion Laboratory and is sponsored by the U.S. Department of Energy under Interagency Agreement DE-AI01-76 ET 20356 through NASA Task RD152, Amendment 66.

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*Since renamed the Flat-Plate Solar Array Project.

FOREWORD

The ability of any ingot-based photovoltaic technology to compete in the future marketplace will depend upon the development of economical silicon-efficient wafering methods. The Low-Cost Solar Array Project at Jet Propulsion Laboratory has supported the development of ingot wafering technology since 1975.

By the middle of 1980, it was clear that further technical breakthroughs in the wafering processes would be required to achieve the economic goals set by the LSA Project. As a first step toward giving the program new energy, a workshop on the wafering of silicon and related topics was planned.

In June 1981 more than 80 specialists representing five countries came to Phoenix to participate in an information-packed three-day meeting. Often for the first time, wafering empiricists were exposed to the theories underlying their wafering processes and theoreticians were given an accurate perspective of sawing as a business. Martin Wolf observed that the Workshop "fulfilled the task of bringing the diverse workers in the field to a common level of up-to-date information on all aspects of this area, making them aware of the accomplishments, the unknowns and needs in setting the stage for further fruitful work as well as further information exchange." In fact, it seemed that everyone went home with new contacts and new ideas based on a better technical foundation. We saw new partnerships forming for research studies. We identified as important overlooked aspects of wafering technology for which R & D support is clearly needed. Based on the work presented at the conference and contained in these proceedings, we were all able to better understand the potential of the technology.

Peter Iles closed the meeting with the observation that for the silicon-based PV industry "the success of this conference will be traced very accurately by just watching how well the ribbons do."

Andrew Morrison
Workshop Chairman

THE USE OF DIAMONDS FOR STONE-SAWS

The idea of making use of the extraordinary cutting qualities of these gems in the production of stone-saws has been carried out practically during the past year by H. & J. L. Youngs, of New-York City. At the exhibition of the American Institute in New-York, several of these saws were worked with the greatest success. In general appearance and movement they resemble the ordinary stone-saws; but the edges of the blades are provided, at intervals, with small movable teeth, in which the diamonds are set. The diamond saw, it is claimed, is applicable to the sawing of all kinds of rock, including freestone, limestone, marble, slate, bluestone, and granite. It is especially valuable on the harder and more difficult kinds. Its speed of cutting is from ten to thirty times faster than by the best machinery heretofore in use for this purpose. It makes as narrow or narrower kerf, a better average quality of work, and saws as thin stuff.

It saves two thirds of the labor bill for sawing and handling, three fourths of the room and one third of the power.

The cost for diamonds and setting is less than for the sand and iron required to do the same quantity of work by the old method; and in sawing, marble will be wholly recovered by the value of the marble-dust obtained pure by this method, but entirely lost by the other.

On granite and other rocks too hard to be practicable in sand-sawing, and in a wide range of work now done exclusively by hand, the economies are still greater.

The invention is now in constant use on the largest scale, that is, with a machine capable of sawing blocks 11 ft. long by 6 ft. 6 in. high, by 4 ft. 6 in. wide, with complete freedom from practicable drawbacks.

No special skill is required for setting the diamonds.

The invention is embodied in machines of two distinct types, viz., the "Rip Saw", or single-blade machine, and the "Gang Saw", for any required number of blades.

The essential feature of the improvement is that the diamonds cut one way only. Without this provision the debris is carried backward and forward in the cut, choking the blade, wearing away the setting of the diamonds and hindering them from getting down properly to their work. Notwithstanding the extraordinary economics of working by these machines, it is said that the entire plant of an establishment using them, including the necessary engines, boiler, shafting, belting and buildings, will cost less than for the same productive power by the best sand saws.

– Science Record, 1873

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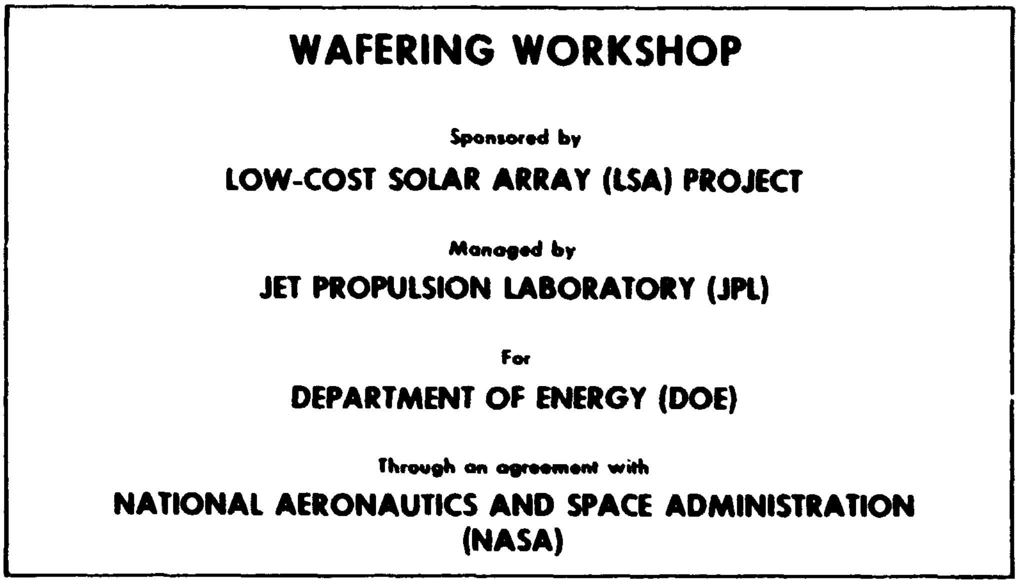
Welcoming Remarks

A. D. Morrison

Ladies and Gentlemen, welcome to this first-ever Wafering Workshop. This Workshop is sponsored by the Low-Cost Solar Array Project, which is managed by the Jet Propulsion Laboratory for the Department of Energy. For those of you who have not been part of the DOE/JPL/NASA/LSA Program, this Figure will serve as an introduction to our program.



WAFERING WORKSHOP

Sponsored by

LOW-COST SOLAR ARRAY (LSA) PROJECT

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For

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Through an agreement with

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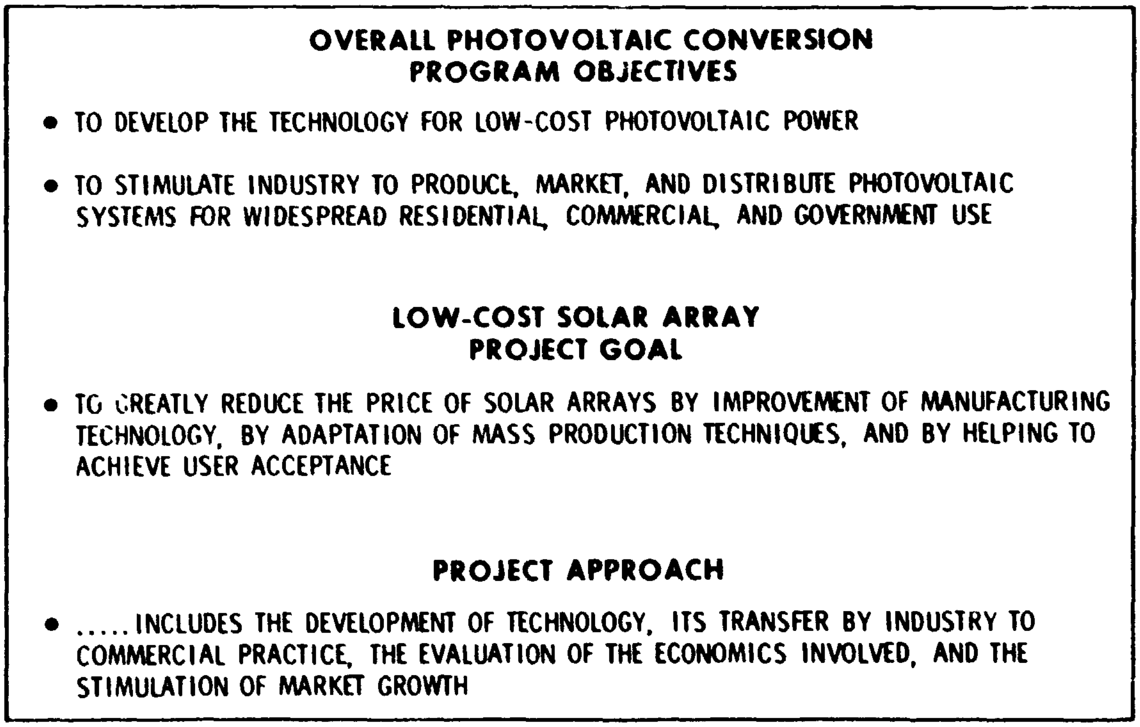
Established in 1975 under ERDA, the overall program emphasized technology development.



OVERALL PHOTOVOLTAIC CONVERSION PROGRAM OBJECTIVES

- TO DEVELOP THE TECHNOLOGY FOR LOW-COST PHOTOVOLTAIC POWER
- TO STIMULATE INDUSTRY TO PRODUCE, MARKET, AND DISTRIBUTE PHOTOVOLTAIC SYSTEMS FOR WIDESPREAD RESIDENTIAL, COMMERCIAL, AND GOVERNMENT USE

LOW-COST SOLAR ARRAY PROJECT GOAL

- TO GREATLY REDUCE THE PRICE OF SOLAR ARRAYS BY IMPROVEMENT OF MANUFACTURING TECHNOLOGY, BY ADAPTATION OF MASS PRODUCTION TECHNIQUES, AND BY HELPING TO ACHIEVE USER ACCEPTANCE

PROJECT APPROACH

- .....INCLUDES THE DEVELOPMENT OF TECHNOLOGY, ITS TRANSFER BY INDUSTRY TO COMMERCIAL PRACTICE, THE EVALUATION OF THE ECONOMICS INVOLVED, AND THE STIMULATION OF MARKET GROWTH

ORIGINAL PAGE IS
OF POOR QUALITY

The Project at the Jet Propulsion Laboratory has stressed the improvement of photovoltaic technology and its approach has included technology development and technology transfer.

Ingot wafering is a very important part of the technology. The goals which were originally established for wafering have not yet been achieved. There is a pressing need now to identify the specific barriers to success and specify and pursue the R & D necessary to overcome them. We need to do better and we need to do it soon. That is a real problem, and we are here to talk about it.

"We deal with it by talking about it."

Drawing by Koren; (c) 1975
The New Yorker Magazine, Inc.

All of us in the Project hope that this workshop will be of real value, not only to the Project by helping us achieve our goals, but to everyone here by helping you to achieve yours.

CONTENTS

OPENING SESSION

Chairman: A.D. Morrison, Jet Propulsion Laboratory 1

LSA Project Perspective of Wafering Technology Development:
K.M. Koliwad, Jet Propulsion Laboratory 3
Discussion 11

Comparison of Various Silicon Sawing Methods:
M. Wolf, University of Pennsylvania 13
Discussion 22

KEYNOTE ADDRESS

The Industrial Point of View: J.W. Yerkes, ARCO Solar, Inc. 25

Some Disconnected Speculations on Slicing Silicon:
P.A. Iles, Applied Solar Energy Corp. 29

ID TECHNOLOGY

Chairman: L.D. Dyer, Texas Instruments, Inc. 33

ID Wafering Technology: P. Aharonyan, Silicon Technology Corp. 35
Discussion 43

Allowable Silicon Wafer Thickness vs Diameter for
Ingot-Rotation ID Wafering: C.P. Chen and M. H. Leipold,
Jet Propulsion Laboratory 47
Discussion 59

Current Economic and Sensitivity Analysis for ID Slicing
of 4" and 6" Diameter Silicon Ingots for Photovoltaic Applications:
E.G. Roberts and C. M. Johnson, Kayex Corp. 61
Discussion 69

MATERIALS

Chairman: G.H. Schwuttke, IBM Corp. 79

Effect of Lubricant Environment on Saw Damage in Si Wafers:
T.S. Kuan, K.K. Shih, and J.A. Van Vechten, IBM Corp.,
T.J. Watson Research Center 81
Discussion 88

Influence of Fluids on the Abrasion of Silicon by Diamond:
S. Danyluk, University of Illinois 89
Discussion 99

The Uses of Man-Made Diamond in Wafering Applications:
D.B. Fallon, General Electric Co. 101

Wire-Blade Development for Fixed-Abrasive Slicing
Technique (FAST) Slicing:
C.P. Khattak, F. Schmid, and M.B. Smith, Crystal Systems, Inc. 111
Discussion 119

MULTIBLADE TECHNOLOGY

Chairman: R.L. Lane, Kayex Corp. 125

Design and Use of Multiple-Blade Slurry Sawing in a
Production Atmosphere:
F.P. Lynah, Jr., and J.B. Ross, P.R. Hoffman Co. 133

Kinematical and Mechanical Aspects of Wafer Slicing:
P.G. Werner, University of Bremen, Federal Republic of Germany 141
Discussion 152

Corrosion Inhibitors for Water-Base Slurry In Multiblade Sawing:
C.P. Chen and T.P. O'Donnell, Jet Propulsion Laboratory 159
Discussion 172

ECONOMICS

Chairman: M. Wolf, University of Pennsylvania 175

Field Experience with Various Slicing Methods:
H.I. Yoo, Applied Solar Energy Corp. 179
Discussion 185

Some Trade-Offs in Ingot Shaping and Price of Solar Cell
Modules: T. Daud, Jet Propulsion Laboratory 187
Discussion 196

Sensitivity Analysis of Add-On Price Estimate for Select Silicon
Wafering Technologies: A.R. Mokashi, Jet Propulsion Laboratory 197
Discussion 208

Wafering Economies for Industrialization From a Wafer Manufacturer's
Viewpoint: T.P. Rosenfield and F.P. Fuerst, Semix Inc. 211
Discussion 221

NEW TECHNOLOGY

Chairman: G.S. Kachajian, Silicon Technology Corp. 231

Overview of a New Slicing Method--Fixed Abrasive Slicing:
F. Schmid, M.B. Smith and C.P. Khattak 233
Discussion 241

System for Slicing Silicon Wafers:
E.R. Collins, Jet Propulsion Laboratory 243
Discussion 248

Diamond Sheet--a New Diamond Tool Material:
C.R. Mackey, Scomac, Inc. 249

ID Slicing and the Automated Factory:
T. Lewandowski, Silicon Technology Corp. 253
Discussion 257

Wafering Insight Provided by the ODE Method:
S.I. Soclof and P.A. Iles, Applied Solar Energy Corp. 259

CHARACTERIZATION

Chairman: P.A. Iles, Applied Solar Energy Corp. 267

Exit Chipping in ID Sawing of Silicon Crystals:
L.D. Dyer, Texas Instruments, Inc. 269
Discussion 278

Fundamental Studies of the Solid-Particle Erosion of Silicon:
J.L. Routbort and R.O. Scattergood, Argonne National Laboratory 279
Discussion 287

Pre and Post Annealing of Mechanical Damage in Silicon:
G.H. Schwuttke, IBM Corp. 289
Discussion 300

Status of SEMI's Solar-Grade Substrate Standards:
Brian D. Gallagher, Jet Propulsion Laboratory 305
Discussion 308

Index of Authors and Speakers 309

OPENING SESSION

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LSA PROJECT PERSPECTIVE OF WAFERING TECHNOLOGY

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ABSTRACT

Wafering is a necessary part of ingot technology in the production of silicon sheet for photovoltaic application. The Low-Cost Solar Array (LSA) Project is also pursuing the development of technologies that are capable of producing silicon sheets of required dimensions directly from the melt, hence eliminating the need for wafering. The ultimate choice of one versus the other is driven primarily by the economics and secondarily by maturity, access to technology and scaleability, among other factors. Technical progress made in both the ingot and the non-ingot technologies supported by the LSA Project is described briefly in the context of process economics. It is emphasized that significant breakthroughs in wafering technology are required to make ingot technology competitive with other silicon sheet growth technologies.

INTRODUCTION

The Low-Cost Solar Array (LSA) Project was formally initiated at the Jet Propulsion Laboratory (JPL) in January 1975 with the objective of developing, by 1986, a national technological capability of manufacturing low-cost, long-life photovoltaic modules at production rates that will realize economies of scale and at a price of less than $\$0.70/W_p$. (All dollar figures in this paper refer to 1980 dollars.) The LSA Project is part of the Photovoltaics Program of the U.S. Department of Energy (DOE), which is responsible for direction of the national effort to develop cost-competitive photovoltaic systems.

To achieve the stated objective, the LSA Project has emphasized the development of the following key high-risk, long pay-off technologies:

Silicon Material
Silicon Sheet Growth
Encapsulation Material
Solar-Cell and Module Fabrication.

It is extremely important to note that these developments are guided by the price goal. Table 1 shows these goals or targets. These goals take into account the potential trade-offs between solar-cell efficiency, material utilization, material throughput and other indirect costs associated with a silicon-sheet process.

This paper briefly discusses the critical technology element of sheet-growth processes in general and wafering processes in particular, along with

Table 1. LSA Project Summary of $0.70/W_p Module Price Goals

Module Component		Price Goal
Silicon Material		14.0 \$/kg
Sheet Alternatives	CZ ingot with wafering	27.4 \$/m^2
	Cast ingot with wafering	36.3 \$/m^2
	EFG ribbon	23.3 \$/m^2
	Dendritic web ribbon	38.6 \$/m^2
Cell Fabrication		21.0 \$/m^2
Encapsulation Materials		14.0 \$/m^2
Module Assembly		14.0 \$/m^2

the technical progress made to-date. Finally, the critical areas of research in wafering are delineated and their payoff potential is discussed.

SILICON SHEET TECHNOLOGY

Silicon sheet is the centerpiece of the photovoltaic module. Its growth process, shape and quality impose considerable requirements on the polysilicon material and solar cell and module fabrication. Materials costs dominate the cost of photovoltaic modules; hence, the photovoltaic technology must be based on unique material-conserving sheet processes. The technology strategy of the LSA Project is aimed primarily at developing that base. To that end, the LSA Project is pursuing the development of the following sheet-growth technologies:

Ingot Technology

Advanced Czochralski ingot growth
Ingot casting
Advanced wafering

Ribbon Technology

Edge-defined film-fed growth
Dendritic web growth.

The direction of the development of these technologies has been toward minimizing material utilization while achieving maximum throughput (m^2/h) and higher sheet quality within the bounds of the price guidelines mentioned above. One can exploit the trade-offs between these features. Specific technical goals have been assigned to each process through such trade-off analysis, and progress is measured with respect to those goals. Tables 2 through 7 show the specific technical goals related to material utilization, throughput and sheet quality (solar-cell efficiency) for each of the sheet technologies and the progress made.

The tables also contain other goals that are related indirectly to these three features and that strongly influence the process cost. It should be noted that to achieve the stated price goals, one has to achieve these features simultaneously. For example, achievement of the required throughput cited above is not sufficient if it uses more polysilicon material or results in sheet of unacceptable quality. Also listed in these tables are estimations of add-on sheet price, calculated using Interim Price Estimation Guidelines

Table 2. Advanced Czochralski Growth Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Output/crucible	(kg)	150	150	150
Ingot diameter	(cm)	15	15	15
Growth rate	(kg/h)	4	3.8	2.7
Throughput rate	(kg/h)	2.5	2.2	1.5
Furnaces/operator		4	1	1
Cell efficiency	(% AM1)	16	16	(16)
Equipment cost	($)	160,000	-	(160,000)
Ingot yield	(%)	90	>90	>90
Automation		Full	Partial	Partial
IPEG growth add-on	($/kg)	15.6	-	26.60
IPEG sheet add-on	($/$m^2$)	31.56*	-	64.00**
IPEG sheet add-on	($/$W_p$)***	0.22	-	0.45

*Assumes 0.74 m^2/kg (17 wafers/cm) wafering add-on of $10.48/$m^2$

( ): Estimated

**Assumes 0.70 m^2/kg (16 wafers/cm) wafering add-on of $26.00/$m^2$

***Encapsulated cell efficiency 14.25% AM1

Table 3. Heat Exchanger Method (HEM) Casting Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Yielded ingot mass	(kg)	35	45	35
Ingot dimensions	(cm)	30 x 30 x 15	33 x 33 x 17.7	30 x 30 x 15
Cycle time	(h)	56	Varies	56
Silicon growth rate	(kg/h)	1.3	3.1	1.3
Yield	(%)	86	85	(75)
Cell efficiency	(%AM1)	15	15.7	(14)
Machines/operator		10	(5)	(5)
Machine cost	($)	35,000	(60,000)	(60,000)
Mat'ls & util/cycle	($)	150	(300)	(300)
I Growth add-on	($/kg)	18.12	-	20.78
P Sheet add-on	($/$m^2$)	33.24*	-	50.59**
E Sheet add-on	($$W_p$)***	0.23	-	0.36
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*Assumes 1 m^2/kg, $15.12/$m^2$ wafering add-on ( ): Estimated

**Assumes 0.85 m^2/kg, $29.81/$m^2$ wafering add-on

***Module efficiency at 14.24% AM1

Table 4. Ubiquitous Crystallization Process (UCP) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Yielded ingot mass	(kg)	123	17	17
Ingot dimensions	(cm)	48 x 48 x 22	20 x 20 x 15	20 x 20 x 15
Yield	(%)	98	83	83
Material form		Semicrystalline	Semicrystalline	Semicrystalline
Cell efficiency	(% AM1)	15	15	NA
IPEG sheet add-on	($/$W_p$)	0.194	NA	NA

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*Assumes 1 m^2/kg, 14.25% AM1 module efficiency

Table 5. Advanced Wafering Technology Status

Technical Feature		Goal		Individual Demonstration		Simultaneous Demonstration	
Wafer size	(cm)	10 x 10	15 dia	10 x 10	15 dia	10 x 10	15 dia
Wafers/cm		25	17	25	17	25	17
Wafer thickness	(mil)	10	14	8	13	7	12
Kerf thickness	(mil)	6	10	8	11	9	12
Wafer throughput	($\min^{-1}$)	1	0.5	0.6	0.25	0.6	(0.25)
Yield	(%)	95	95	98	>90	(90)	>90
Machines/operator		6	6	(3)	(3)	(3)	(3)
Equipment cost	($)	30,000	30,000	-	-	(30,000)	(30,000)
IPEG add-on	($\$/m^2$)	11.58	10.48	-	-	25.71	17.33
IPEG add-on	($\$/W_p$)	0.08	0.07			0.18	0.12

*Encapsulated cell efficiency at 14.25% AM1 ( ): Estimated

(IPEG), a methodology developed at JPL to assess the progress of these technologies toward meeting the price goals. It is obvious that if the technology were frozen at the level of today's simultaneous achievements, the price objective of the LSA Project would not be met. However, the technical path has been very clearly defined by the LSA Project and if the momentum of the development is continued, the silicon-sheet objective of the LSA Project can be met. It is also worth noting that the difference between the price goal and the price estimate based on the frozen technology is smaller for ingot technology than for ribbon technology. That simply reflects the relative maturity of the two technologies. In other words, ribbon technology has stronger potential for improvement in material utilization, throughput and quality than ingot technology, and it requires more development in all those three areas. The potential improvements in ingot technology, on the other hand, lie only in improving material utilization and throughput. Advances in wafering will be a key to achieving those improvements.

Wafering Technology

Ingot technology is the most mature of the sheet technologies and is well entrenched in the photovoltaic industry today. For reasons stated above, without significant breakthroughs in wafering technology, achievement of low-price photovoltaic modules based on ingot technology will be in

Table 6. Edge-Defined Film-Fed Growth (EFG) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Ribbon width	(cm)	10	10	10
Growth rate	(cm/min)	4	4.2	3.3
Ribbon thickness	(μm)	200	150	300
Ribbons/furnace		4	5 (5-cm width) 3 (10-cm width)	3
Furnaces/operator		3	1	1
Cell efficiency	(%AM1)	12	13.2 (5-cm width) 10.5 (10-cm width)	(12)
Equipment cost	($)	49,000	NA	(60,000)
Growth period	(h)	160	15	5
Duty cycle	(%)	90	90	60
Melt replenishment & auto control		Yes	Yes	Yes
Yield	(%)	90	90	55
IPEG sheet add-on	($/m^2)	14.41	-	75.58*
IPEG sheet add-on	($/W$_p$)	0.13	-	0.69**

*Assumes growth period of 116 h
**Module efficiency of 11.4% AM1

( ): Estimated

jeopardy. The LSA Project has recognized this and has continued to focus its effort on this critical element of ingot technology.

The LSA Project has pursued development in inner diameter (ID) wafering, multiblade slurry sawing (MBS) and the fixed-abrasive slicing technique (FAST). The general thrust has been to achieve:

High material utilization (wafers/cm or m^2/kg)
High throughput (wafers/min)
Low expendables costs ($/m^2)
Low labor requirement (machines/operator).

Table 7. Web-Dendrite Growth (Web) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Ribbon width	(cm)	5	4	3
Growth rate	(cm^2/min)	25	27	15
Ribbon thickness	(µm)	150	150	150
Furnaces/operator		18	1	(2)
Cell efficiency	(%/AM1)	15	15	15
Equipment cost	($)	15,400	NA	(25,000)
Growth period	(h)	72	24	8
Duty cycle	(%)	90	71	71
Melt replenishment & auto control		Yes	Yes (8 h)	No
Yield	(%)	90	70	70
IPEG sheet add-on	($/$m^2$)	18.39	-	116.60*
IPEG sheet add-on	($/$W_p$)**	0.13	-	0.82

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*Assumes growth period of 72 h, melt replenishment & auto controls

**Module efficiency of 14.25% AM1

( ): Estimated

Table 5 lists the specific technical goals and the progress made to-date. It is a difficult and challenging area of investigation. The convening of this workshop is an indication of that fact. There is a great need for basic investigations for understanding mechanisms of cutting silicon, exploring ways to increase cutting rates, developing new blade and wire technology, etc. Existing knowledge in these and other critical areas is not sufficient. There are opportunities in wafering technology development, and the risks are worth the long-term payoff.

CONCLUSIONS

From the perspective of the LSA Project, the following conclusions are obvious:

1. Ingot technology is entrenched in the photovoltaic industry today.

2. The potential of ingot technology in achieving Project goals is extremely limited by the wafering component of that technology.

3. Considerable opportunities exist to advance the wafering technology through basic investigations and to achieve the required material utilization and throughput levels.

4. Ribbon technologies have made remarkable advancements; they still require significant development to achieve the goal.

DISCUSSION:

SCHMID: The graph that you put up is very interesting in that the web technology is extremely sensitive to throughput, far more so than any of the slicing.

KOLIWAD: That is correct. We know that, in the web process, the most difficult thing is the throughput. To achieve 25 square cm/min, we are talking of pulling a 5-cm-wide ribbon at 5 cm/min growth rate. If you try to grow 10-cm-wide web with 5 cm/min growth rate, you already get into the limits of the physics of the growth. But if you assume that it can do that, then the curve shows that web technology is much better than any other technology. Keep in mind that that is not the only parameter that goes into the technology analysis, but that was just an example. You may take another parameter where it may be the other way around.

Comparison of Various Silicon Sawing Methods

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INTRODUCTION

Solar energy utilization requires large areas to be covered with collectors, while the thickness of these collectors is usually relatively unimportant. For photovoltaic solar energy conversion, some of the common methods of material preparation generate this material in the form of boules of 10 to 50 kg, with crossectional dimensions of 10 to 30 cm. The slicing or wafering operation has the task of converting these boules into the thin sheets required for large area coverage. Slicing is thus an operation which is needed to match the requirements of one technology to the results of another, and it is expected to accomplish this with a minimum of cost and material loss. The sheets or wafers produced by this process sequence are in direct competition with those which result from crystal growth processes which lead directly to ribbons or sheets, and which do not entail material losses comparable to those of the slicing operation. Wafering thus is needed only as a companion operation, if the well established technology of boule generation is to be further applied in the manufacture of solar modules. To maintain competitiveness of the boule growing/slicing approach, the costs of the process and the material losses in slicing need to be substantially reduced.

Although a substantial number of different methods have been explored for the cutting of semiconductor materials, and particularly silicon, only four basic approaches are now in contention for the wafering of boules of large crossection. They fall into two categories: slurry sawing, and fixed-abrasive sawing. In each of the categories, two approaches based on differing tool shapes are being pursued. In the slurry sawing methods, the tool has the form of either blades or wires. In either case, a number of such tools is aggregated into a "blade pack". In the fixed abrasive sawing, the primary approach has evolved to the use of a circular blade with the cutting edge located at the circumference of a hole in this blade ("ID saw"). The newer approach (FAST) has the abrasive attached to wires which are arranged in a blade pack.

In the slurry sawing methods, the abrasive is suspended in a suitable oil ("vehicle"), often with certain additives, to form a slurry. The abrasive is frequently silicon carbide powder. In the fixed abrasive methods, diamond powder is always used as the abrasive. It is imbedded at and near the cutting edge of the tool by deposition of a metal matrix, which frequently is nickel.

STATUS OF TECHNICAL PERFORMANCE

Table I depicts the slicing capabilities available in 1978, projected improvements to be accomplished in the near term (ca. 1982), and the capabilities available now. These current capabilities are based on simultaneous attainment of the various attributes, as documented in LSA contractor project reports, and represent data which indicate repeatable accomplishments. The table indicates that considerable technical progress has been made, and that the projections are being approached by all methods, with the exception of multi-wire slurry sawing. The latter already met advanced specifications, and has not progressed further. While no projection had been made for the ID-saw, it has progressed substantially, and appears competitive with the other methods with respect to the number of wafers producible from a unit length of boule, or superior with respect to the ingot diameter cut.(1-8)

TECHNICAL DIFFERENCES BETWEEN THE CUTTING METHODS

The basic distinctions between the four major cutting methods have been mentioned in the introduction. They are also listed in Table II. Besides resulting in differing cutting performance, the various abrasive arrangements directly result in differing costs for expendables, which are saw blades in the fixed-abrasive case, or blades and slurry in the case of slurry sawing. The costs for these expendables will be discussed later with the other economic aspects. In the fixed abrasive method, the cutting action has been thought to be essentially at the edges of the abrasive particles, which thus would act like the teeth in the common machine tools, such as the steel saw blades. In the slurry methods, the cutting action has been thought to occur at the surface of the abrasive grains which roll over the workpiece under the activation of the tool. In consequence, the cutting action in the fixed abrasive method has been interpreted to be more like one of scraping, while in the slurry methods, the influence may more resemble the crushing of a thin surface layer.

As Table II shows, the tool can, in principle, have the shape of a wire, a ribbon, or a disk, for either cutting method. But the choice of tool shape controls the amount of normal force which can be exerted between the tool and the workpiece. In addition, the shape of the tool limits the types of tool motion which can be employed. The third independent variable is the tool motion, which, in principle, can be oscillatory or rotary. In rotary tool motion, much larger tangential velocities between the tool and the workpiece can be attained than with oscillatory motion, due to the mechanical constraints of the machine. However, there seems to be no practical possibility for application of multiple tools with rotary motion, be it a rotating disk or a rotating loop, such as in a band saw. In contrast, with oscillatory motion, a large number of tools can be used simultaneously, for instance, by arranging them in a blade pack. Up to 940 blades or wires have been used simultaneously in either slurry or fixed-abrasive methods.

The viability of any of these methods is ultimately determined by the add-on price of the operation. This add-on price is strongly influenced by two attributes: the productivity, and the mass of silicon used per unit sheet area (Table III). The productivity is a function of the linear cutting speed ("feed rate") attained, of the number of wafers cut simultaneously, and of the yield of the operation. The linear cutting speed depends primarily on the tangential tool velocity and on the normal force which can be exerted between the tool and the workpiece, as will be discussed in more detail later. The yield, finally, is a function of these same variables, and additionally of the quality of the tool, including its maintenance which may include periodic "dressing", as well as of the operational control which may include control of blade flutter or bending.

The amount of sheet area produced per unit mass of silicon depends firstly on the thickness of the kerf which, in turn, is a function of the thickness of the tool as well as of tool flutter and "run-out". The conversion of mass to area is further controlled by the minimum thickness of the wafer attainable with acceptable yield. This thickness depends, to a large degree, on the forces exerted by the tool onto the wafer. Further variables in the mass to area conversion are non-uniform thickness ("taper") or bowing of the wafers, as well as the thickness of the damaged layer which needs to be removed before device processing. Within limits, the variables are determined by the tool characteristics and the abrasive particle size. And again, yield enters into the conversion rate as a function of the variables already mentioned.

In addition to productivity and the mass-to-area conversion rate, the add-on price of the operation is based on the original price of the machine, on the cost of maintaining it, on the expendables, the labor cost, and the plant facility requirements. The question thus becomes: which of the available sawing methods will provide the best compromise between all these variales, or summarily stated, will result in the lowest price per unit area of silicon wafer?

For a while, fixed-abrasive sawing had been advocated as inherently capable of higher cutting speeds than slurry sawing. Also, it had been felt that a wire can be adequately tensioned longitudinally to exert the desired normal force on the workpiece, and that a wire can be more readily configured to a smaller thickness than a blade, in order to yield a lower kerf. This thought has led to the multi-wire slurry saw (Yasunaga YQ-100) and to the multi-wire fixed-abrasive system called "FAST" (Crystal Systems, Inc.). The compromise is the multi-blade sawing system, for which machines have been sold for a long time by Varian, Meier and Berger, and Hoffman. The most commonly used method for silicon sawing is the fixed-abrasive ID-blade method, which evolved from the previously applied sawing with OD-blades. In the ID sawing method, substantial blade stiffness is obtained by the particular arrangement of the cutting edge and by the considerable radial tension applied to the blade. Machines for ID-sawing are sold by Silicon Technology Corporation, Siltec, and Meier and Berger.

Table IV lists the characteristic attributes of the four methods, which may help in understanding the performance differences. The first attribute listed is the tangential velocity v_t of the tool relative to the workpiece. For the rotary motion of the ID-blade, this tangential tool speed is one to two orders of magnitude larger than achieved by the oscillatory motion in the multi-wire and multi-blade systems. It may be noted that the FAST system has attained a tangential tool speed a factor of 3 to 5 higher than attained in the previous machines with oscillatory movement.

The next attribute of the sawing method is the "blade load" F_n, which is the force in the direction of penetration of the tool into the workpiece (normal force). It is seen that the multi-wire and multi-blade systems all work with comparable blade loads, while the ID blade has a blade load one to two orders of magnitude larger. In consequence of the differences in tangential tool speed and blade load, the feed rate v_c in the multi-wire and multi-blade systems is two to three orders of magnitude smaller than in the ID method. The same consequences are seen for the productivity which is defined as the wafer area cut per minute and per blade.

These direct attributes may be used to derive two parameters which may be more basic indicators of the process characteristics: the relative cutting rate v_c/v_t, and the abrasion rate. The relative cutting rate expresses the depth of penetration into the workpiece per unit length of tangential movement of the tool. The abrasion rate expresses the volume of material removed per unit time and per blade. The same large differences between the multi-wire and multi-blade systems on one side and the ID systems on the other are apparent in Table IV for the abrasion rate as was observed for the feed rate, but the relative cutting rates are much closer, with the wire-slurry saw performing close to the ID-saw. The fixed-abrasive wire saw, for which a higher relative cutting rate would have been expected, fits right in with the slurry saws. Thus, another variable must more strongly influence the cutting process, and a look at Table IV would suggest the blade loads. As the reports on ID-sawing did not contain any blade load information, an inquiry at STC produced a small data matrix obtained in an earlier experiment there.(9) Plotting these data as feed rate v_c versus blade load F_n, with v_t as parameter, gave, in good approximation, three straight lines through the origin (Fig. 1). Further plotting the slopes of these lines as function of tangential tool speed v_t could again be well approximated by a straight line through the origin (Fig. 2). The linear cutting speed, or feed rate v_c is thus essentially proportional to both the tangential tool velocity v_t and the blade load F_n. While this relationship has been obtained with the ID saw at high F_n and v_t values, applying this relationship to the data for the multi-blade and multi-wire slurry sawing and the FAST methods with their low F_n and v_t values revealed an amazingly close fit to their experienced feed rates. Introducing a correction for the kerf thickness k, since the effect of the blade load on the cutting action should be inversely proportional to the kerf thickness, brought a further improvement of the approximation (Table V). The following relationship was thus found to well represent the feed rate for the sawing methods investigated here:

$$v_c = 4.2 \cdot 10^{-6} \frac{v_t \; F_n}{k} \; [\text{cm min}^{-1}] \quad (v_t \text{ in cm mih}^{-1},\ F_n \text{ in g, k in } \mu\text{m}) \qquad (1)$$

While this representation of all cutting methods for silicon by the same "General Cutting Equation" is striking, it is to be recognized that it is strictly empirical, and that the "constant" should depend on details of the cutting action. This is apparent, for instance, in Varian run 2-1-02 and Solarex Yasunaga run 14, where a soft blade and a finer abrasive were used, respectively. Nevertheless, equ. (1) indicates that the supposed substantial difference in cutting action between the fixed abrasive and the slurry methods can be of only minor influence under the cutting conditions generally applied. In contrast, blade loading and tangential tool velocity are the important attributes for obtaining high cutting speeds. Clearly, the tool arrangement has a substantial influence on the normal force which can be exerted by the tool onto the workpiece. Probably the worst arrangement for this purpose is the wire saw where the normal force is usually only a small fraction of the longitudinal force F_L in the wire, with the latter limited by the mechanical strength of the wire (Fig. 3). The situation should be substantially better in the blade approach, which acts essentially as a beam, and where the longitudinal forces are applied primarily to prevent buckling. In the ID saw blade, the force distribution is quite complicated, but this should be the most favorable arrangement of the three with respect to attaining high blade loads with a given blade material. In consequence, it seems that the emphasis should shift more to better blade design for high blade loading, and to machine design for higher tangential tool velocities, to attain higher cutting speeds in order to achieve more economical sawing.

Experience has shown that the ID cutting method generally results in a thicker damaged layer than the other methods. In light of the preceding discussions, it may be speculated that the blade loading rather than the cutting method may be responsible for the larger saw damage. It is tempting to generalize that higher blade loading would always result in increased saw damage. It will therefore be worthwhile to investigate this aspect, and to determine the appropriate trade-off between damaged-layer-thickness and blade loading for optimum economy in the cutting operation.(10)

ECONOMIC ANALYSES

Several organizations have performed cost analyses for the various wafering machines on the market or under development, and have arrived at comparable add-on prices for similar slicing systems, when they have used the SAMIS-IPEG method.(2-6,8) Also, a comparative analysis of the add-on prices and the total wafer prices (in 1975 dollars) had been carried out three years ago(1) for the four slicing methods discussed in the preceding sections, based on production experience as far as available, on experimental runs, or on projections made by the various companies. The then current prices and projections, now expressed in 1980 dollars, are compared in Table VI with those resulting from the current technology status, or from recent projections. Most of the available analyses give the "direct add-on price" of the operation itself, which gives an incomplete picture, although it has the advantage of being independent of the silicon price. More informative is the "total add-on price", which includes the cost of the silicon lost in the operation, which varies between the different methods and with technology status. Of highest information value is the "wafer price", which includes also the cost of the silicon contained in the good wafers, which is determined by the wafer thickness which is also a function of method and technology status.

For the multi-blade slurry saw, Table VI contains 1977 production data, projections made at that time for 1982 technology, prices achievable with the current technology, derived from experimental runs, and data projected by Varian for technology improvements expected to be available by 1984. It is evident that substantial progress in reducing the direct add-on price has been achieved for the multi-blade slurry saw, although it does not yet approach the 1978 projection. Also, the projections to 1984, made in light of newly gained knowledge, fall reasonably close to the earlier projection. It may be noted that a recent analysis by P.R. Hoffman Comp. has resulted in comparable numbers. Further reducing the kerf thickness, and thus the cost of lost silicon, would significantly help to reduce the total add-on price. It may be noted that a projected silicon price of $100/kg, after grinding to uniform diameter, has been applied in consequence of an earlier projection which expected single crystal silicon to be available at that price by 1982. Also, a reduction of the ground ingot price to approximately $40/kg had been projected for 1986.

This would reduce the wafer price to about $80/m^2 using the Varian projection. This value is substantially higher than the sheet price allocation of $27.4/m^2 for achieving the 1986 module price goal of $0.70/W(peak).

For ID sawing, the 1978 price analysis had been made on the basis of ASEC experimental runs, and no projection for further technology improvements had been made. Significant progress has, however, been made in ID sawing, particularly in reduction of wafer thickness and kerf, as well as in machine productivity. Thus, both the direct add-on price and the amount of silicon used have been reduced by approximately 1/3, so that the currently possible wafer price essentially matches the projected price of the MBS saw.

The multi-wire slurry saw (Yasunaga) has been used experimentally for silicon slicing, without any known technology improvements. Consequently, the 1978 data are still valid. Primarily because of the high material costs, the direct add-on price for this process is high. Although the process requires the minimum use of silicon, this attribute is not adequate to achieve competitive wafer prices.

The FAST method is still in the developmental stage. The data provided by Crystal Systems(8) have been used for an IPEG price analysis based on extrapolation to a production situation of the best simultaneous data achieved so far. In addition, a projection has been made based on Crystal Systems' "Optimistic Estimation" data. This projection includes the assumptions that 1500 wafers can be cut simultaneously with 2 cutting systems on the machine, and that 10 loads can be cut with each blade pack with 0.14 mm/min average cutting speed in 10cm x 10cm blocks.

CONCLUSIONS

Of the three existent methods subjected to technical and economic analysis in 1978, the MBS and the ID sawing methods have undergone further technology development. Also, considerable development has been carried out on the new fixed-abrasive multi-wire saw (FAST). While considerable technology advancement has been achieved with all three methods, the ID saw system is the only one commercially ready, that has approached the price projections made three years ago. However, even at the projected price of $40/kg for ground ingots, the achievable wafer price of $80/m^2 would not be adequate to meet the solar module price goal for 1986. With the exception of the multi-blade slurry saw, projections for further technology improvements are not available. Advances might be available from further improvements in machine and blade design to achieve higher tangential tool velocities and blade loadings. Such advances may be sought through better utilization of material properties, design possibilities, and perhaps material selection, without substantially increasing the expendable costs. The thickness of the damaged layer on the wafers may depend on the blade loading. This aspect should be further investigated, and it may set a limit to the economically useful blade loads, and consequently cutting speeds.

REFERENCES

1. Wolf, M., et al., Rec. 13th IEEE Photovoltaic Spec. Conf., IEEE Cat No.

78 CH 1319-3, pp. 271-280, June 1978.
Goldman, H., and Wolf, M., Univ. of Pennsylvania Quarterly Report DOE/JPL-954796-78/4, Nov. 1978.

2. Yoo, H., et al., Rec. 13th IEEE Photovoltaic Spec. Conf., IEEE Cat No. 78 CH 1319-3, pp. 147-151, June 1978.
   Yoo, H., Opt. Coating Lab. Final Report DOE/JPL-954830-78/2.
3. Aharonyan, P., Silicon Technology Corp. (STC) Quarterly Report DOE/JPL-955131-79/1, June 1980.
   PIM Presentation, Feb. 1981 under DOE/JPL contract 730105.
4. Fiegl, G.F., and Bonora, A.C., Rec. 14th IEEE Photovoltaic Spec. Conf., IEEE Cat. No. 80 CH 1508-1, pp. 303-308, Jan. 1980.
   Fiegl, G.F., SILTEC Corp. Quarterly Report DOE/JPL-955282-80/7, Oct. 1980, and preceding Quarterly Reports.
5. Fleming, J.R., et al., Varian Assoc. Fin. Rep. DOE/JPL-954374-10, Sept.'79.
6. Ross, J.R., P.R. Hoffman Comp. Fin. Rep. DOE/JPL contract 955563, May 1980.
7. Anderson, F.R., Rec. 14th IEEE Photovoltaic Spec. Conf., IEEE Cat. No. 80 CH 1508-1, pp. 309-311, Jan. 1980.
   Solarex Corp. Final Report DOE/JPL-955077-79, Mar 1980.
8. Schmid, F., et al., Crystal Systems Quarterly Report DOE/JPL-954373-80/16, and other Quarterly Reports.
9. Lewis Fisher, STC, private communication.
10. Daud, T. et al., Rec. 13th IEEE Photovoltaic Spec. Conf., IEEE Cat. No. 78 CH 1319-3, pp. 142-146, June 1978.

Table II THE KEY VARIABLES IN SILICON CUTTING

Independent Variables	Choices		Dependent Variables
Abrasive Arrangement	Fixed	Movable (Slurry)	Expendables (Tool with imbedded abrasive, or blade and slurry)
Location of Cutting Action	Edges of "Teeth"	Surface of Rolling Grains	
Type of Cutting Action	Scraping	Crushing	
Tool	Wire, ribbon (band), disk		Normal force between tool and workpiece
Tool Motion	Oscillatory, Rotary		Relative tangential velocity between tool and workpiece

Table III INFLUENCE OF THE KEY VARIABLES ON THE CRITICAL ATTRIBUTES

Attribute	Immediate Variable	Ultimate Variable
Productivity	Linear Cutting Speed	Tangential Tool Velocity, Normal Force, Cutting Action
	Number of Wafers Cut Simultaneously	Tool Arrangement
	Yield	All Above, Tool Quality, incl. Dressing, Operation Control
Sheet Area per Unit Mass of Si	Kerf	Tool Thickness, Flutter
	Wafer Thickness	Tool Forces on Wafer
	Taper, Bow, Thickness of Damaged Layer	Abrasive Size, Tool Forces, Operation Control
	Yield	(See under "Productivity")
Price	Productivity Sheet Area per Unit Mass of Si Machine Price Maintenance Costs Expendables Labor Facility Requirements	

Table I TECHNOLOGY PROGRESS 1978 TO 1981

	UNITS	SLURRY SAWING						FIXED ABRASIVE SAWING						
		MULTI-BLADE			MULTI-WIRE			MULTI-WIRE			ID-BLADE			
		1978	PROJ'D	1981	1978	PROJ'D	1981	1978	PROJ'D	1981	1978	PROJ'D	1981	
INGOT SIZE	CM DIA	10	12	10	7.6	10	8		10x10	10	10		10	15
KERF THICKNESS	µM	330	200	270	200	100	200		300	175	350		275	325
WAFER THICKNESS	µM	330	250	250	210	200	200		100	225	260		125	300
WAFERS/CM	CM^{-1}	15	22	18-20	24	33	25		25	25	14		25	16
YIELD	%	84	95	90-95	100	100	90		100	80-95	98		98	85
PRODUCTIVITY	CM^2/(MIN. BLADE)	0.07	0.06	0.02-0.12	0.08	0.04	0.08		0.1	0.04-0.1	20		20	44
NUMBER OF BLADES	-	230	900	400 (940)	215	333	75		250	? (750)	1		1	1

Table IV Characteristic Attributes of the Different Sawing Methods

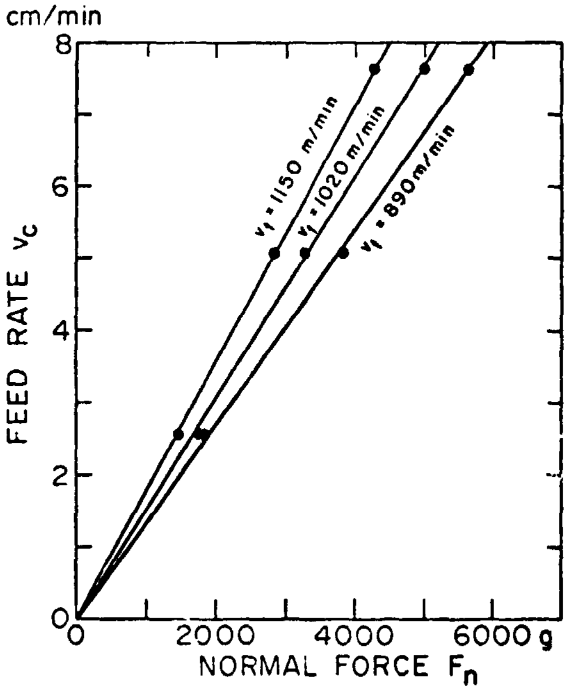
ATTRIBUTE	UNITS	SLURRY SAWING		FIXED ABRASIVE SAWING	
		MULTI-BLADE (VARIAN 686, M&B1, HOFFMAN PL-4)	MULTI-WIRE (YASUNAGA YQ-100)	MULTI-WIRE (CRYSTAL SYSTEMS FAST)	ID-BLADE (SILTEC AND STC
TANGENTIAL TOOL SPEED	M/MIN	12-50	72-82	60-150	800-1200
BLADE LOAD	G/BLADE	50-300	~100 AVE.	20-45	1500-6000
FEED RATE (LINEAR CUTTING SPEED)	10^{-3}CM/MIN	0.4-17	6-19	4-15	400-3800
PRODUCTIVITY	CM^2/(MIN· BLADE)	0.01-0.12	0.03-0.08	0.04-0.1	10-44
RELATIVE CUTTING RATE	$\cdot 10^{-6}$	0.1-3.4	6-16	0.7-1.2	5-38
ABRASION RATE	$\cdot 10^{-4}$ CM^3/(MIN· BLADE)	2.5-30	9-16	22	500-5000

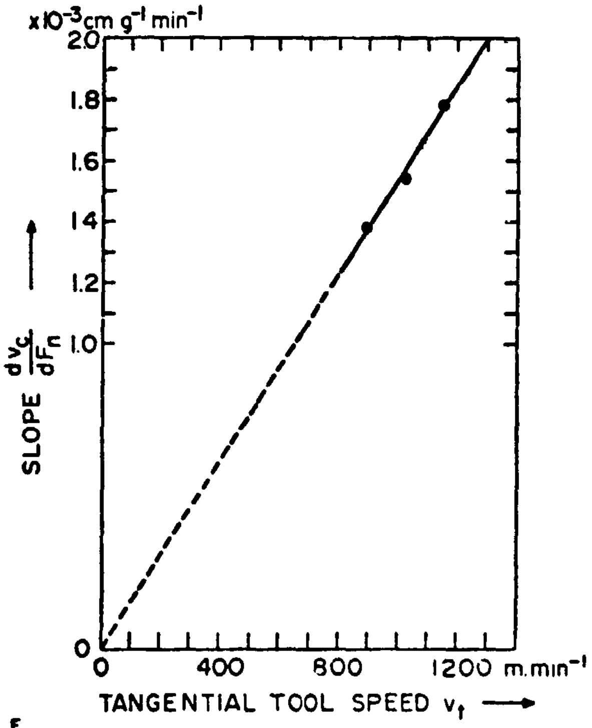
Table V COMPARISON OF EXPERIMENTAL FEED RATE WITH FEED RATES CALCULATED FROM GENERAL SILICON CUTTING EQUATION

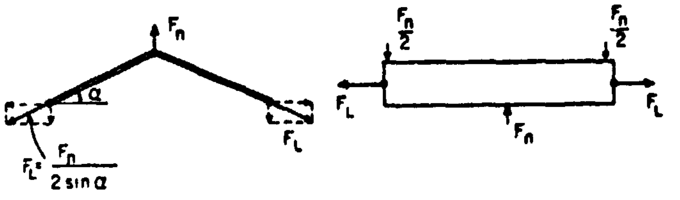
METHOD (CONTRACTOR)	MBS SAW (VARIAN)				YASUNAGA YQ-100 (SOLAREX)				FAST (CRYST. SYST.)			ID SAW (STC)
RUN #	2-1-02	2-3-04	2-5-14	2-7-06	3	8.4	11	14	2-002	328-SX	448-SX	(REF)
INGOT DIA. (CM)	10	10	10	10	8	8	7	6	10	10	10	9.8
NO. BLADES	150	137	150	940	75	75	80	75	114	144	167	1
PARAMETERS	LAB SAW #600 SIC SOFT BLADE	686 SAW #500/600/800 SIC	686 SAW #600 SIC	LARGE SAW #600 SIC	15µM SIC	15µM SIC	10µM SIC	5µM SIC	163µM WIRE 45µM DIAM'D.	AS RUN 2-002	125µM W WIRE CSI COD P'D	NA
YIELD (%)	86	83	83	90	87	100	95	99	97	77	80	NA
V_T (CM/MIN)	3870	4300	3900	3850	7200	8200	8200	7900	6100	12200	8900	102,000
F_N (G)	85	85	113	85	102	102	104	102	37.8	42.4	32.5	5270
κ (µM)	240	250	260	240	200	250	200	220	270	250	230	275
V_C (CALC) (10^{-3} CM/MIN)	5.8	6.1	7.1	5.7	15.4	14.1	17.9	15.4	3.9	8.7	5.3	5100
V_C (EXP) (10^{-3} CM/MIN)	2.3	7.5	6.1	4.3	13.9	13.8	15.7	6.1	5.9	14.3	9.4	5100

Table VI **COST AND PRICE COMPARISONS**

(1980) $/M²	MBS SAW 1978	MBS SAW PROJ'D	MBS SAW 1981	MBS SAW PROJ'D (VARIAN)	ID SAW 1978	ID SAW 1981 (STC)	YASUNAGA 1978	FAST 1981	FAST PROJ'D
MATERIALS	49.31	9.90	22.36	11.63	6.33	4.37	97.45	15.92	1.76
LABOR	35.98	3.26	20.55	4.04	9.16	9.86	15.54	58.15	3.16
CAPITAL COST	10.96	6.30	12.98	7.94	10.40	5.71	13.65	10.63	0.91
RETURN EQUITY	36.92	9.87	31.00	14.38	21.31	12.72	42.80	34.32	2.65
DIRECT ADD-ON	133.91	29.61	87.81	38.48	47.88	33.04	[illegible] 21	119.75	8.54
LOST SI	76.-	51.-	60.-	46.-	82.-	79.-	64.-	71.-	40.-
TOTAL ADD-ON	210.-	8[illegible].-	148.-	84.-	130.-	112.-	234.-	191.-	55.-
SI CONTENT	97.-	58.-	59.-	59.-	84.-	47.-	47.-	47.-	41.-
WAFER PRICE	307.-	139.-	207.-	143.-	214.-	159.-	261.-	238.-	96.-
WAFER µM	400	250	250	250	360	200*	200	200	175
KERF µM	275	200	200	150	350	280	200	250	225
YIELD %	95	95	95	95	95	95	90	90	95
DIA. CM	2x7.5	12	10	12.5	10.16	10	7.6	10	10x10
BLADES	250	900	300-400	900	1	1	75	250	2x750
MISC.	SPECTRO-LAB PROD'N VARIAN 686		IN-HOUSE BLADE-PACK ASS'Y.	DTO. 33% ABRAS. RECYCLE LOWER-COST OIL	5.1 CM/MIN ASEC EXPER. RUNS	5.1 CM/MIN *LIMITED BY ETCH REQUIREM'T	ASEC & SOLAREX EXPER. RUNS	0.1 MM/MIN 3 WAF./BLADE $70.-/BLADE 5 MACH/OPER.	0.14 MM/MIN 10 WAF./BLADE PACK 10 MACH/OPER







FORCES ON SAW WIRE FORCES ON SAW BLADE

Fig. 1 (above left)
Fig. 2 (above)
Fig. 3 (left)

DISCUSSION:

SCHMID: We are cutting at 4 mils a minute and that was our projection. The machine is designed to cut 750 wafers per blade head with two blade heads. We have never done 750, we are doing 230 actually and that is with 25/cm. The big difference in throughput is really not cutting rate, it is just the number of blades that we have cutting (230 as opposed to 1500). The reason that we have two blade heads is in fact to go to the higher speeds. Speed and pressure are clearly the determining factors in the cutting effectiveness of this whole thing. Even at the 230 blades right now we are able to compete quite effectively.

WERNER: Your equation is in very close accordance with some basic theories on grinding as established by Peters and Leweven and some other people including myself.

DYER: I would like to make two comments. First of all, if you don't get the yield in the laboratory, I very much suspect that you are not going to get it on the production floor. I don't think anybody here will disagree with that; if you don't get it there you won't get it anywhere.

WOLF: I have both experiences and at one place we were able to do much better in the laboratory than the production line did, and in another place, it was the other way around. The production line was very well controlled and they could do better than the lab could do. So both things can exist.

DYER: The other comment is on the phenomena going on in the cutting. You had divided these into scraping and crushing action in the two cases of the wire and the fixed abrasive. In either case these are contact problems that involve fracture which has been almost ignored in most of the saw literature and a lot of the discussions. I would [illegible] make a plea for the fact that this literature of perhaps 60 years [illegible] tens of thousands of papers in it should not be ignored in this consideration. I am sure that you are aware of this.

WOLF: I had read years ago some reports that made the difference of cutting versus one that is more grinding on the basis of peeling where you have a cutting tool which lifts off a part of the workpiece and forms a divot. If you can lift up a part of the material with a tooth of the tool you certainly should expect to get a higher cutting rate, than if you just crush the surface. I think this was the basic theory about the fixed abrasive being able to lift off a part of the material versus a crushing of the surface layer in the slurry system.

SCHWUTTKE: I am not so suprised that you will find such a simple relationship that you need only a few data points to come up with a simple cutting equation. It really relates to the fact that you are separating bonding in silicon and that is a constant number. It doesn't matter how you cut silicon, it is always the same force required to do this. In the cutting process itself, what you really do is generate successively great numbers of shear loops in the silicon and there is always a certain amount of energy needed to generate a shear loop, so you have to come out with a very simple straightforward equation. You really don't need many data points to get to that.

WOLF: If you could really form a chip and lift off a whole layer of the material at once with the same force, you should be able to remove more material, but we have not found a method that does it effectively. We all use the same method of essentially crushing the surface layer and doing the damaging of the bond and removing a little bit of the material at a time.

SCHWUTTKE: I can comment on what crushing and abrasion means. Crushing actually is nothing but a generation of microcracks and abrasion is a generation of shear loops. But, if you generate too many shear loops you have a pileup of shear loops and they lead to microcracks. So you can extrapolate from a fast technique to a slow technique; it is always the same thing. You put the same amount of energy in. In one case you do i fast and the other you do it slow.

WERNER: In these microremoval processes, lapping, grinding, or honing, the experts speak about specific energy to remove a certain amount of material and that is a constant, or nearly a constant value, so you are both right. It is a material-related constant value.

SCHMID: With respect to surface damage as a function of load, we did some work along that line in which we were working with 30-gram and 100-gram loads and looked at both the cutting speed and the surface damage. With the 30-gram load we got a surface damage of about 5 microns and I think our cutting rate was in the 3 mils a minute range. With 100 grams we were up around 7 mils a minute and the surface damage went up to 18 or 20 microns so it was very significant. I suspect that that would be true with respect to the type of particle that you use. If you are using a large particle size, you would probably have less particles contacting the workpiece so it really would be a function of that plus the kerf. It all boils down to the pressure and speed at the cutting point. Our work has only been done with pressure; I don't know what the affect of speed would be, but that is something that we would hope to get at.

N82 23653 D3

ARCO SOLAR, INCORPORATED THE INDUSTRIAL POINT OF VIEW

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Sawed slices for use in the solar cell industry maybe reaching their zenith during the next two years or......

Sawed ADVANCEDCZ and SEMIX or SILSO wafers continue to dominate the photovoltaic electric business for the last ten years.

The photovoltaic electric market has progressed due to present multimegawatt per year status in a short time. It has become a rapidly growing business by making slices sawed with ID saws and grown from semiconductor silicon.

ADVANCED CZ

Rapid improvements in the size, speed and automation of CZ growers have been made since 1979. ARCO Solar regularly uses JPL developed recharge equipment for multiple crucible pulls. Proprietary modifications to growers have dramatically increased average pull speeds. Microprocessor control systems assure repeatability and minimize training requirements. Making CZ ingots in production is now a very fast, simple task.

POLYCRYSTALLINE BLOCKS

Work done in Germany by Wacker Chemie and in the USA by Solarex have developed pilot production casting systems for manufacturing large grain polycrystalline blocks, casting the block in a square mold partially offset the lower average solar cell efficiency and wider variation of yield now experienced by these materials.

ARCO Solar was the first company in the USA to receive the processed SILSO material from Germany in late 1976. Meetings with Task II personnel at JPL cast doubt on the commercial promise of this concept. Fortunately, the Germans were not stopped by these opinions and neither were the Hungarians.

In the last three years, ARCO Solar has processed several tons of POLYCRYSTALLINE SILSO blocks and has a production ready process. The blocks, however, still cost over twice that of in house CZ ingots. Our cost estimates consider direct labor material, overhead and the fact that ARCO Solar CZ cells AVERAGE over 14% AM 1 efficiency without antireflection coating. Wacker Heliotronic is installing a larger pilot casting and machines and Solarex is continuing to develop SEMIX production. Both systems are improving, but, so is ADVANCED CZ.

Sharp Corporation in Japan has recently come on-stream with a four inch CZ module with sizeable production capability. The market during 1982-83 will prove very competitive.

LOWER COST SAWED WAFERS

Very simple and are now proprietary at least ten to twenty megawatts of production capacity between CZ and the cast-block producers. The obvious minimum risk most predictable cost reductions are:

A. Low cost polysilicon to make the wafer materials cost less making curf loss less important.

B. Better saws capable of sawing larger ingots and blocks reliably with more slices per inch.(less curf, etc.)

Item A has been discussed at other meetings and is underway by several commercial companies including ARCO Solar.

Item B as reported to me and from my own experiences, is still a "Non Event."

ID SAWS

ID saws are getting larger with 27" and 32" proposed (more diamonds). These saws will require less blade changes and saw bigger wafers (more watts per minute). Revolutionary efforts, such as rotating ingots at Siltec went down in flames.

WIRE SAWS

Crystal Systems has not been able to demonstrate production feasibility under JPL funding, but, there is hope. Motorola was rumored to have wire saw technology that is a proprietary company secret?? Solarex tested a Japanese wire saw with poor results.

BLADES

Varian Associates had a good contract from JPL but forgot there was a real commercial market for their product. Management did not continue funding their project, hence, technical problems were not over powered. Reports from Switzerland indicate the Meyerberger efforts have not met the speed/productivity goals set, even when a larger curf allowed.

NEW STARTS

Flat-lining or cutting back the DOE program plus emphasis on "Thin-Film" or "Ribbon" breakthroughs have cast sawing technology into a scrap heap. Our minds are in neutral. I would guess the right people to solve this problem may not even be at this conference.

If you don't devise and develop a fast, reliable production saw, then history can record that:

> After developing the industry into a multimegawatt position from 1973-83, solar wafer growing or casting and sawing remain a technique for the semiconductor industry. The solar cell industry abandoned these techniques for:
>
> A. Silicon ribbon
> B. Various thin films

If you view this as inevitable, then, that is what will happen. If you believe you have a better idea, let industry know about it.

Your better idea can lengthen the productive life of at least 100 million dollars worth of investment.

Discussing the latter view is the purpose of this meeting.

SOME DISCONNECTED SPECULATIONS ON SLICING SILICON

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This talk has two purposes:

1) To remind workshop participants of the basic principles needed to qualify wafering methods.

2) To briefly describe some offbeat approaches we have considered, mainly to encourage others to volunteer unconventional ideas.

The main purpose of the workshop is to open up new areas of applicable technology. To overuse a current phrase, we are to explore and extend the "cutting edge" of cutting edge technology.

First the basic principles:

We must slice silicon from large grown or cast ingots (tens of kg mass, dimensions hundreds of centimeters). Although some pre-slabbing is OK, the slices must be 75-100cm deep.

The method must have:

- High slicing yield (m^2/kg).
- High throughput (m^2/hour).
- Minimal damage.
- Reliable equipment, applicable to single or poly crystals.
- Low cost.

High yield results from reduced sum of the (slice + kerf) (S+K) thicknesses (Figure 1). We see that high yields result from reduced kerf and also from reduced slice thickness.

Although reduced kerf is less important when the silicon cost is lower, the cost of generating this scrap must be included. Generally, reduced K and S are obtained by reduced slicing speed; to maintain reasonable throughput, this leads to the need to form many slices simultaneously. This reduced slicing rate will, however, reduce work damage. The formation of many slices must not lead to increased complexity, monitoring or maintenance; if possible, the scrap silicon should be available for reprocessing. Remember, that all necessary conditions must be met by a successful slicing method.

I will now turn to the offbeat approaches:

Like many others, we were frustrated at having to waste so much high quality silicon in our daily slicing procedures. We had also envied the kerfless operations of baloney slicers, or of foam plastic cutters in a neighboring factory. For this reason, we speculated on possible uses of cleaving to form slices. In cleaving, the kerf loss is zero, although some crystallographic orientation is required, and we knew from experience that cleaving thin slices was difficult, because the cleavage forces turned towards the free surface, even when we tried damping this surface.

At the time we considered this, a popular TV ad showed the vibration-free Ford Granada automobiles, by demonstrating a skilled diamond cutter cleaving a valuable diamond while in the back seat of a moving Granada - very dramatic, and we all sighed with relief when he achieved a perfect "cut" of this valuable item near the end of the ad. On short analysis, we ruled this method out, because of the high labor cost of the cutter and of the always present, non-productive companion who was describing the process, the slow throughput, (one per ad) and also because we could not afford to buy the Granada.

We next turned to geology for a possible method. The phenomenon we considered can break large granite boulders, by using the expansion of water trapped in small crevices when it freezes. We combined this method with our ODE slicing method, wherein many close spaced, narrow slots are formed parallel to the (111) planes which are natural cleavage faces for silicon. We formed fairly deep slots, filled them with water and froze the water by immersion in liquid nitrogen. We were not successful in cleaving the silicon, although there is a chance that with modifications this method could work. Since this method used slow application of force to cleave the silicon, we next turned, in a whimsical mood, to consider fast impulse applications. Also around this time, an article in Scientific American analyzed the forces involved in Karate blows used to break concrete or wooden blocks (see Figure 2). Short calculations show that with suitable concentration of this force in narrow slots (perhaps aided by a small wedge), we could exceed the rupture strength of silicon, and that slices of silicon several centimeters thick should be achievable.

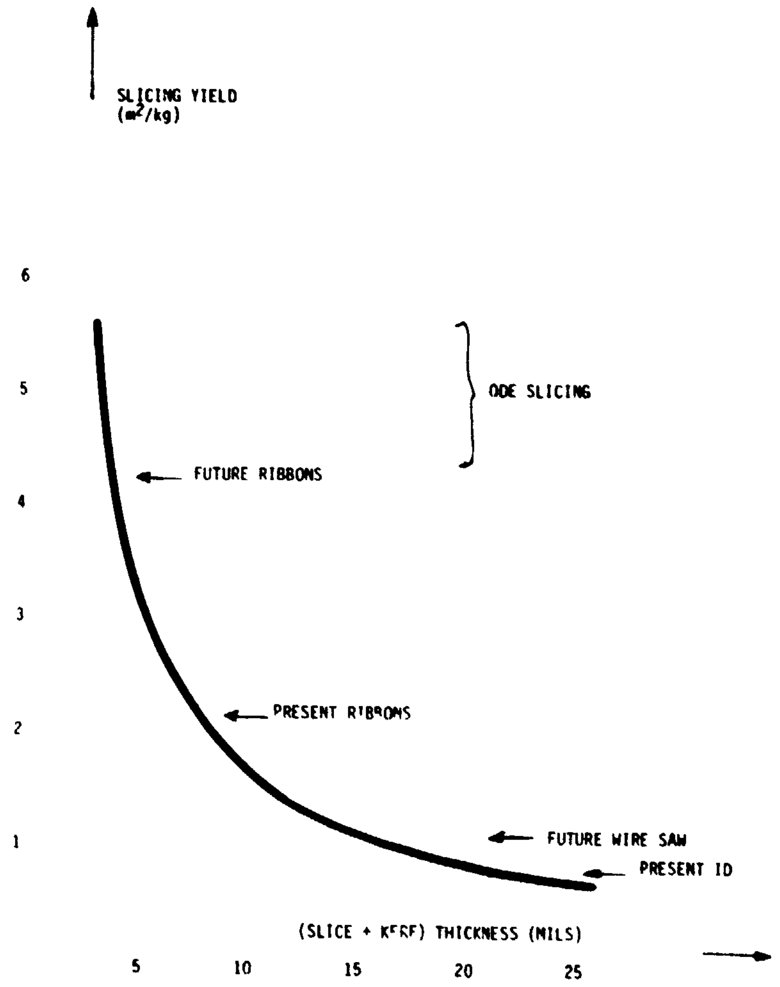
However, before making an actual test, we considered several disadvantages to this method which made it less attractive. We realized the labor costs would be high, because highly skilled (brown or black belt) Karate practitioners would be required, and their throughput would be low because of the need for extended concentration periods between blows. Also the maintenance and repair costs on their hands would be high, and there was generation of noise pollution (shouts) for each slice. We did not consider that ganging of the Karate operators would lead to a compact operation, or allow easy simultaneous slicing.

We were particularly sorry to drop this method because we had already coined an apt acronym. In line with the Crystal Systems method called Fixed Abrasive Slicing Technique (FAST), we could have described our process as the Fast Impulse Slicing Technique, or FIST for short.

Well that concludes the talk. It will have achieved its purpose if it encourages other people to speculate freely, to try and uncover new wafering methods which can be applied, to prevent ingot methods from being dominated by the ribbon growth methods in the near future.

FIGURE 1

SLICING YIELD VS. (SLICE+KERF) THICKNESS



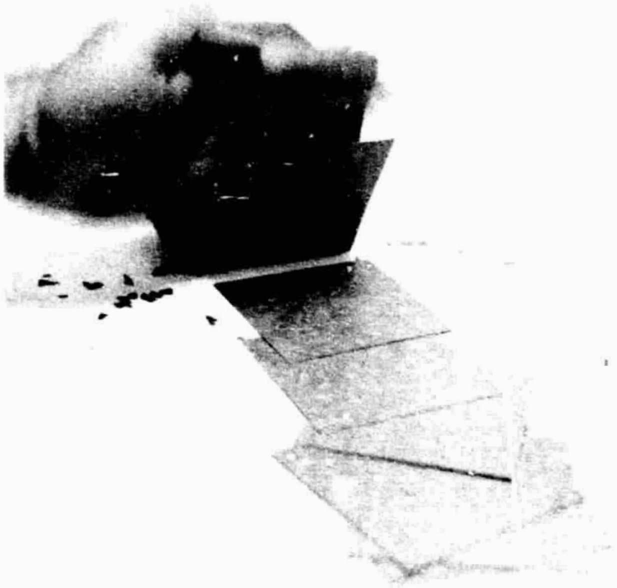


Figure 2. Fast Impulse Slicing Technique (FIST)

ID TECHNOLOGY

Chairman: L.D. Dyer, Texas Instruments, Inc.

N82 23655 D5

I.D. WAFERING TECHNOLOGY

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First developed in the late 1950's, I.D. wafering began to replace other wafering techniques such as the multi-blade slurry saw and the O.D. saw. By 1963 I.D. wafering had become the preferred production tool for wafering silicon and other semiconductor materials. During the past two decades, semiconductor wafer manufacturers have investigated a wide variety of slicing techniques, such as laser cutting, high pressure fluids, wire saws and band saws. Today, the I.D. saw still remains the most accurate and economical way of wafering semiconductor wafers.

The majority of wafers cut are usually three to four inches in diameter with five and six inch wafers beginning to be used on a limited basis. These dimensions compare with one-half inch and one inch crystal diameters in the 1960's. The machines have also increased in size from early saws that had six or eight inch blades to our experimental machine which supports a thirty-two inch blade, capable of slicing nine inch diameter wafers.

Production history of the I.D. saw is based on an estimated 2,500 saws being used worldwide. Majority of wafers are usually 20-30 mils thick with 10-14 mils of kerf loss. Estimated add-on costs are about $.29 per wafer for the semiconductor industry.

Although semiconductor manufacturers are concerned with wafering costs, raw materials represent only a small fraction of the cost of a finished device. Wafer quality, flatness and dimensional accuracy are very important. In photovoltaics the cost of a silicon wafer represents a substantial portion of the cost of a finished panel. To reduce raw material costs, research has been aimed at reducing the cost of silicon, reducing the amount of material per unit area of photovoltaics cells, and reducing the add-on cost for manufacturing silicon in sheet form suitable for solar cells. In terms of material usage and add-on cost, a variety of ingot wafering technologies and other technologies which do not require slicing such as silicon ribbons have been investigated both by government and private funding.

During the past few years, I.D. wafering has emerged as a viable alternative for slicing silicon ingots for solar cells. Unlike semiconductors, the main goals for wafering for photovoltaics are reduction in the amount of silicon used per unit area and a reduction in the add-on cost of wafering.

Based on a desired goal of producing photovoltaic power at $.70 per peak watt by 1986, and a projected cost for inexpensive silicon, wafering technology must be able to yield 25 wafers per cm from a 4 inch ingot and 18 wafers per cm from a 6 inch ingot. (The cost for producing ingots becomes less as ingot size is increased. It also becomes more difficult to handle very thin. large diameter ingots.) The add-on cost for wafering must be about $15 per square meter of wafers produced.

SLICING INFLUENCES

Some of the work we have been doing for the past two years indicates that the I.D. saw can reach these goals in the desired time frame.

As crystals are made larger, the blade size must also be increased, and in order to keep the blade from wandering axially in the cut, blades must be made thicker.

TABLE 1
BLADE SIZES

Max. Crystal size	Blade size	Av. Kerf loss
3-1/2 inch	16-5/8 inch	11 mils
5 inch	22 inch	13 mils
6 inch	27 inch	14 mils
9 inch	32 inch	16 mils

One of the primary causes for blade failure is due to blade wander during slicing and rubbing either the crystal or the wafer on the blade core. Cross sectional analysis of many blades that have been replaced after a few thousand cuts has shown that much of the original cutting edge diamonds still remain. A blade would have to slice more than 10,000 wafers before the diamonds on the cutting edge are completely worn.

One area of research is being aimed at finding suitable core materials which can be made thinner and yet provide adequate strength to minimize blade wander. We have begun to make experimental 22 inch blades using 4.8 mil cores as compared with our standard 6 mil cores. The 4.8 mil cores have yielded blades with 10.5 mil kerf loss. Using these blades, we have been able to slice some 4 inch material down to 5.5 mils thick which yields 25 wafers per centimeter. We have also sliced 6 inch diameter crystals at a thickness of 12 mils with 13 mils kerf loss which has yielded 16 wafers per centimeter. The 6 inch diameter crystal was sliced on our experimental 32 inch saw. We will be introducing a 27 inch saw for slicing 6 inch diameter crystals during June 1981. The 27 inch saw with the smaller blade should yield 18 wafers per centimeter for 6 inch diameter wafers. Add-on costs have been $42.50 for the 4 inch wafers and $25.76 for the 6 inch wafers. Add-on costs are calculated using the IPEG 2 equation as developed by the Jet Propulsion Laboratory. A version of the IPEG 2 equation which can be directly used for analyzing I.D. wafering costs is presented at the end of this paper. The equation assumes a three-shift operation. The second line of the equation adds the cost of silicon. A 1.2 factor has been applied to the cost of silicon. If only add-on costs are needed, the cost of silicon can be made zero. Blade cost is spearated as the third line of the equation. Blade life is represented as number of cuts per blade.

During our slicing experiments, we found that our results depend on the type of crystal we are slicing. Ordinarily, solar cells are sliced along the 1-0-0 crystal orientation because the wafers can be texture etched. Our tests indicate that the 1-1-1 orientation is much easier to slice, allowing thinner wafers at a lower add-on cost. Also, 1-1-1 wafers have much less chipping and breakage. We have also found a great deal of difference among the variety of cast polycrystalline ingots. We were able to slice one type of cast ingot at 5.5 mils thickness at one inch per minute. In one of the other samples, wafer thickness had to be increased to 8 to 10 mils to maintain the same slicing speed. Our yields with the second sample were very poor because the wafers were very weak and tended to break during cleaning. We think that the difference between the samples was due to stress and cracks in the poorer ingots. Annealing and etching the ingots may help theif performance.

ECONOMIC ANALYSIS

There is a definite inverse relationship between the length of time it takes to slice a wafer and wafer thickness. If ingot cost is included in the total cost of a wafer, there will be a trade-off between increased add-on cost, as wafer thickness is decreased, and increased material cost, as slicing speeds are increased. Figure 1 shows our estimates on wafer thickness and corresponding time to slice. Kerf loss and yield are kept constant. The calculated costs are shown in figure 2. The cost of silicon is varied from \$20 to \$200 per kilogram. The optimum speed and thickness appear to be relatively insensitive to ingot cost. For low cost silicon, wafer cost increases much more rapidly if the wafer is made thinner as opposed to increased costs due to an increase in wafer thickness. The curves we generated for wafer thickness and slicing speed were our estimates for our own slicing laboratory. Other slicing operations will usually have thicker wafers for the same speeds, however, the shape of the curves should be similar.

Fig. 1

TIME PER SLICE VERSUS WAFER THICKNESS

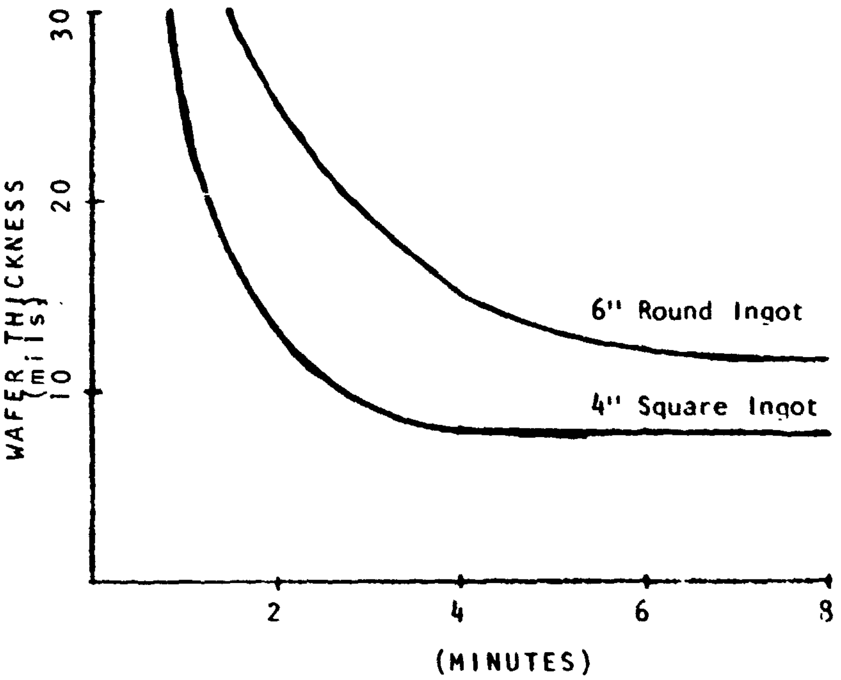


Fig. 2a

4 INCH SQUARE INGOTS

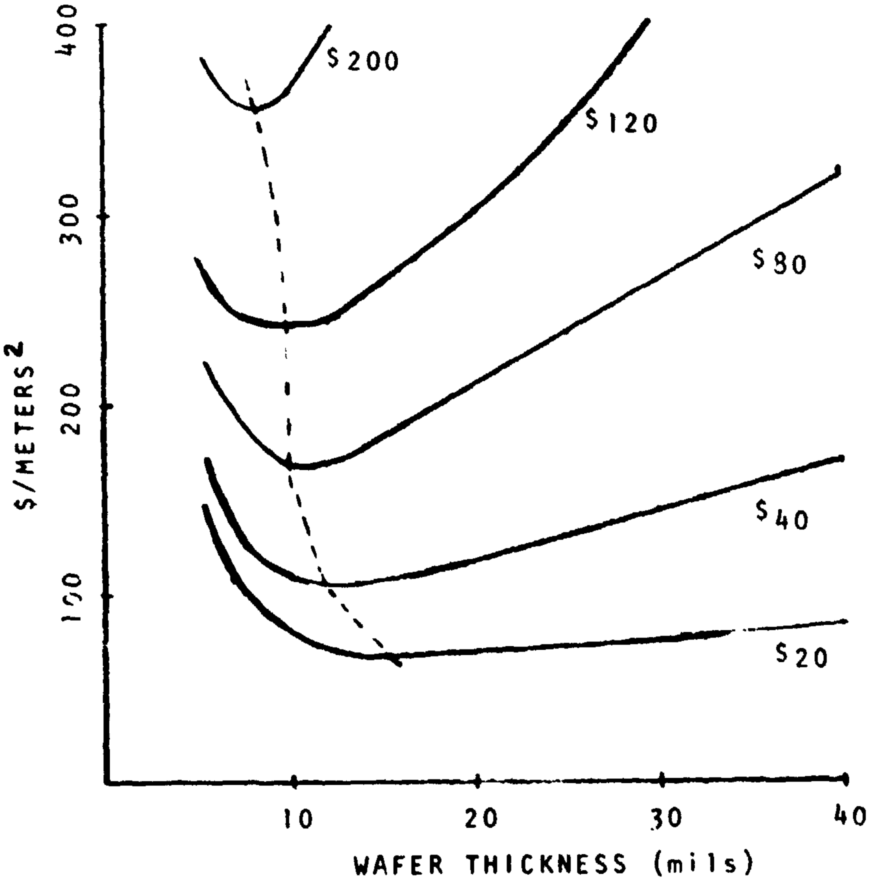
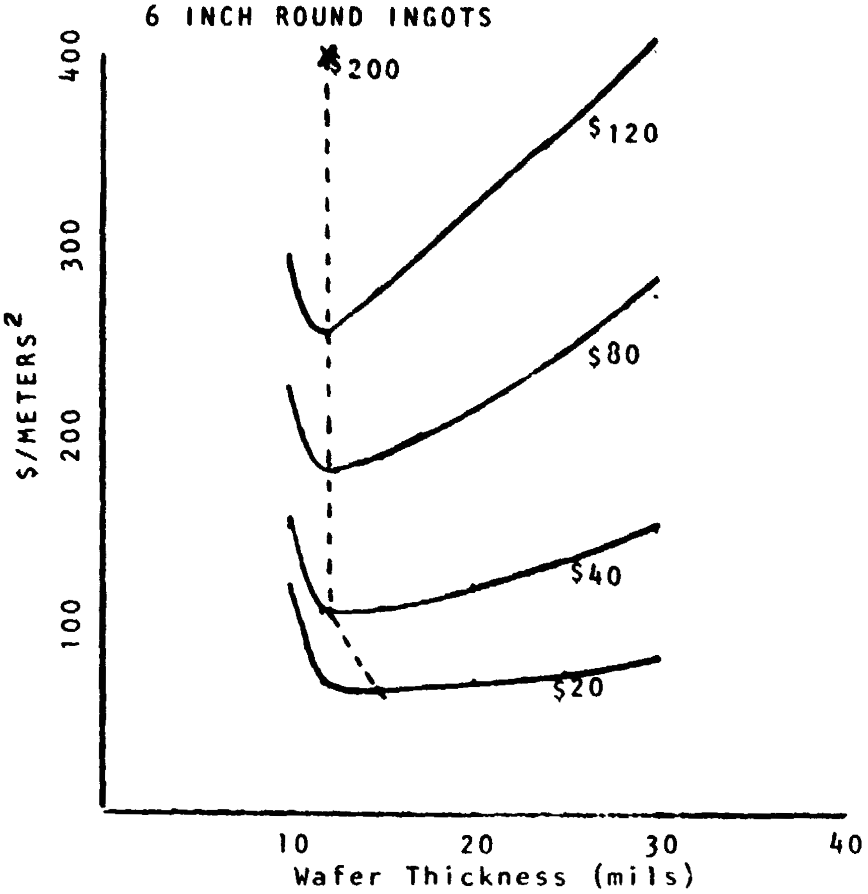


Fig. 2b



The dotted lines represent minimum cost.

Table 2 is an analysis of the relative importance of all the cost parameters, given one particular scenario for present day wafering capability. The third column is a dimensionless number which shows the percent change in total cost with percent change in the various parameters. Yield is by far the most important factor in controlling wafer cost. The calculated sensitivity values depend on the absolute value of the parameters; however, they give a good indication of the relative importance of each of the cost elements.

TABLE 2

COST SENSITIVITY ANALYSIS
on 10cm Square Ingots

COST PARAMETER	VALUE	$\frac{\Delta \text{TOTAL COST} / \text{TOTAL COST}}{\Delta \text{PARAMETER} / \text{PARAMETER}}$
Yield	.95	-.99
Ingot Cost	$40	.67
Ingot Size	10cm	-.37
Wafer Thickness	12mils	.34
Kerf	11.5mils	.33
Hours/day	20	-.29
Days/year	360	-.29
Slicing Speed	2 inches/min	-.28
Equipment Cost	$40,000.	.13
Labor Cost	$12,500.	.10
Floor Space	84 Sq. Ft.	.06
Blade Cost	$100.	.04
Blade Life	3000	.04
Utility Cost	$1,676.	.01

Total Cost = $105.17/Meter^2

DEVELOPMENT PROJECTS

Our work will be aimed at larger capacity machines, machine automation, and blade development. We have reduced blade core thickness by 1.2 mils for the 22 inch blades. We plan to investigate other material which may allow us to further decrease kerf loss. We will also investigate other matrixing material for bonding diamonds to the cutting edge.

Our next generation machines which will be introduced in June 1981 will have a 6 inch wafering capability. The machine will be fully automated in retrieving and cassette loading wafers. We have incorporated microprocessor controls which will allow future developments in communication with a centralized computer and feed back controls to further automate the machine.

Long-term development projects include 8 and 9 inch wafer capacity machines with centralized computer control and feed back loops to control feed rates and dressing. We also plan to introduce other equipment which will automate the line.

Based on D.O.E. requirements and our development pla the economic analysis for the future generation of saws is given in table 3 for 4 and 6 inch wafers, respectively.

TABLE 3

ECONOMIC ANALYSIS

4" SQUARE INGOT

T = 7 mils
K = 9 mils
S = 4 inches/min.
Equipment = $40,000
Floor Space = 84 square feet
Labor rate = $12,500/year, 4.7 shifts/year, 10 saws/operator
Utilities + Material = $1,676 /year
20 hours per day
360 days per year
Blade cost = $50.00
Blade Life = 4,000 wafers
Add-on Cost = $16.33
25 wafers/cm

6" ROUND CRYSTAL

T = 12 mils
K = 10 mils
S = 3 inches/min.
Equipment = $40,000
Floor Space = 84 square feet
Labor rate = $12,500/year, 4.7 shifts/year, 10 saws/operator
Utilities + Materials = $1,676/year
20 hours per day
360 days per year
Blade Cost = $80.00
Blade Life = 4,000 wafers
Add-on Cost = $15.83
18 wafers/cm

WAFERING COST MODEL BASED ON THE IPEG 2 EQUATION

$$\text{Cost/M}^2 = \left[\frac{10{,}000\ (.52 \times E + 109 \times FT^2 + 2.8 \times L + 1.2 \times U)}{\frac{60rsD}{(r+s)} \times \frac{\pi}{4} \times (\text{hrs/day}) \times (\text{Days/Year})^{*}} \right.$$

$$+ \quad 2.33 \times 1.2 \times (T+K) \times (\text{Ingot Price})$$

$$\left. + \quad \frac{1.2 \times 10{,}000}{\frac{\pi}{4} \times D^{2**}} \times \frac{(\text{Blade Cost})}{(\text{Blade Life})} \right] \times \frac{1}{\text{Yield}}$$

*Substitute $\frac{60rs\ L \times W}{(r+s) \times L1} \times (\text{hrs/day}) \times (\text{Days/year})$

for Square or rectangular ingots

**Substitute $\frac{1.2 \times 10{,}000}{L \times W}$

for square or rectangular ingots.

Where:

E = Equipment Cost
Ft^2 = Equipment Area in Square Feet
L = Direct Labor Cost/machines per operator
U = Utility cost plus supplies
S = Slicing Speed (cm/min)
r = Return speed of blade (cm/min)
D = Diameter of round ingot (cm)
L&W = Lenth & Width of rectangular ingot
L1 = Cutting stroke length on square or rectangular ingot
T = Wafer thickness (mm)
K = Kerf (mm)
Life = Number of slices/blade

DISCUSSION:

WERNER: You mentioned new methods or ideas to put the diamond on the blades. Can you be a little more specific about that?

AHARONYAN: All blades are plated using nickel today. We have thought about using different plating materials and perhaps getting away from plating and using some sort of an epoxy bond for the diamonds or maybe a sinter bond.

In our lab, we have vibration analyzers on our machine. The main reasons the machines go out of balance is that some dirt is thrown up into the cutting head while it is spinning at fairly high rpm--1500 or 1600 rpm--and this causes a vibration. The head has to be kept clean, so we are looking at new ways of doing it, but besides warning that the thing is out of balance there is really not too much we can do. We have looked at putting automatic balancing into some of these machines and we may experiment with that. But the best way to do it is to keep the machine clean.

DYER: Are these heads twice as massive?

AHARONYAN: They are at least twice as massive, but the spindles themselves are larger and stiffer so that we actually wind up with less deflection on the bigger heads than we did with the small ones.

QUESTION: You mentioned that you got some yield improvement by heat-treating the crystal before cutting it.

AHARONYAN: We have heard of that. We haven't done it ourselves. We know some people that do and there seems to be an indication that there is some yield improvement.

FUERST: We are interested in the possibilities of heat-treating ingots before slicing too. Looking at it offhand, you cannot really heat-treat silicon like you would steel where you actually have to recrystallize the structure of the steel. You wouldn't be able to do this with the silicon.

SCHWUTTKE: First of all if you heat-treat a crystal to improve your yield, this indicates that the crystal has a lot of strain. Now the source of strain most of the time is too fast a cooling rate and to get rid of the strain you follow it up by an annealing period. I would suggest, particularly to the polycrystalline people, changing the cooling rate in the first place and they wouldn't have that much strain in the crystal and wouldn't use up time in heat-treating. Same as ribbon material; if you cool too fast, you have a lot of strain.

LANE: You showed a graph earlier that said that if you increase the time of slicing you can get the slice thinner; later, in your cost calculation, you seemed to indicate that the only way we can get the cost down is to slice faster; finally, you showed 25 slices per centimeter in that cost calculation. Do you see that what you are saying raises a critical problem?

AHARONYAN: The reason I did that was because that is a goal that has been set. In the curves I showed, the cost didn't go up steeply at all as we increased the thickness because we were able to cut faster. It may be more advantageous to cut a little bit thicker and reduce some of the other costs, which include the cost of the machine and the factory cost.

LANE: Do you see any routes to going faster in the cut and still getting a thin wafer? Do you have any approaches to that?

AHARONYAN: We are looking at programmed feed and controlling the blade. We have some feedback devices that we are working on now that may allow us to cut faster. Right now the maximum cutting speed is just at the weakest point of that wafer. In other words, right now, if the wafer breaks at the exit edge at a particular speed we go below that speed all the way through. But you may be able to cut faster elsewhere in the wafer. Therefore, programmed cutting may improve speeds somewhat.

YERKES: Is all of your testing done with water?

AHARONYAN: We normally use water with our own coolant. We have cut 4-inch material at an inch a minute. We have cut 5 1/2-mil wafers at an inch a minute but I think that is really pushing the process, and that was not the point of the graph.

YERKES: Now did you cut 100 slices that way, or two or three?

AHARONYAN: We cut maybe a few dozen; we didn't cut many because silicon is expensive and we didn't have that much of the particular crystal that we were cutting. As I said before, the type of crystal made a difference and this crystal happened to be very easy to slice, compared with some of the other crystals.

YERKES: Was that a Cz crystal?

AHARONYAN: It was a casting. This material happened to be, for some reason, a little easier to cut than Cz.

YERKES: Even if the Cz was reoriented to the (111)?

AHARONYAN: (111) may be able to cut at that thinness. We have got a lot of experience with 3-inch cutting with relatively thin dimensions and at fairly good rates. We can cut (111) at 3 1/2 or 4 inches a minute fairly consistently. It just cuts a lot easier than the (100) orientation.

YERKES: When do you plan to have this programmable saw that can saw faster at one point and then slow down at the end?

AHARONYAN: The machine that is going to be introduced this month will have that feature, the 27-inch machine.

SCHMID: Have you noticed any effect that small grain sizes cut easier or better than large grain sizes?

AHARONYAN: It is hard to say. We had three types of cast ingots that we experimented with. The smallest grain size seemed to cut the easiest. I don't know if you can say that it is grain size contributing or it is the method of growing the crystal that was really the important factor.

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ALLOWABLE SILICON WAFER THICKNESS VS DIAMETER FOR INGOT-ROTATION ID WAFERING

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ABSTRACT

In order to meet Low-Cost Solar Project goals, thinner silicon wafers are needed. Inner diameter (ID) wafering of ingot rotation has been investigated as a means of reducing the ID saw blade diameter. The blade thickness could then be reduced, resulting in minimal kerf loss. However, significant breakage of wafers was found to occur during ingot-rotation wafering as the wafer thickness decreased. Fracture mechanics concepts were used to develop an equation relating wafer thickness, diameter and fracture behavior at the point of fracture by using a model of a wafer, supported by a center column and subjected to a cantilever force. The analytical model indicated that the minimum allowable wafer thickness would not increase appreciably with increasing wafer diameter; it was found to be approximately 500 μm for the conventional sizes of ingot-rotation ID wafering. Fracture through the thickness rather than through the center-supporting column was found to limit the minimum allowable wafer thickness. This model suggested that the minimum allowable wafer thickness can be reduced by using a vacuum chuck on the wafer surface to enhance cleavage fracture of the center core and by using <111> ingots.

INTRODUCTION

Crystal growers have made efforts to grow larger-diameter Czochralski silicon ingots, because increased diameter results in lower wafer cost per square meter. However, greater wafer thickness was expected to be necessary to withstand the greater stresses during wafering, cell processing and handling. Most cell manufacturers determine their minimum silicon wafer thickness for unconventional sizes by trial and error. Semiconductor Equipment & Materials Institute (SEMI) standards for these dimensional requirements for semiconductor industries are neither cost-effective nor practical for solar cell industries.

In order to meet Low-Cost Solar Array Project goals, thinner silicon wafers are needed. Ingot-rotation ID wafering has been investigated as a means of reducing the ID saw-blade diameter. The blade thickness could thereby be reduced, resulting in minimal kerf loss. However, significant breakage of wafers was found during ingot-rotation wafering as the wafer thickness decreased. The breakage usually took the form of circular cracking, often to the extent that the entire center of the wafer was broken out. The equations developed here provide guidelines for the fabrication of wafers of unconventional sizes by ingot-rotation slicing.

In Reference 1, fracture mechanics analysis was used to develop an equation describing the stress conditions of a wafer during conventional ID wafering. This equation predicted the minimum wafer thickness as a function of diameter for ID sawing. The required wafer thickness increased with increasing wafer diameter and was appreciably smaller than the existing SEMI standard.

In this paper, fracture mechanics concepts were extended to analyze the loading conditions of a wafer during ingot-rotation ID wafering. It is expected that this analytical model can be used for estimating the allowable wafer thickness vs diameter for ingot-rotation ID wafering in terms of fracture mechanics parameters.

FRACTURE MECHANICS MODEL

Ingot wafering is one of the most critical processes in controlling cell production yield. A wafer with center support subjected to a cantilever force can be considered to represent the stressed condition of a wafer during ingot-rotation ID wafering (Figure 1). The diameter of the rigid center support, d, can be considered to be the diameter of the center core (uncut area) during ingot-rotation wafering. The applied cantilever force, P, on the wafer may be due to saw-blade vibration and surface tension, and increases with cutting rate (Reference 1). The force on a wafer during slicing could be either a distributed loading or a cantilever force. In either case, an equivalent concentrated force P (Figure 1) can be used to describe the force conditions affecting a wafer during ingot-rotation ID slicing. The dragging force parallel to the wafer surface was found to be insignificant compared with the stress level within the wafer or in the center core, as the height of the center core is very small (i.e., 300 μm). Only the cantilever force perpendicular to the wafer surface was found to be significant during slicing.

Fracture of materials is the result of the extension of a pre-existing flaw under stress. Fracture mechanics defines the flaw size required for the onset of rapid propagation and fracture (for a given stress level) as the critical flaw size (a_c). This critical size in turn depends upon the values of the critical stress intensity factor (K_{IC}) for the material. Therefore, the fracture strength of material is controlled by a_c and K_{IC} of the material. For a small semicircular flaw, the relationship equation of fracture stress as a function of a_c and K_{IC} was derived (Reference 1) and can be expressed approximately as:

$$\sigma = \frac{K_{IC}}{\pi a_c} \qquad (1)$$

Thus, to determine the failure in any direction, it is necessary to know σ, K_{IC} and a_c. K_{IC} is a material constant, although directional, and a_c is a function of wafering technology. The surface damage to a wafer controls a_c.

Application of a force P at the edge of the wafer results in a stress both in the wafer and in the center support. These stresses can result in failure by propagation of microcracks in directions A and B, respectively. The propagation through the wafer thickness (direction A) destroys the wafer; propagation through the central core (direction B) reduces total wafering time. Considering first the stress in the wafer (failure in direction A), the maximum stress in the wafer was found to occur at the edge of the center support and can be expressed analytically (Reference 2) in an equation:

$$\sigma_A = \frac{P}{t^2} \beta \qquad (2)$$

where:

σ_A = stress in the wafer at the edge of the center support

P = applied cantilever force

t = wafer thickness
$= \frac{3}{\pi} \sum_{o}^{\infty} e_n$

and $\sum_{o}^{\infty} e_n$ is a Fourier series in which e_n is a function of:

ν = Poisson's ratio

d = diameter of center support

D = wafer diameter

$n = \ , 1, 2, \ldots \infty$

Substituting Equation (1) into Equation (2), the wafer thickness, t, can be written as:

$$t^2 = \frac{\sqrt{\pi a_{cA}}}{K_{IC}} P_A \beta \qquad (3)$$

where

a_A = critical flaw size for propagation in direction A

P_A = allowable force to cause crack propagation in direction A

A computer calculation of β as a function of d/D for n up to 30 and $\nu = 0.22$ for silicon (Reference 3) is shown in Figure 2. Thus Equation (3) expresses the relationship between the required wafer thickness and diameter of a solar cell. Next, considering the tendency of the stress in the center support to cause crack propagation in direction B, the fiber stress, $_{B}$ can be expressed from structure analysis (Reference 4) as follows:

$$\sigma_B = \frac{16 P_B D}{\pi d^3} \qquad (4)$$

Substituting Equation (1) into Equation (4), the allowable applied force (P_B) of the center-support column, in terms of wafer diameter and fracture mechanics parameters, can be written in a form:

$$P_B = \frac{\sqrt{\pi}}{16} \frac{K_{IC}}{\sqrt{a_{cB}}} \frac{d^3}{D} \qquad (5)$$

In this equation, P_B and a_{cB} are allowable force and critical flaw size, respectively, for the center support column. They may be of a different value from P_A and a_{cA} for wafers in some cases, as will be discussed below. It should be noted that P_B does not depend on wafer thickness.

APPLICATION OF ANALYTICAL MODEL

Application of the model to ID wafering of rotated silicon ingots is straightforward. The fracture mechanics studies (Reference 5) on single-crystal silicon found that the critical stress intensity factor K_{IC} in several crystalline planes is as follows:

$$\begin{aligned} K_{IC} &= 0.82\ \text{MNm}^{-3/2} \quad \text{in} \quad \{111\} \\ K_{IC} &= 0.90\ \text{MNm}^{-3/2} \quad \text{in} \quad \{110\} \qquad (6) \\ K_{IC} &= 0.95\ \text{MNm}^{-3/2} \quad \text{in} \quad \{100\} \end{aligned}$$

The typical wafer surface damage from ID sawing was measured (Reference 6) and found to be approximately 50 μm or:

$$a_c = 50 \times 10^{-6}\ \text{m}$$

Substituting these values of K_{IC} and a_c into Equation (3), the allowable applied force, P, for wafer failure at several wafer thicknesses for slicing 100-mm ingots is shown in Figure 3. It is noted that, from Equation (3), P_A decreases with increasing a_{cA}. An example of the effect of changes in a_{cA} is shown by error bars on the $t = 300\ \mu$m curve. Points to the left are for $a_{cA} = 60\ \mu$m and to the right for $a_{cA} = 40\ \mu$m.

As shown in Figure 3, the minimum required wafer thickness without cracking at very small values of d (e.g., 2 mm) is very sensitive to the force P. Therefore, decreasing the cutting rate near the small d region is important for ingot-rotation wafering in order to maintain minimal wafer thickness. Deflection of the wafer is directly proportional to the applied force P. Controlling wafer deflection can be a means of controlling the bending stress in the wafer, so that a minimal usable wafer thickness can be achieved.

Again, Figure 3 shows the effect of the center-core diameter on the allowable applied force P of the wafer fracture. Observations from Figure 3 can be summarized as follows:

(1) At each wafering thickness, the allowable force on the wafer decreases with decreasing center core diameter. In other words, the probability of cracking a wafer during ingot-rotation wafering increases with increasing depth of cutting.

(2) The allowable applied force P for a wafer decreases rapidly as the center core diameter is reduced to a small value (e.g., 5 mm). Therefore, cracks in the wafer are usually found near the center of the wafer from ingot-rotation wafering (Figure 4).

(3) In typical conventional ID slicing at a cutting rate of 51 mm/min, a P force was estimated (1) to be 0.5 newton. Using $p = 0.5$ N, for example, to evaluate ingot-rotation a 200-μm-thick wafer is very likely to be cracked at $d = 50$ mm, while a 300-μm-thick wafer would be cracked at $d \approx 14$ mm. However, successful ingot-rotation wafering occurs when a wafer is broken off from the ingot at the center core without generating cracks in the wafer. A typical wafer surface from ingot-rotation slicing is shown in Figure 5. The diameter of the center core is ≈ 1.5 (0.06 in.).

From Equation (5), the fracture force for the center supporting core as a function of core diameter is plotted in Figure 3 by using $a_{cB} = 50$ μm and $K_{IC} = 0.82$ $\mathrm{MNm}^{-3/2}$. If an applied force P_B is 0.5 N (a typical value for ID sawing, as discussed above), the fracture of the wafer center supporting core for a 100-mm-dia wafer can occur, in Figure 3, at $d = 1.6$ mm. This calculated d value has the same magnitude as the observed value of d in Figure 5.

It has been pointed out that the fracture force P_B vs the core diameter d in Figure 3 is independent of the wafer thickness. It is found that 700-μm-thick wafers can be sliced at regular cutting speed for $P = 0.5$ N and the center core will fracture at ≈ 1.7 mm. A 600-μm-thick wafer can be sliced by reducing cutting force (0.5 N) from near $d = 2.5$ mm at a rate following its P vs d curve to $d = 1.5$ mm, where fracture of the center core occurs at $P = 0.34$ N. Figure 3 suggests that 500-μm-thick wafers require force reduction to less than 0.2 N and 400-μm-thick wafering appears to be impossible with ingot-rotation slicing. This limit is generally consistent with the present state of the art of ingot-rotation slicing.

TECHNOLOGY IMPLICATIONS

This analysis has implications for potential improvements in ingot-rotation slicing. These include control of a_c, K_{IC} and directional stress, σ_B. Thus, to enhance fracture in the B direction, a_{cB} and σ_B should be maximized, while K_{IC} should be minimized.

At present, ingot-rotation wafering is done mostly in <100> ingots. Because the fracture strength of the material is directly proportional to K_{IC}, as shown in Equation (1), the allowable fracture force for the center core in <100> can be greater than that in <111> axis, because K_{IC} on {100} is greater than K_{IC} on {111} as shown in Equation 6. Thus, if <111> ingots were used, easier fracture in the central core would occur. However, the difference is small (Figure 3). In addition, the fracture surface of silicon in {111} was found (Reference 5) to be a clean cleaved fracture; the fracture surface in other crystalline planes reveals rough crack branching.

It is also possible to control fracture by means of stress. If σ_B can be made greater by means of some additional force other than (P), then fracture in the B direction is favored. This can be accomplished by means of a uniform force on the wafer (e.g., by a vacuum chuck).

The application of a vacuum chuck to ingot-rotation wafering can be shown schematically. As shown in Figure 6, the total vacuum force on a wafer can be calculated:

$$F = p \frac{\pi D^2}{4} \tag{7}$$

where p = vacuum pressure, max p is 1 atm $\approx 0.1\ MNm^{-2}$.

The relationship of D and d can be expressed:

$$\frac{D}{d} = \sqrt{\frac{\sigma_n}{P}} \tag{8}$$

where σ_n = nominal stress in the center core.

Because of the existence of stress concentration in a deep groove, Equation (8) can be rewritten:

$$\frac{D}{d} = \sqrt{\frac{\sigma_c}{k_t p}} \tag{9}$$

where:

k_t = stress concentration factor in the bottom of the groove

σ_c = stress on the flaw

The stress concentration factor, k_t, for a grooved bar in tension is given (Reference 7) in Figure 7, in terms of the ratio of groove root radius, r and d. For ingot-rotation ID slicing, the typical value of r/d is very small (e.g., <0.02), and D/d is very large (e.g., 20); k_t value can be very large (Figure 7). Assume that:

$$D = 100 \text{ mm}$$

$$k_t = 15$$

$$K_{IC} = 0.82 \text{ MNm}^{-3/2}$$

$$a_{cB} = 50 \times 10^{-6} \text{m}$$

Substituting these values into Equations (1) and (9), the calculations indicate that the fracture of the center core occurs at $D/d = 6.6$ or $d = 15$ mm, as indicated by the line in Figure 3. In this case, if $P = 0.5$ N, from Figure 3, the minimum allowable wafer thickness can be reduced to approximately 300 μm, compared with 700 m without the auxiliary force. It is important to use <111> ingot to maintain clean cleaved fracture in direction B, as mentioned above.

The most indefinite parameter in this calculation is the value of the stress concentration factor (k_t). This factor in a machine notch of brittle ceramic can be a very large value, because microcracks are usually found in the bottom of the notch. The microcrack is of the order of 10^{-9} m; the value of r/d can be extremely small. The data in the large k_t region are not available in Figure 7. Experimental determination of k_t value in this region is necessary. Thus, the exact location of the fracture curve in Figure 3 using the vacuum chuck is imprecise; however, there will be a large enhancement of direction B fracturing as a result of this additional force.

CONCLUSIONS

(1) An analytical model of a thin circular wafer, supported by a center core and subjected to a cantilever force at the wafer edge, was used to describe the loading condition of a wafer during ingot-rotation ID wafering.

(2) A fracture-mechanics concept was found to be useful in developing a relationship equation for the allowable wafer thickness vs diameter as:

$$t^2 = \frac{\sqrt{\pi a_{cA}}}{K_{IC}} P\beta$$

where β is a factor relating to the ratio of D and d and Poisson's ratio ν.

(3) The allowable thickness is dependent upon the depth of surface damage (flaw size a_c) of the wafer.

(4) It is important to reduce applied force P by minimizing saw vibration and cutting rate in order to maintain minimal wafer thickness, especially at small center-core diameters.

(5) At the present state of the art of ingot-rotation ID wafering, a limit of minimum wafer thickness was found to be $\approx 500\ \mu m$ for the conventional wafer diameters (e.g., 100 mm).

(6) Fracture in the center core at large diameters was found to be important in controlling the minimum allowable wafer thickness during wafering. Use of the vacuum chuck to enhance cleavage fracture of the center core of <111> ingot in ingot-rotation wafering was shown to have great potential to maintain useful wafer thickness at a minimum.

REFERENCES

1. Chen, C.P., "Analytical Calculation of Thickness versus Diameter Requirements of Silicon Solar Cells," Proceedings of the Symposium on Materials and New Processing Technologies for Photovoltaics, J. A. Amich, et al., eds., Vol. 81-3, pp. 187-195, 1981.

2. Reissner, V. H., "Ueber die Unsymmetrische Biegung duenner Kreisringplatten," Ingenieur-Archiv, Vol. 1, pp. 72-83, 1929.

3. St. John, C., "The Brittle-to-Ductile Transition in Pre-Cleaved Silicon," Phil. Mag., Vol. 32, pp. 1193-1212, 1975.

4. Shanley, F.R., Strength of Materials, Chap. 15, McGraw-Hill, New York, 1957.

5. Chen, C.P., and Leipold, M.H., "Fracture Toughness of Silicon," Am. Ceram. Soc. Bull., Vol. 59, pp. 469-472, 1980.

6. Meek, R.L., and Huffstutler, M.C., Jr., "ID D[illegible]nd Sawing Damage to Germanium and Silicon," J. Electrochem. Soc., [illegible]. 116, pp. 893-898, 1969.

7. Peterson, R.E., Stress Concentration Design Factors, p. 33, John Wiley & Sons, New York, 1953.

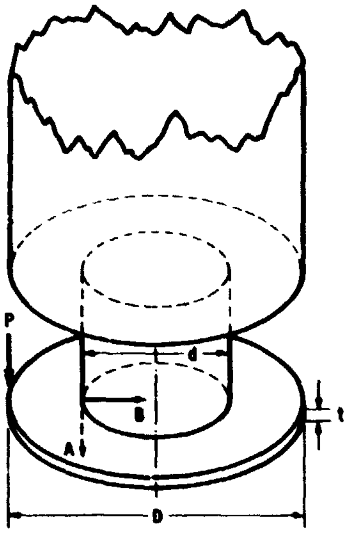

Fig. 1. Thin Wafer, Center-Supported, Subjected to a Cantilever Force

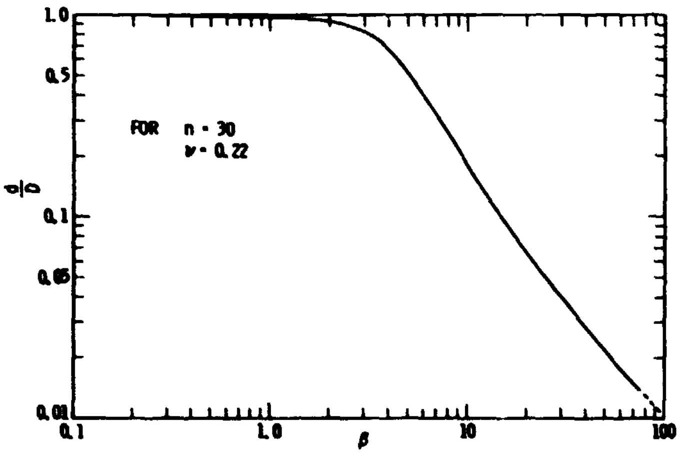

Fig. 2. Factor β as a Function of d/D

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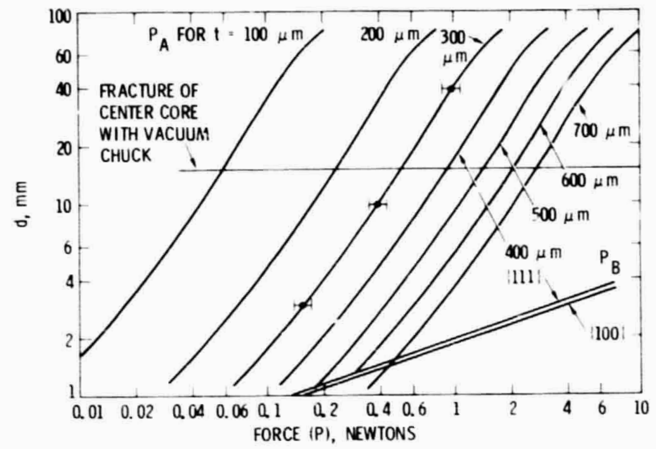

Fig. 3. Failure Force (P) vs Core Diameter for Ingot-Rotation Wafering of 100-mm Wafers (Flaw Size 50 μm, Except for Error Bars, Which Are 40 to 60 μm; P_A Based on K_{IC} for <111> Plane)

Fig. 4. Cracks Found Usually Near the Center of Wafer in Ingot-Rotation Wafering (Arrows)

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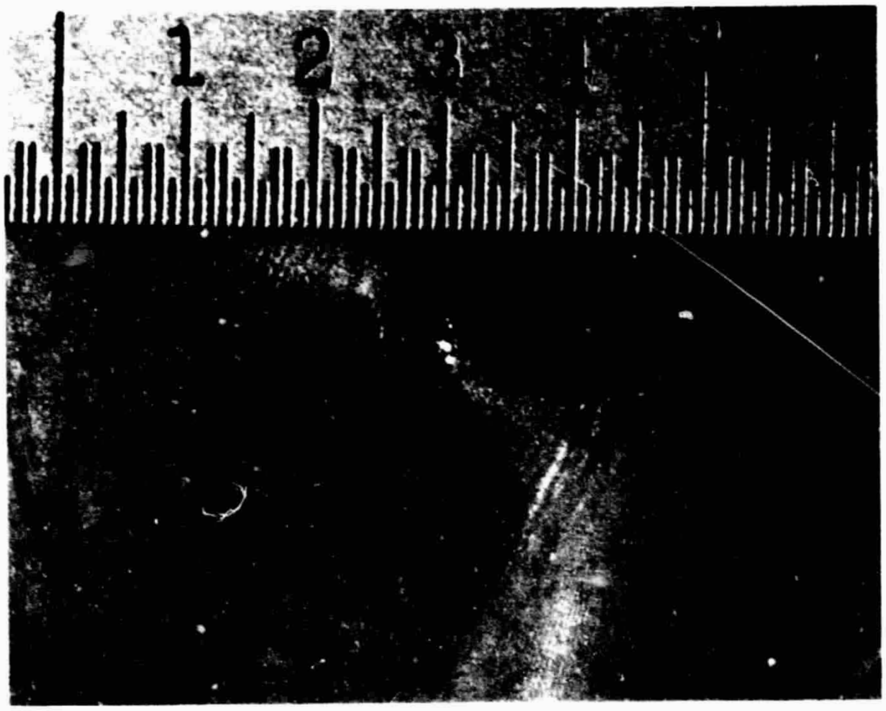

Fig. 5. Typical Surface Condition of Product of Ingot-Rotation Wafering

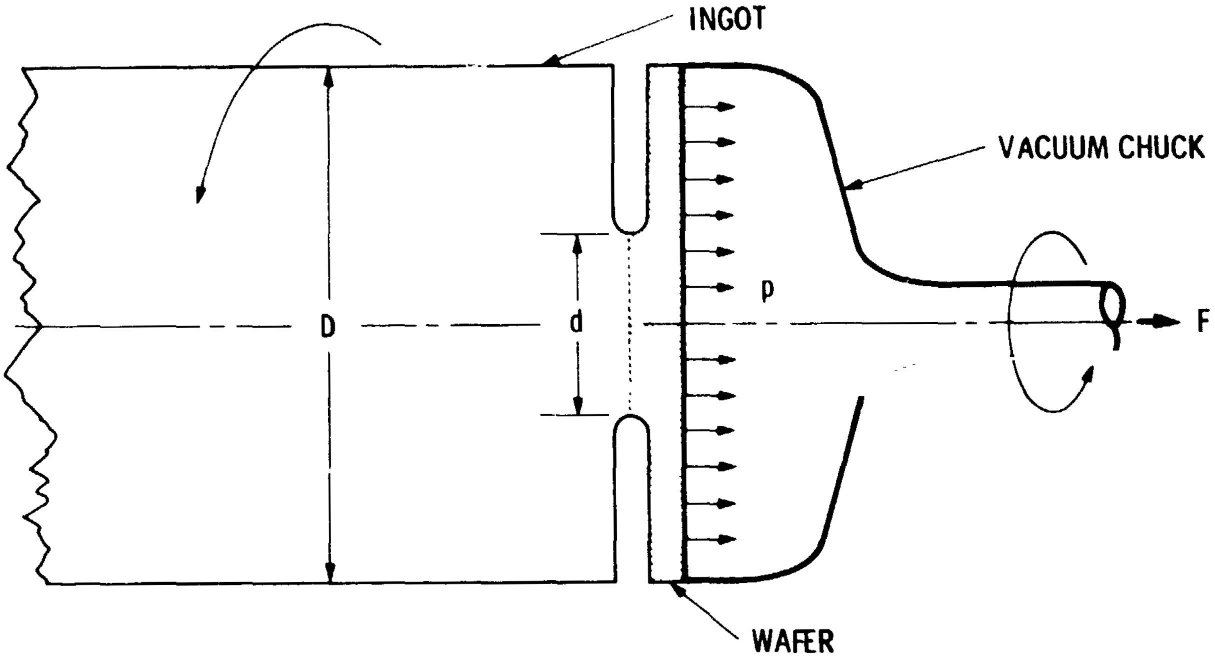

Fig. 6. Use of Vacuum Chuck in Ingot-Rotation Wafering

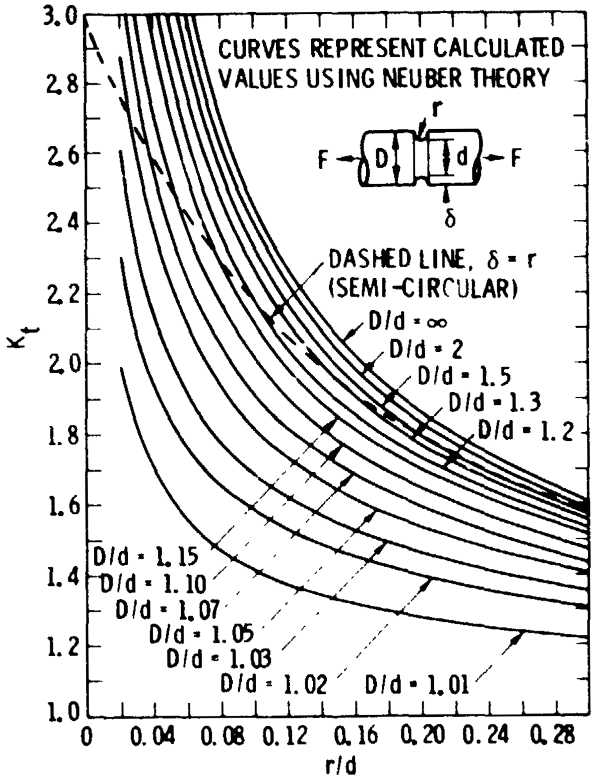

Fig. 7. Stress Concentration Factor K_t for a Grooved Bar in Tension (Reference 7)

DISCUSSION:

SCHWUTTKE: It looks to me that your model applies to the crystal lying horizontally. If you do ingot rotation wouldn't it be more favorable to have the crystal vertical?

CHEN: Some people claim horizontal is better than the vertical and some claim that vertical is better than horizontal. My model doesn't suggest either.

SCHWUTTKE: You assume that there is no advantage or disadvantage.

CHEN: This question relates to your paper and to the preceding one. Several times the subject came up that it is more favorable to use (111) orientation, in your case because you induce cleavage readily, and in the former paper because the cutting rate would be larger. Now silicon is an anisotropic material in terms of hardness. That means if you use a (111) plane for cutting the crystal you may go faster because the (111) is the softest plane. On the other side, the saw damage you incur will be much larger. So you have to remove more crystal material and these things have to be taken into consideration if you want to be cost-effective.

DYER: Dr. Schwuttke, a number of years ago, showed that for the saws that he evaluated, the horizontally held blade gave worse results than the vertical blade as far as the depth of damage is concerned. How do you think that gravity would be as a force in this? How about the weight of the slice pulling away? Does that put tension on those cracks that you are talking about?

CHEN: If you are talking about 500 microns and what kind of mass would contribute to the breakage in the center core, I would think it very small. But you could have other reasons for slicing in a vertical direction.

DYER: It has been shown in the literature, I believe it was in Meek and Huffstutler's paper in 1969, that if you have too much lubricating fluid carried into the kerf slot, it increases the hydraulic pressure in that slot and that might be another thing contributing to that force P. I realize that your analysis doesn't apply to that.

CHEN: That is right, so I've got to generate another model to describe that.

YERKES: I notice that some of the speakers call this lubricating fluid and Peter Aharonyan called it coolant. I presume that it is there for both purposes but it would seem to me that it is a damping material or it could cause a hydraulic pressure. Has the whole dynamics of this interface been studied? It seems to me that your model is simplistic compared to what is really going on where the diamonds touch the silicon and where all of this fluid is. It seems to me that is a rather complex thing that is happening millions of times during a cut. Statistically and otherwise, it would seem to me it is something that is the real root of the problem.

DYER: What do you think about, instead of concentrating on reducing the force P or doing these other things, just back up the slice with something rigid and if it has to rotate, make a device to make it rotate, e.g., instead of just letting the slice be free floating as you cut it, back up the slice with a thick rigid piece of steel, for example, just barely in contact and not pull on it and not push on it, have it rotate synchronously with the crystal?

CHEN: If you have a rigid backing on the wafer, essentially you can reduce the P force resulting from the blade vibration. That would help to reduce the P force and would cause smaller stress in the A direction. On the other hand, you reduce the stress in the B direction. If you have a rigid vacuum chuck technique that can control the deflection of the wafer in the A direction or you can increase the stress in B direction, this will be more favorable for rotation ingot wafering.

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CURRENT ECONOMIC AND SENSITIVITY ANALYSIS FOR I.D. SLICING OF 4" AND 6" DIAMETER SILICON INGOTS FOR PHOTOVOLTAIC APPLICATIONS

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INTRODUCTION

This paper relates to the economics and sensitivities of slicing large diameter ($\geq$ 4") silicon ingots for photovoltaic applications.

In order to arrive at economics which directly relate to the current low cost solar array activity, SAMICS costing methods were utilized. All economics are projected in 1980 dollars.

Currently, the manufacture of 6 inch diameter silicon ingots by the Czochralski process is a contract requirement of the LSA project. Ingot diameter does not present any technological problems to the CZ growth process. Indeed, diameters of up to 8 inches are considered feasible. However, it is considered that the slicing of silicon ingots in excess of 5 inch diameter at the required thickness and yield (25 slices/cm or 63 slices/inch) using current I.D. slicing techniques is unproven.

The current LSA slicing cost goals assume that 1 kg of silicon ingot will produce 1 meter^2 of wafer area. Failure to achieve this goal negates the assumption and thus will directly impact on the ingot add-on cost.

Kayex inhouse wafering of 6 inch diameter CZ ingot for solar cell fabrication indicated that the slicing of nominally 0.020 inch wafers was possible. It should be noted that the amount of wafering undertaken was minimal. In a photovoltaic manufacturing environment, only one slicing specification would be required. Standard semiconductor materials operations, although slicing to more difficult specifications, have the potential of utilizing the blade more adequately by progressively slicing less demanding specifications, e.g. smaller diameters, thicker wafers, etc.

Current economics and slicing add-on cost sensitivities have been calculated using variable parameters for blade life, slicing yield and slice cutting speed. All five standard SAMICS categories were calculated assuming fixed parameters.

It is considered that large diameter ($>$5") silicon ingot slicing by I.D. blade techniques for P.V. applications is still in a development stage. As such, the factors most likely to directly influence slicing add-on costs were chosen as the variables. It is appreciated that the standard SAMICS categories could also be calculated on a variable basis and directly affect slicing add-on costs, but to a lesser degree.

Data generated using the previously described variables indicate that cutting speed has the biggest impact on slicing add-on cost. This is followed by slicing yield and, to a lesser degree, by blade life as the blade life increases.

DATA INPUT

Only a minimal amount of I.D. slicing of large diameter (nom. 6") silicon ingots was performed at the Kayex Corporation. The slices were used for conversion into solar cells. Approximately 10 slices were produced per ingot. Based on this work, routinely achieveable parameters were determined, e.g. slice thickness plus kerf of 0.034" (11.6 slices)/cm or 29.4 slices/inch).

Additionally, various I.D. slicing reports were analyzed to more fully determine the current "state of the art", such that projected techniques and related costs could be arrived at.

A DOE/JPL 1978 final report$^{(1)}$ by H.I. Yoo of Applied Solar Energy Corp. was used as a reference to simulate SAMICS FORMAT A to develop cycle times, projected labor and material costs for the I.D. slicing of 6 inch diameter silicon ingots.

A further DOE/JPL 1980 report$^{(2)}$ by M.H. Leipold, C. Radics and A. Kachare of JPL was used as a comparison to better qualify present day manufacturing capabilities and future projections.

SAMPLE SAMICS ANALYSIS

Analyses were performed to realistically develop the cost of slicing of large diameter ingots in \$ per m^2 as a function of wafer diameter and wafer yield The approach differed from the Leipold et.al. wafering cost analyses, in that a total production quantity (wafer area) was not utilized as the starting point.

Determination of slicing cycle time was the initial parameter developed. The cycle times for the slicing of 4 inch and 6 inch diameter wafers is illustrated in FIG. 1 and FIG. 2.

Actual SAMICS cost analyses were performed for both 4 inch and 6 inch diameter silicon ingot slicing using the standard IPEG price equation. The 4 inch diameter costs generated are felt to be a reasonable approximation of present manufacturing achievements. The 6 inch diameter costs generated represent a projection of the cost of slicing using current "state of the art" techniques.

FIG. 3 shows an example of the SAMICS cost analysis for slicing of 6 inch diameter ingot. This example arbitrarily assumes a cutting speed of 1 inch/minute, a blade life of 1500 slices/blade, and a wafer yield of 75%. A series

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SLICING OF 4" WAFERS

A. Description of Slicing

1. A Continuous Process

Cut Rate: Two (2) inches/minute
Wafer Yield: 94%

2. Average Slicing Cycle per Wafer

Slicing Time:	2.500 minutes
Machine Down Time:	0.057 minutes
Total	2.557 minutes/wafer

3. Wafers per Operating Minute:

$\frac{1}{2.500}$ = 0.4 wafer/operating minute

4. Process Usage Time Fraction:

$\frac{2.5}{2.557}$ = 0.978

FIG. 1

SLICING OF 6" WAFERS

A. Description of the Slicing

1. A Continuous Process

Cut Rate: Two (2) inches/minute
Wafer Yield: ~75%

2. Average Slicing Cycle per Wafer: 3.6 minutes

Slicing Time:	~3.5 minutes
Machine Down Time:	~0.1 minutes
Total	~3.6 minutes/wafer

3. Wafers per Operating Minute:

$\frac{1}{3.5} \cong$ 0.286 wafer/operating minute

4. Process Usage Time Fraction:

$\frac{3.5}{3.6}$ = 97.2%

FIG. 2

SAMICS ANALYSIS
(Slicing of 6 Inch Diameter Silicon Ingots)

Process Parameters:

Cutting Speed - 1 inch/minute

Blade Life - 1500 slices/blade

Wafer Yield - 75%

Equipment	C1	$57,322; 7 yr life x $0.54/yr	$ 30,954.00
Space	C2	55 sq ft/saw x $110.61/sq ft	6,083.55
Direct Labor	C3	$2.14/yr factor $10,692 + $78.19 = $10,770.19	23,048.21
		(Operator's yearly salary = $10.492; 3 operators for one 24 hr day/1 operator for 3 saws)	
		Maintenance Mechanic II $15,576 yearly salary	
		Time required 50 minutes/cycle x 49.84 cycles/yr = 41.53 hrs/yr/saw	
Direct Mats	C4	$1.23/yr	8,309.14
		49.84 blades/yr x $110/blade = $5,482.40 + 1,273 = $6,755.40	
Utilities	C5	$1,350 x 1.23/yr	1,660.50
			$ 70,055.40

It costs approximately $70,055.40/yr to produce 56,070 good wafers.

Therefore, add on cost = $1.25/wafer or $70.74/m^2

FIG. 3

Batch Cycle Times - ID Slicing of 6" Diameter Silicon Ingots

Process Parameters:

Cutting Speed - 1 inch per minute

Blade Life - 1500 wafers/blade

Wafer Yield - 75%

Total Slicing Time per Wafer = 6.6 minutes	
Therefore, one batch of 1500 wafers requires	9900 minutes or 165 hrs
Add machine down time per blade	67 minutes
Total Batch Cycle Time	9967 minutes or 166.12 hrs

Total hours available per year = 345 days x 24 hrs = 8280 hrs x 60 = 496,800 minutes
Therefore, Total Cycles per Year = 49.84

Total Wafers Cut per Year = 74,760 x 75% yield = 56,070 good wafers

Total m^2 of good wafers per year - 1 wafer (150 mm) = 0.0176625 m^2/wafer x 56,070 wafers = 990.34 m^2 production capability per year

FIG. 4

of calculations were then made by varying these three parameters. This was done to measure the sensitivity of the parameters on add-on cost.

For the purpose of calculation, the following three SAMICS parameters were held constant:

a) Equipment (C1) at $57,322
b) Space (C2) at 55 sq.ft.
c) Utilities (C5) at $1,350 per year.

Direct labor and direct materials were varied only to allow for varying blade life.

Since batch cycle times are directly influenced by blade life, a series of calculations were made to determine these relationships. An example of batch cycle time related to a specific blade life is illustrated in FIG. 4, together with total cycles per year, total wafers cut per year, total wafers produced after the wafer yield factor is applied and the conversion of good wafers produced into total surface area (m^2).

ADD-ON SENSITIV: ALYSIS

As a result of the calculations made during the SAMICS cost analysis, the effects on the ingot slicing add-on costs as a result of varying the blade life, slice yield, and cutting speed factors are illustrated in Tables 1, 2, and 3. The overall sensitivities are also expressed graphically in FIG. 5 and FIG. 6.

The intent of the data generated is not to produce a specific silicon ingot slicing add-on cost, but rather to illustrate the effects of varying specific process parameters as they relate to slicing add-on cost per wafer and to the slicing add-on cost per meter^2.

It is realized that variation of some of the SAMICS factors that were held constant could also obviously affect the slicing add-on costs. Indeed, a calculation was made showing the effect of utilizing 1 operator for 10 saws. An add-on cost reduction, in terms of dollars per meter^2, of 23% can be achieved as illustrated in FIG. 7.

COMPARISON OF 4" AND 6" DIAMETER SLICING ADD-ON COST

Defined process parameters were used to calculate the add-on costs for both 4" and 6" diameter wafers as follows:

- Slice yield of 94%
- Blade life of 1500 slices per blade
- Cutting speeds of 2"/min. and 3"/min. respectively.

The completed slicing add-on costs in both cost per wafer and cost per meter^2 for the slicing of both 4" and 6" diameter ingots are illustrated in FIGS. 8 through 11.

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TABLE 1

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 1 INCH/MINUTE)

CUTTING SPEED (INCHES/MIN)	BLADE LIFE (SLICES/BLADE)	WAFER YIELD (%)	ADD ON COST $/M^2	ADD ON COST $/WAFER
1.0	250	75	107.78	1.90
	500		85.55	1.51
	750		78.14	1.38
	1,000		74.43	1.29
	1,500		70.74	1.25
	2,000		68.88	1.22
1.0	250	85	95.09	1.68
	500		75.48	1.33
	750		68.95	1.22
	1,000		65.68	1.14
	1,500		62.42	1.10
	2,000		60.77	1.07
1.0	250	95	85.08	1.50
	500		67.54	1.19
	750		61.69	1.09
	1,000		58.76	1.02
	1,500		55.85	0.986
	2,000		54.37	0.96

TABLE 2

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 2 INCHES/MINUTE)

CUTTING SPEED (INCHES/MIN)	BLADE LIFE (SLICES/BLADE)	WAFER YIELD (%)	ADD ON COST $/M^2	ADD ON COST $/WAFER
2.0	250	75	78.98	1.39
	500		56.76	1.00
	750		49.52	0.87
	1,000		45.65	0.81
	1,500		41.95	0.74
	2,000		40.10	0.71
	3,000		38.24	0.675
	4,000		37.32	0.659
2.0	250	85	69.69	1.23
	500		50.08	0.88
	750		43.69	0.77
	1,000		40.28	0.71
	1,500		37.01	0.65
	2,000		35.39	0.62
	3,000		33.74	0.596
	4,000		32.93	0.58
2.0	250	95	62.35	1.10
	500		44.81	0.75
	750		39.10	0.69
	1,000		36.04	0.64
	1,500		33.12	0.58
	2,000		31.66	0.56
	3,000		30.19	0.53
	4,000		29.46	0.52

TABLE 3

ADD ON COST FOR SLICING 6" DIAMETER SILICON INGOTS

(CUTTING SPEED - 3 INCHES/MINUTE)

CUTTING SPEED (INCHES/MIN)	BLADE LIFE (SLICES/BLADE)	WAFER YIELD (%)	ADD ON COST $/M^2	ADD ON COST $/WAFER
3.0	3,000	75	28.66	0.506
	4,000		27.73	0.49
3.0	3,000	85	25.29	0.447
	4,000		24.46	0.432
3.0	3,000	95	22.62	0.40
	4,000		21.89	0.387

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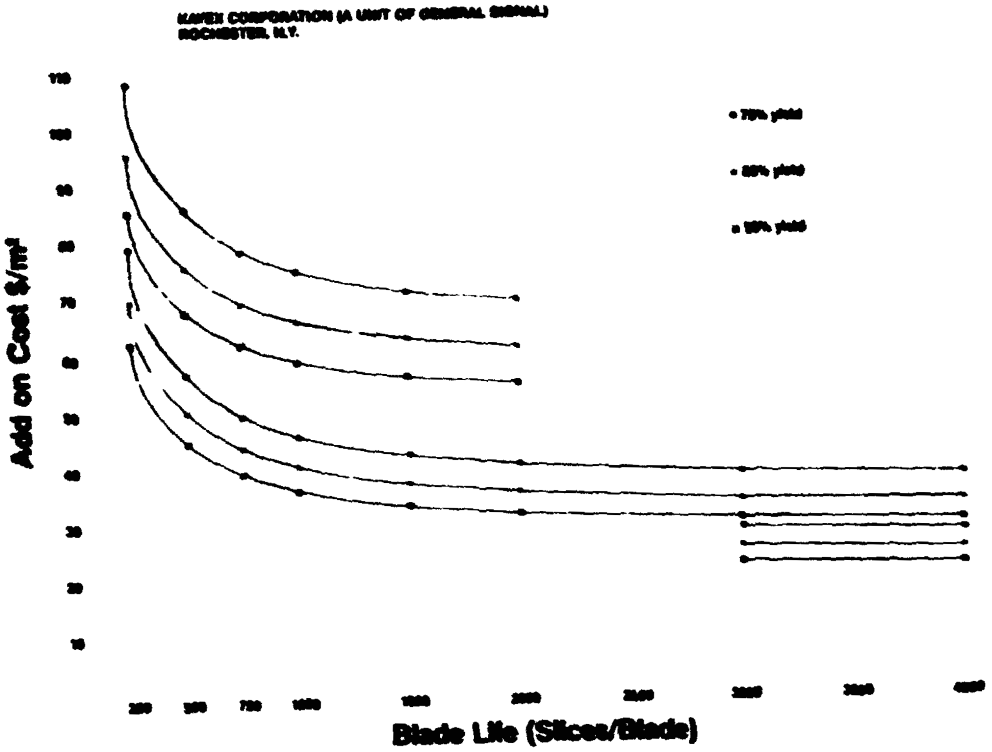

Fig. 5 Sensitivity Analysis of Add on Cost for I.D. Wafering of 6" Diameter Silicon Ingots

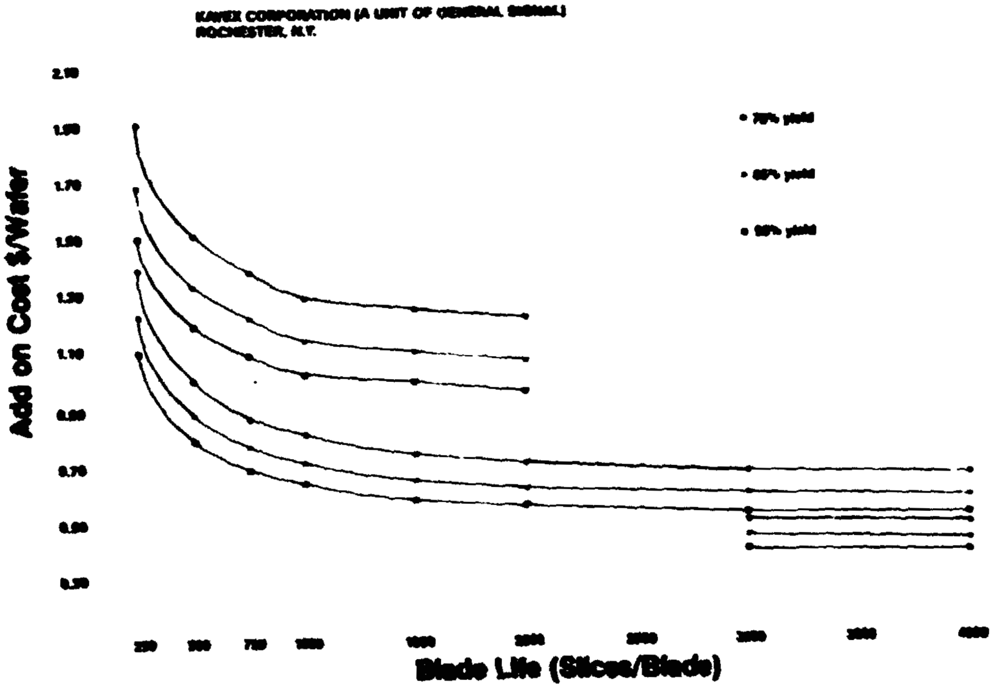

Fig. 6 Add on Cost in $/wafer for ID Wafering of 6" Diameter Silicon Ingots

LABOR VARIATION COMPARISON (PARAMETER C3)

(1 Operator for 10 ID Saws)

Direct Labor change from one operator for three (3) saws to one operator for ten (10) saws

Cutting Speed (in/min)	Blade Life (Slices/Blade)	Wafer Yield %	Add on Cost/m^2 (1 op/3 saws)	Add on cost/m^2 (1 op/10 saws)	% Reduction
3	4000	75	27.73	21.36	23
		85	24.46	18.87	22.9
		95	21.89	16.89	22.8
1	1500	75	70.74	54.57	22.9
		85	62.42	48.15	22.9
		95	55.83	43.08	22.9

FIG. 7

SAMICS ANALYSIS

(Production Slicing of 4" Dia Si Ingots)

Cutting Speed = 2"/min — 1500 slices/blade (94% yield)

Equipment	C1 = $0.54/yr ($57,322)	= $ 30,954.00
Space	C2 = $110.61/sq ft (55 sq ft)	= 6,083.55
Direct Labor	C3 = $2.14/yr (1.0 op for 4 m/cs = $8019/m/c) + $212.6	= 17,615.67
Direct Mats	C4 = $1.23/yr 130.33 blades/yr x $110 + 1273 = $15,609.3	= 19,199.44
Utilities	C5 = $1.23/yr Approx $1350	= 1,660.50
	Total	= $ 75,513.11

It costs $75,513.11 to produce 181,765 good wafers/mc/yr

Therefore, add on cost = $0.41/wafer or $50.56/m^2

FIG. 8

SAMICS ANALYSIS

(Production Slicing of 4" Dia Si Ingots)

Cutting Speed = 3"/min — 1500 slices/blade (94% yield)

Equipment	C1 = $0.54/yr ($57,322)	= $ 30,954.00
Space	C2 = $110.61/sq ft (55 sq ft)	= 6,083.55
Direct Labor	C3 = $2.14/yr (1.0 op for 4 m/cs = $8019/m/c + $287.07	= 17,774.99
Direct Mats	C4 = $1.23/yr 176.05 blades/yr x $110/blade + 1273 = $ 20,638.3	= 25,385.36
Utilities	C5 = $1.23/yr Approx $1350	1,660.50
	Total	= $ 81,858.40

It costs $81,858.40 to produce 348,230.5 good wafers/machine/yr

Therefore, add on cost = $0.23/wafer or $40.56/m^2

FIG. 9

SAMICS ANALYSIS

(Production Slicing of 6" Dia Si Ingots)

Cutting Speed = 2"/min — 1500 slices/blade (94% yield)

Equipment	C1 = $0.54/yr ($57,322)	= $30,954.00
Space	C2 = $110.61/sq ft (55 sq ft)	= 6,083.55
Direct Labor	C3 = $2.14/yr (1.0 op. for 3 m/cs = $10,692/m/c) + $162.52	= 23,185.87
Direct Mats	C4 = $1.23/yr 90.87 blades/yr x $110/blade + $1273 = $ 11,268.7	= 13,860.50
Utilities	C5 = $1.23/yr Approx $1350	= 1,660.50
	Total	= $75,744.42

It costs $75,444.12 to produce 128,126.7 good wafers/machine/yr

Therefore, add on cost = $0.59/wafer or $33.36/m^2

FIG. 10

SAMICS ANALYSIS

(Production Slicing of 6" Dia Silicon Ingots)

Cutting Speed = 3"/min — 1500 slices/blade (94% yield)

Equipment	C1 = $0.56/yr ($57,322)	= $30,954.00
Space	C2 = $110.61/sq ft (55 sq ft)	= 6,083.55
Direct Labor	C3 = $2.14/yr (1.0 op for 3 m/cs = $10,692/m/c) + $196.32	= 23,[illegible].01
Direct Mats	C4 = $1.23/yr 125.23 blades/yr x $110/blade = 1273 = $15,048.3	= 18,509.41
Utilities	C5 = $1.23/yr Approx $1350	= 1,660.50
	Total	= $80,508.47

It costs approximately $80,508.47 to produce 176,574.3 good wafers/machine/yr

Therefore, add on cost = $0.46/wafer or $25.81/m^2

FIG. 1

Analysis of the data generated indicates that a lower add-on cost per wafer can be achieved when slicing 4 inch diameter ingot; however, significant reductions can be made to the cost per meter^2 when slicing 6" diameter at comparable cutting speeds, yields and blade life.

CONCLUSIONS

A cost analysis, using the SAMICS FORMAT A indicates various sensitivities that affect slicing costs.

Based on the analysis of the data generated, it is considered that:

1. Cutting speed has the biggest impact on I.D. slicing add-on cost, particularly as blade life is optimized.
2. Slice yield has a significant bearing on I.D. slicing add-on cost, but to a lesser degree than cutting speed.
3. Above 500 slices per blade, blade life has the least impact on I.D. slicing add-on cost.

It is also apparent that potential cost improvements to the slicing add-on cost can be gained as the diameter of the ingot to be sliced is increased. This also impacts on equipment throughput capability.

REFERENCES

1. H.I. Yoo, Applied Energy Corporation. DOE/JPL Contract No. 954830 Final Report, February 28, 1978.
2. M.H. Leipold, C. Radics, A. Kachare, Jet Propulsion Laboratory. DOE/JPL - 1012-37, February 15, 1980.
3. Jet Propulsion Laboratory. LSSA Project SAMICS Workbook Publication Number 5101-15, September, 1977.

DISCUSSION:

WOLF: Since you didn't include the cost of the lost silicon, I think you came to somewhat the wrong conclusion. I think the yield probably is the more important one, once you include the silicon cost.

ROBERTS: As I say, all of the calculations we did were on slicing add-on cost alone.

WOLF: Right. But I think that by itself can mislead you.

DAUD: In your analysis you had three speeds, 1-inch a minute, 2-inch a minute, and 3-inch a minute. That would roughly take you anywhere from 10 hours to 30 hours for an ingot of 30-centimeter length. What would the operator do? Don't you think the guy would be just sitting there for hours and hours?

ROBERTS: No, not really. Somebody has got to mount the ingot, somebody has got to change blades and if you can honestly tell me that that one operator can run 10 saws, can mount his own ingot, can change his own blades, then you have got a pretty damn good guy in there. What we are saying is the blade has to be changed, the time has to be allowed for, and that is why we put it in. How you utilize the operation is up to yourself. We are not specifically saying this guy is only going to be in there changing the blade for 40 hours a year and the remainder of the time he is going to be sitting down. It is a way of getting the time into the analysis.

DAUD: Have you in your analysis ever considered, as it was suggested some time back, cutting more than one ingot at a time?

ROBERTS: I think a lot of people are having a lot of difficulty cutting one ingot at a time. We haven't got an active ID slicing contract ongoing at the moment, these are just projections of how we see the situation. Personally, I'd be somewhat skeptical of ganging of ingots, particularly above 4-inch diameter.

ILES: Could we get the experts to tell us why it is so difficult to gang ID saws? I know the problems in translating, but is it an insuperable job? It would be very nice to get 3 blades running in parallel instead of one.

FARBER: Monsanto holds a patent on slicing more than one slice at once. If you throw a slice it is almost impossible to get it out from the blade. That is basically the disadvantage.

DYER: We have at least three saw manufacturers here. Would they care to comment on this?

BOUJIKIAN: I reiterate what Jeff said. There is no way you can take out a wafer when it breaks between the two blades. There is no way you can get it out of there even if it is a small piece of silicon. Even the slurry between the two blades, when it gets in there, is almost impossible to remove. If you were cutting one wafer it would be all right.

YOO: How about making the blades far apart so you can still put the hand down inside and take out the broken wafers?

AHARONYAN: I think what Henry said could work out very well in that you would be able to slice and you would have room in there to get rid of coolant and slurry and so on. But, from a machine design point of view, and from some of the things we want to do in terms of controlling the blade, getting optimum loads on the blade, etc., it would be a very difficult thing to do. If one blade is not cutting well the other blade is limited by it. It just becomes a very tough thing to control.

FARBER: Did you have a minimum thickness of slice in mind when you did all of your calculations?

ROBERTS: Yes, we used a 20 thousandths-slice thickness and 14-thousandths kerf for a total of 34. We kept it constant throughout all of the calculations that we made.

FARBER: Do solar-cell manufacturers have anything against the 10-mil, or 11-mil or 100-mil slice?

ROBERTS: The question is being able to utilize the materials so that the basic assumption of one kilogram of ingot being equivalent to one square meter is achieved.

KOLIWAD: It disappoints me when I hear "no way can it be done." Those of you who have been in the semiconductor industry probably know, in '65, when people proposed growing 3-inch dislocation-free ingots, there were a lot of people in the ECS meeting who said "no way." Today the same people, the same manufacturers, claim that they can produce 6-inch ingots, dislocation-free. I think that like Bill Yerkes was saying, we should attempt to project the technology and look at the various possibilities.

DYER: Re the difficulty of getting the broken slice out between the blades: is this a design problem, is it that no one has sat down and designed a solution? Or has someone considered it for a long time and decided that it is just impossible to design something that would stop the saw, force out a piece and get it going again? Or is it just one problem and there are 20 others?

OSWALD: It is very difficult to mount one blade and tension it properly and keep it concentric. I don't know how in the world you would do two.

DYER: Dr. Yerkes brought up the question of "is it a lubricant, is it a coolant?"

BOUJIKIAN: I am not in the lubricant manufacturing business and I don't handle one and I don't recommend one. However, the primary purpose of the lubricant or the coolant additive, as you call it, is to break down the surface tension of the water and to wet the diamond and the grinding action between the diamond and the silicon. The main objective again is to minimize the surface tension. Now that, as everybody knows, is just plain simple detergent that is available in the market. Now obviously simple detergent is not going to work in your operation because you have other defects such as algae forming for which you throw some chlorine in it or some other swimming pool stuff and then you have a rust inhibitor so the blades on the machine don't rust. In some cases they put wax remover in it because you have some epoxy and wax surrounding your ingot. A coolant, really, is nothing but a 50 cents a gallon detergent and some additives in it which you can buy in a swimming-pool supply house, add some rust preventive in it and you have got the best coolant in the market.

DYER: Can we have a comment now from someone who would like to speak from the lubricant industry?

HEIT: I wish to take exception to the last series of remarks. There is of course a necessity to have a surface active agent present in a composition. There is no doubt that a contribution is made by a choice of a suitable surfactant to wet the surface of the work so that you get a good spread of coolant water and you can absorb through that water the energy released in the cutting operation. We incidentally do not bother most of the time to put in an algaecide or a biocide. Most systems are used heavily enough that you don't require the action of a biocide to suppress biological activity. However, if the composition of the additive to the water does not contribute toward a prolongation of the life of the saw, then you have a problem. The batting average of a particular composition with which ACE Lube is associated is high in terms of prolonging the life of a blade. This was measured some time ago by measuring the nickel, not the diamond, that emerges in the effluent. It required a painful accumulation of the runoff from the operation and correlation with the throughput of the water used to cool the blade. We found out that the amount of nickel per run time in hours was on the order of magnitude of micrograms. We had to measure fractions of parts per million of nickel by atomic absorption spectrophotometry. This is a sophisticated effort. I wish to advise that there is more to it than meets the eye about formulating a properly constituted coolant.

DYER: Would you say the liquid going into the saw kerf slot is mainly a lubricant or a surface tension agent or a coolant, or is it all three?

HEIT: One of the things that we developed was choosing a certain anionic phosphorated derivative which adds extreme pressure effects, something that was not mentioned and that you will not get out of a conventional detergent, either anionic or nonanionic. There is an extreme pressure juncture at which [illegible] the right material is not used, you get a ripping action. The net result of our particular blend is a great prolongation of the life of the blade and a great freeing of the surface of the work from the kind of blemishes I've heard comments on from the floor before.

FRIZELL: I would like to point out to you some of the problems that develop when you don't have the right coolant. We found over years of working with this material that you can get a great decrease in your output and quality of your wafers and in the results of all of your sawing if you don't have the proper coolant-lubricant. We know that yields have gone up tremendously in just changing from one type of coolant to another. They have dropped off dramatically when errors are made in the amount of coolant that is in the water. People forget the importance of this in their operations at times. If you don't keep your mixtures right and you don't keep your rate of flow proper you are going to lose your slices like everything. It is a very important factor and I think it is one that is badly overlooked by almost everyone that does the work in this room today.

DANYLUK: I would like to give a different point of view on the effects of fluids on surfaces. Our opinion is that the effect of lubricants is a chemoabsorption effect, it is an absorption phenomenon that occurs in the cutting process that can drastically affect surface mechanical properties of nonmetals. In fact, this phenomenon has been known for quite a long time, which surprised me when we first starting working this area. We too have had preliminary experimental results that show that there can be significant reductions in surface hardness of silicon with fluid absorption.

LANE: Some time ago we were attempting to cut quartz with ID saws and we concluded that the only coolant lubricant to use was oil. It didn't work with water. Naturally when you have a saw running and you have silicon ingots in the plant you look at silicon too. We did quite a bit of slicing with silicon and the wafers that came off were dramatically different in surface finish. The finish was much smoother. The surface of the wafers was iridescent, suggesting totally different surface characteristics. We were told by our marketing people who were serving the semiconductor industry that what we desired there was an apparently lapped surface and this iridescent colored surface was undesirable, it did not have the right appearance. It looked to us like there was a dramatic difference in the resulting surface and probably in the damage to the wafer but we don't have any data on that.

SALTZMAN: We are sawing quartz; as I told you, we are not in the silicon sawing business per se. These people were actually running that experiment for me and possible other customers and as a result of their success in using oil I purchased one of their machines. Since that time we have gone into a technique that is not even discussed in this meeting. It is called band slicing. We have band saws with very low kerfs that are sawing large cross sections up to 9 inches square using Greenlee Diamond blades (a Division of DoAll). We had never been successful with this sawing process until we switched to 100% oil. We now end up with a very long blade life, sawing hours of somewhere between 300 and 400 hours. So my comment is yes, coolants are very important. Coolants are just as important to the process as the blades themselves and the machine. They are very highly interrelated and must be taken into consideration.

KOUNDAKJIAN: I manufacture ID blades. Most of our experimental runs are probably 12 or 20 pieces. We really would like to get some cooperation from the users. When we sell any blades we don't get the full information on what's the problem they have. Whether it's the coolant, or the tensioning, or this or that, because we are not in the slicing business. If we have to improve ID blades we'd really like to cooperate with the slicer. Mostly they blame the problem on the blade. We could try softer-bound, harder-bound, different things, but we are scared to send any blades that are new. If they don't work out we could cut out our business. Actually, if we have the full cooperation of the slicing department, we think we could improve this ID blade life. We could do it with nickel. Probably we could do it with other plating, but we never had the chance to get real cooperation, to have some real manufacturer willing to test the blades six months or a year.

DYER: How do you view the main influence of the fluid as it comes in?

KOUNDAKJIAN: If you want the truth, we get it from here and there and that is the whole thing. We don't have it really pointed out which lubrication works well. We know somehow certain lubrication helps in clearing out the nickel but we don't have full information from the slicers in it.

DYER: For those who don't know, I point out the fact that in an ID saw, the water can come in anywhere you want it, but generally you use one stream of water coming into the kerf slot and then after the blade passes through the kerf slot, you use another stream of water. You may use other streams to clear out any trash that collects in the blade housing.

BOUJIKIAN: I did not say that the coolant is not important, the coolant and the distribution of coolant. The additive coolant is very very important and it is an absolute necessity. Anybody who tries to go from tap water or any other deionized water is going to be very badly surprised. The coolant is very essential and very important.

The other comment I would like to make is on ID blades. Mr. Aharonyan mentioned in his lecture that they are working on the design of saws, and also mentioned that there is room for improvement in diamond blades. Now I can take the last 10 years and statistics show that in diamond-blade performance, not including the kerf loss gain, there is something like 30 times, 3000%, improvement in the diamond blade life. Today in the international market or worldwide market, the number of diamond blades is approximately the same as it was 10 years ago. At the same time, the number of square inches or square meters sliced today is about 30 times larger. So there has been improvement in the diamond blade. This isn't all credited to the diamond blade, however. We know for a fact that sometimes the saw manufacturers credit the diamond blade life with 10% improvement or 15% improvement. I can show you customers who have blades that cut 1000 slices, and blades that cut maybe 80,000 slices. So the bladelife is in there, it is designed into the blade. The diamond, the blade, the nickel, never wears if everything goes properly. It is a combination of blade manufacturing, machine usage and application, with the cooling and dressing being parts of it.

KUAN: I have done some work on the effect of lubricants. My results seem to indicate that the lubricants act as lubricant, coolant and also surface catalyst for breaking silicon bonds. I can say that because I have tested different kinds of lubricants including oil which is chemically not active with silicon.

AHARONYAN: We also manufacture blades. I wanted to comment on a statement that John Boujikian made. We can take several blades from a single batch where we know that all of the processes have been the same, we can take the blades and put them on the machine exactly the same way and think they were running without variation from blade to blade and we get different lifetimes, we got different results. There are a lot of influences on it but I think the blade, the machine, and the operator come into play. You can't point your finger at one particular parameter and say this is the problem. We have made progress in the equipment. We make better blade mounts, better machines today. You can't make the statement that the blade mounts today are the same as they were 10 years ago.

WERNER: I don't have special experience in ID sawing of rigid hard material like silicon, but I can refer you to a recent ASME Session on metal-working lubrication, where the stress was on metal. My contribution to that points out that in any grinding process, an ingoing cut perpendicular to the work material, without having the ingot rotating, generates a rather long contact zone, much longer than in conventional grinding processes. ID sawing basically is a grinding process, it has a rather small grinding wheel, same as stone cutting with a saw blade is also a grinding process. This, together with the fact that rigid hard material ground by diamond results in relatively high frictional forces rather than chip removal or chip formational forces, requiring the application of a lubricant rather than a coolant, because in this case, where frictional forces and frictional energies are relatively high, the active reduction of energy by lubrication is more important than the out-flux of energy in the form of a cooling effect. However, in practice, as I learn here, the application of oil in silicon grinding or silicon sawing is not the state of the art. I believe that is the reason why removal rates and cutting speeds in terms of the tangential cutting speed of the saws is limited.

(The recording tape was replaced at this time and part of the discussion was lost. --Ed.)

....and is just removed and if you even very suddenly stop your grinding process you never see those layers of restructured graphite type of carbon atoms, but at 20 to 50 contacts, with high flash temperatures, per second you really wear down your crystal rather fast. Whenever you have high contact temperatures, or frictional conditions, these flash temperatures occur, you have that kind of wear. If you increase your grinding speed and your in-feed rate, you come to a point where the high surface energy that is affecting your diamond is such that your diamond crystal wears rapidly. In this case, the only way out is to apply a lubricant, not a coolant, because a coolant can only have an effect after the single crystal left the contact zone. So, cooling means removing of energy that was established and lubrication means avoiding an energy to be established or to be transformed from mechanical into thermal energy. If you have a high degree of friction, and I think we have that, if you have a higher than normal cutting rate and removal rate, then I think an oil type of lubricant would be the best answer.

YERKES: Looking at the chart that was put up this morning about the various kinds of saws, you saw the higher speeds, linear speeds and higher pressures in the ID saw. But there is also apparently some bandsaw work over here that apparently could be the same. Do you think these speeds can be increased, where do we fall in the context of high-speed grinding on things like this?

WERNER: High-speed grinding is a very controversial issue. About five years ago, or a little more, the grinding world was thinking that higher speeds is the answer to the higher demand for increase of removal rates. There are areas where high-speed grinding, 100 m/s and more, for example and fluting of drilling tools, resulted in tremendous removal rates. In this fluting of drilling tools, the removal rates are 20 to 100 times higher than in milling and at the same time you cut into hardened material without visible thermal effect on the work surface. Now that would be nice if that would be true for all materials. It is only true for certain materials which have what I call a very good thermal-related grindability. That means, while I grind with increased removal rates my thermal level does not go up, but remains at the same level. That is only true for those materials that show a clear drop of cutting forces if you increase the grinding speed, the circumferential speed of the wheel. There are other materials that do not show this beneficial drop of forces if you increase the circumferential speed. Those materials have a relatively high frictional portion of the energy in the cutting process and I suspect that silicon belongs to those materials. Therefore, I would be rather careful in increasing the circumferential speeds for a given machine tool and material. However, I think it might make sense to experiment a little bit by applying a coolant that goes more into the direction of a lubricant.

BOUJIKIAN: I would like to make a comment first on the diamond. There are hundreds of papers written on so-called wear of the diamond, including in ID blades and OD blades and there are three types of wear reported. One, the thermal disintegration at flash point; two, the cracking of the diamond--the diamond will actually break because of an already existing crack that will fall apart, and three, the whole diamond pulling out of the matrix, which in ID blades is more severe than in OD blades because you have the tension. According to hundreds of papers, over 90% of the wear of diamond is attributed to thermal disintegration, or carburization, as it was referred to. This morning, Prof. Wolf presented charts where the pressure or the speed is directly proportional to the wear of the grind. This is correct up to that point, but when you disregard the fact that you are using diamond as a wear factor, this is not correct because the diamond will start disintegrating at a much faster rate as the speed increases. If you look at those curves, they will flatten out and start coming down as your speed increases. This is why every material that you are cutting, being GGG or silicon or any other material, has an optimum cutting speed, in surface speed per minute, at your point of contact. The silicon case happens to be somewhere around 3300 surface feet per minute. Now if you try to go 5000 surface feet per minute, as per that chart, you would increase your efficiency, which is not correct. You will decrease your efficiency all the way down.

AHARONYAN: I would like to make one comment on the wear of the diamond. It is very rare that a diamond blade is discarded because the diamonds have completely worn off of it. We have taken cross-sectional samples of many blades that have cut a few thousand slices each and almost the full amount of diamonds that was originally plated on that blade still remains. The number for a 22-inch blade may be 10 or 20 thousand slices per blade before all of the diamonds are worn off. Usually we found that the main problem has been the weakening of the core and we think that has to do with rubbing of the crystal and the wafer. Diamond wear has never really been a big problem. We had a paper just a while ago where Dr. Chen discussed the difficulties with silicon slicing in terms of the fracture of the silicon. A lot of what we have been talking about here is shear and also shear of the diamond or at least conversion to graphite, etc. Do we have someone here who is in the materials area who might make a comment or analyze for us just what is it we want in the silicon? Do we want the shear or the fracture or what? Particularly, I know that Dr. Schwuttke has done some work in previous years in this area. What would you say we want mainly, the fracture or the shear?

SCHWUTTKE: Actually, to be honest, I don't know what we want today. I think what you want today is the fastest cutting action and then the next question is how can this be achieved in silicon? The basic mechanism to separate silicon is the shear loop; that means a dislocation loop that is put into the surface by abrasion. If you have a pileup of such shear loops in silicon, you form splits, cracks, and then you separate the silicon because the pileup of shear loops in silicon will put the surface in tension and that will open up a crack. That is the basic mechanism. What I would say is, based on this, you have to strive to get the best possible abrasion process if you want to separate silicon. This may relate directly to how you put in your fluid, your coolant, whatever you name it to get the best possible abrasion of silicon.

CHEN: As far as I know, there are no data available on the shearing strength of the silicon. For brittle material, normally we're talking about No. 1 type, that is, an opening-mode fracture. That's direct opening of the crack. In a shearing crack, it is relatively difficult. The shearing strength should be higher than the tensile strength that caused the opening of the crack for crack propagation.

SCHWUTTKE: That is basically correct, but I said what you need is a pileup of shear loops. You surpass the tensile strength of the silicon very easily this way, and this is normally what happens.

CHEN: This is a different mechanism. Dislocation is due to the shearing stress and therefore localized plastic deformation. However, the crack propagation of the brittle material under the shearing is relatively higher.

SCHWUTTKE: I think the very surprising thing is that in silicon you introduce shear loops at room temperature, which is generally not known. There is no plastic deformation. For instance if you have plastic deformation, you would have cracks in silicon surrounded by dislocations at room temperature. This has never been observed and actually does not occur. Plastic deformation of silicon is a very special and complicated thing and a lot of information in the literature is not correct.

YERKES: You know, I am getting real confused again. It seems to me people were talking about 10-mil or 12-mil-wide grinding holes or slots in the silicon and that has got to have millions or tens of thousands of little molecular cracks and things that Dr. Schwuttke is talking about. It seems to me that right down there where all of these diamonds are impacting the silicon, and where these hydraulic forces are, and the lubrication and the steam and whatever else, it is a very wide track with thousands of events occurring. The poor silicon doesn't know where to crack, and how to proceed next. So it is a very statistical kind of a thing. I liked what Peter (Iles) said earlier about whacking this thing and just having it cut like bologna because if the bologna makers lost half their stuff they would be out of business now. So we really ought to be looking at these very thin shearing effects.

WOLF: I wonder how well you can slice your bologna once you cool it in liquid nitrogen?

HEIT: I have notes bearing on the development work that we did in connection with this coolant surfactant composition. This goes back to '76. We found, in three separate samples, 0.3% to 0.4% silicon. We measured 0.31 to 0.38 parts per million of nickel in those samples. We didn't find the diamond, we didn't look for it, but you can find the nickel. Now the wear on the nickel is essentially constant and it is disappearing into the soup at the rate of 10,000 parts of silicon to 1 part of nickel. That is a traceable, attributable state of affairs. We also measured another specimen using the treatment and we found one half of the amount of nickel. In 500 millimeters per minute we found 0.196, and that is what our claim to fame is, we extended the life of the saw by preserving the nickel matrix into which particular allotropic modification a diamond is embedded.

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MATERIALS

Chairman: G.H. Schwuttke, IBM Corp.

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EFFECT OF LUBRICANT ENVIRONMENT ON SAW DAMAGE IN SILICON WAFERS

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The chemomechanical effect of lubricant environments on the I.D. sawing induced surface damage in Si wafers was tested for four different lubricants: water, dielectric oil, and two commercial cutting solutions. The effects of applying different potentials on Si crystal during the sawing were also tested. The results indicated that the number and depth of surface damage are sensitive to the chemical nature of the saw lubricant. By combining the damage depth profile and the surface structure observations, it was determined that the lubricants that are good catalysts for breaking Si bonds can dampen the out-of-plane blade vibration more effectively and produce less surface damage. Correlations between the applied potential and the depth of damage in the dielectric oil and one of the commercial cutting solutions were observed and possible mechanisms involved were discussed.

INTRODUCTION

The depth of surface damage induced in Si wafers during the I.D. sawing process is known to be sensitive to several operational variables, such as blade size, feed rate, blade tension, wafer size, direction of sawing, etc. (1-5). So far most of the studies of the I.D. sawing process have concentrated on determining the depth of damage and its correlation to the mechanical conditions of the operating system. Little attention was paid to the effect of the nature of the lubricant environment on the sawing process. The physical as well as the chemical nature of the environment is known to influence significantly the efficiency of comminution operations such as grinding and drilling in the cement, ball milling, oil drilling and other industries (6,7). Recently, we have examined the relation between the chemical nature of the I.D. saw lubricant and the surface damage structures (8). The results indicated that saw lubricant is an important operational variable, and the depth and number of surface damage can be reduced by improving the lubricant environment.

The sawing of brittle materials, such as Si, is believed to be largely a cleavage process, but prior to our studies the detailed structure of the sawing induced surface damage and the role of plastic flow in the sawing process have not yet been determined in the literature. The damage structures due to mechanical abrading consist of cracking at the surface and strained dislocation networks underneath the surface. Meek and Huffstutler argued from their etching and stress measurements that the sawing induced defects are predominantly microcracks rather than dislocations (4). Schwuttke, using TEM, characterized the very deep saw damage as microcracks (5). We have observed the saw damage from both the top and the cross-sectional view angles by TEM and have characterized the damage structure as mainly cracks extending roughly along both (110) and (111) planes from the chipped surface. Dislocations were found only at the top ~1 μm layer, and their occurrence was attributed to the abrasive motion of the saw blade (8). The major events that create the kerf are therefore the initiation and propagation of cracks. Those lubricants that facilitate the nucleation and propagation of cracks can reduce the energy expended in the sawing operation and the amplitude of the saw blade vibration which in turn affects the damage structure.

We have tested four different lubricant environments: (i) that of the standard production process-water, which is a strong catalyst for the breaking of Si covalent bonds; (ii) dielectric oil, which is chemically inert; (iii) a commercial cutting solution (Kleenzol-B); and (iv) a commercial coolant (Kleen-Kool[1]) in 80 parts water, which is also an active catalyst for breaking Si and other covalent bonds. The testing results are reviewed in the following sections.

EXPERIMENTAL PROCEDURES

Test wafers were sawn from vertically mounted, Czochralski (100) oriented, p-type, 100 ohm-cm, Si single crystals on a commercial HAMCO ID-diamond saw using a new blade with feed speed of 2.54 cm/min and rotation speed of 2100 rpm. Crystals with diameters of 5.7 cm and 8.3 cm were used. The sequence and operational parameters for the test performed on the 5.7 cm diameter crystal are listed in Table 1. Except for the lubricant and the applied potential, all the other operational variables were kept as constants. The wear of the diamond saw blade was considered to be insignificant since only 30 wafers were sawn in each environment.

Thickness and warpage of the as-sawn wafers were measured by an ADE 6043 microsense capacitance gauge. The surface morphologies of the as sawn wafers were observed by optical microscopy. The density profile of the saw damage was measured by an improved metallographic taper-sectioning method (9). Using this method, samples from six experiments were mounted on a beveling fixture and mechanically polished to obtain a 5 degree angle-lapped surface on each sample. The mechanical polishing is known to generate surface damage. In order not to obscure the pre-existing saw damage, this damaged layer newly introduced from polishing was removed by a chem-mech polish (using Syton HT-40[2]), which does not generate additional surface damage. The polished surfaces were then etched for 25 sec in dilute Sirtl etch solution to reveal the saw damage. The distribution of saw damage was read directly from optical micrographs taken from each etched surface. Figures 1(a) and (b) show the micrographs of samples sawn in dielectric oil and Kleen Kool solution, respectively. The number of damage pits and their distances from the wafer surface were recorded, and damage distribution profiles were plotted for each sample.

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1. DoAll trade name. The active agent in Kleen Kool, previously thought to be methyl silane (8), was later identified as an aqueous solution of a glycol ether.
2. Monsanto trade name.

EXPERIMENTAL RESULTS

The results of thickness and warpage measurements on 5.7 cm diameter as-sawn wafers are listed in Table 2. For the 5.7 cm diameter crystal, sawing in water consumed about 7 μm less material per wafer than sawing in other lubricants. Sawing in dielectric oil environment would, on the average, consume 8 μm more material per wafer if a positive potential is applied to the crystal and 4 μm less material for a negative potential, as compared to sawing without any applied potential. The sawing of 8.3 cm crystal was found to consume about 6 μm less material per wafer in water and about 10 μm less material per wafer in Kleen Kool solution than the sawing of 5.7 cm crystal in water under the same condition . This is probably due to the smaller amplitude of the saw blade vibration in the sawing of larger crystals. As indicated in Table 2, Kleenzol B gives the largest warpage value. The applied potential, whether positive or negative, also increases the warpage value.

When the saw blade cuts through the crystal, cracks are generated at the blade edge, and as they propagate and meet in the crystal, small pieces of Si are knocked off and removed by the rotating blade. The diamonds plated on the edge and sides of the blade also abrade the newly cleaved surface. These two processes give rise to two kinds of surface structures revealed in the micrographs taken from the as-sawn wafers: the original chipped off (or cleaved) regions and the flat (or abrasive) regions with scratches lying in the direction of blade motion. The surface of the chipped off region is about 1 μm below that of the abrasive region. The continuous diamond scratches in the abrasive region have a long range ordering with periodicity of about twice the feed distance per rotation. Since the periodicity distance was found to be the same for the two wafer surfaces that are on opposite sides of the saw blade but different for different lubricant environments, this periodic structure on sawn surface (saw mark) must be predominantly from the out-of-plane blade membrane vibration.

The out-of-plane blade vibration which can be modified in different lubricant environments is believed to be the major damage mechanism during the I.D. sawing of Si wafers (4). The surface percentage of the abrasive region and the depth of the scratches are sensitive to the amplitude of the blade vibration. For instance , as compared to sawing in water, sawing in dielectric oil lubricant (with zero potential) increases while sawing in Kleenzol B and in Kleen Kool solution decreases the size of the abrasive area. It was found that an applied negative potential also markedly decreases the size of this area.

The depth profiles of the number of defects obtained by the taper-sectioning method for 5.7 cm diameter wafers indicated that the number of defects drops markedly in the first 20 μm and remains at a constant low value to about 60 μm. In some cases the saw damage distribution can extend to 90 μm or more under the surface. It was found that sawing the 5.7 cm crystal in Kleenzol B and Kleen Kool solution decreases the number of cracks in the top 10 μm layer by about 20 % and 50 %, respectively, as compared to sawing in water. The dielectric oil increases the number of cracks by a factor of about 3 as compared to water in the first 10 μm,but the rest of the profile follows closely that of water. The applied positive potential noticeably increases the number of defects in the 15-30 μm range by a factor of about 2 and also maintains a higher amount of defect from 30 μm to the depth of 70 μm. On the other hand, the applied negative potential decreases the number by a factor of about 2 in the first 15 μm as compared to the zero potential case. In Table 2 the total numbers of defects counted between 2 and 100 μm from 10 optical micrographs, such as those shown in Figure 1, are listed for different environments. The numbers represent the total amount of defect underneath one line with length of 8.95 mm on the sawn wafer.

The sawing of a 8.3 cm crystal shows much less surface damage than that in a 5.7 cm crystal. The crack distribution profile usually extends to about 12 μm under the surface. Sawing large crystal in the Kleen Kool solution also results in less surface defects than sawing in water. The application of +6 V increases while -18 V decreases the number of defects by about 30 % in the Kleen Kool environment. The application of +18 V or -6 V has a negligible effect on the number of defects.

DISCUSSION

The depth of I.D. saw damage reported in the literature varies from 7 μm to more than 50 μm. The discrepancy is largely due to the differences in crystals, operational parameters, measurement methods, and the definitions of damage used in previous investigations. In this study the optical microscopy observation on etched taper-sectioned surfaces showed that the saw damage distribution can extend to 90 μm or more under the surface in 5.7 cm diameter wafers. Schwuttke has previously reported that some of the saw damage structures are so deeply ingrained in the crystal that they can affect the reliability of the finished MOS device even after 90 μm of material has been etched off from the wafer (5). The depth of damage found in 8.3 cm wafers is, however, only of the order of 10 μm, which is probably due to the smaller blade vibration in the sawing of larger wafers.

The depth of saw damage is determined by the length and direction (with respect to the cutting surface) of cracks propagating into the bulk from the blade edge. Those cracks propagating along directions nearly normal to the surface are mostly affected by the out-of-plane saw blade vibration which imparts on the Si wafer a force component normal to the sawing direction. This is evident from the correlation between the depth of saw mark and the thickness of the damaged layer observed in different environments.

Since the blade tension, feed rate, rotation speed and other mechanical conditions are the same in all the experiments, the change in saw blade vibration must be due to the effect of lubricant environment. However, the mechanisms involved in the modification of saw blade vibration is not clear at present. We can speculate that the blade deflection is different in different environments because the environments alter the hardness of the Si surface and/or the friction condition between the saw blade and the Si surface.

The Kleen Kool solution, Kleenzol B, and water are strong catalysts for breaking Si bonds and therefore could enhance crack nucleation at the blade edge and lower the Si hardness. Westwood and co-workers had shown that for covalent or ionic crystals in an electrolyte, the electrical influence of ionic species adsorbed at the surface can alter the dislocation mobility and near-surface fracture behavior (6). They found that the surface hardness is the greatest and the dislocation mobility is the least when the zeta potential is zero. It was suggested that the adsorbates induce redistribution of the carrier in the near surface regions which in turn affects the velocities of dislocation motion and crack propagation. The Kleen Kool solution and Kleenzol B are electrolytes. The dielectric oil molecule may decompose during the sawing and become an electrolyte. The applied -6 V would then enhance the adsorption of the cations and reduce the near-surface hardness. The applied +6 V may be sufficient to cause the desorption of the cations but not sufficient for the adsorption of the anions, which therefore increases the hardness.

Another possible mechanism is that the adsorbates can act as a lubricant layer between the blade and the Si surface and reduce the drag imparted to the saw blade. The applied positive or negative electrical potential then alters the amount or polarity of the adsorbed ions which in turn affects the frictional property of the Si surface.

CONCLUSION

Chemically active environments can influence the fracture process during the I.D. sawing of Si crystal. Our test results indicated that certain lubricant environments can reduce the sawing induced surface damage. The use of a lubricant which is also a strong catalyst for breaking Si bonds can effectively dampen the out-of-plane blade vibration and produce less surface damage. Applying an electrical potential of proper magnitude and polarity on the Si crystal during the sawing can also enhance the benificial chemomechanical effect of the environment. Our experimental data shows that at least a 50 % decrease in surface damage and a 30 % decrease in the depth of damage can be achieved by using a proper lubricant environment.

REFERENCES

(1) J.K. Howard, J. Regh, and G.H. Schwuttke, IBM TR 22.714 (1968).

(2) M.L. Joshi and J.K. Howard in "Silicon Device Processing", C.P. Marsden, Editor, p. 313-364, NBS Spec. Publ. No. 337, Gaithersburg, Maryland (1970).

(3) W.R. Runyan, "Silicon Semiconductor Technology", p.231, Mc-Graw Hill, New York (1965).

(4) R.L. Meek and M.C. Huffstutler, Jr., J. Electrochem. Soc., 116,893 (1969).

(5) G.H. Schwuttke, IBM TR 22.1588 (1973), TR 22.1692 (1973).

(6) A.R.C. Westwood, J. Mater. Sci., 9, 1871 (1974).

(7) P. Somasundaran and I.J. Lin, Ind. Eng. Chem. Process Res. Dev., 11, 321 (1972).

(8) T.S. Kuan, K.K. Shih, J.A. Van Vechten and W.A. Westdorp, J. Electrochem. Soc., 127, 1387 (1980).

(9) T.H. Irish, IBM TR 22.1933 (1975).

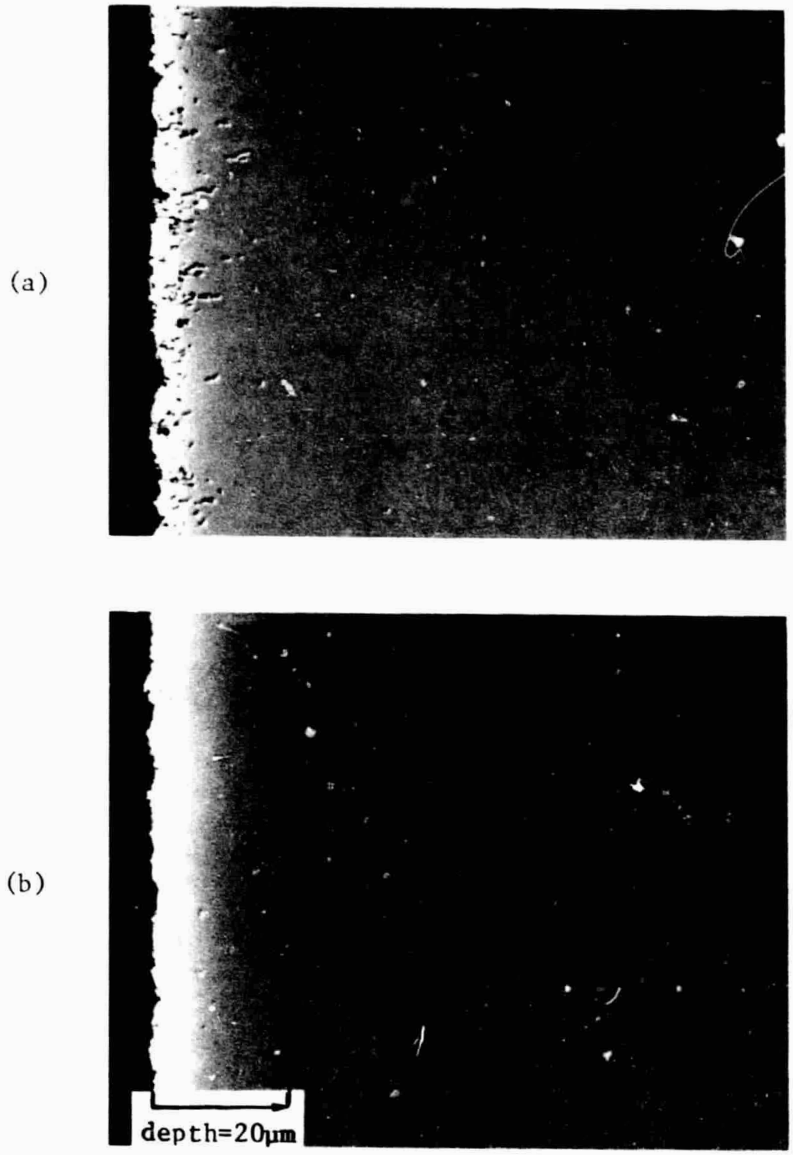

Figure 1 The beveled and etched sample section from wafer sawn in dielectric oil (a), and in Kleen Kool solution (b). The etch pits indicate the number and distribution of defects.

Table 1. Lubricant environments tested in the sawing of a 5.7 cm diameter crystal.

Experiment	Environments
1	Water
2	Solution of Kleen Kool in 80 parts water
3	Kleenzol B
4	Dielectric oil with no potential
5	Dielectric oil with +6 V on crystal
6	Dielectric oil with -6 V on crystal

Table 2. Thickness, warpage, and surface damage measurements on 5.7 cm diameter wafers sawn in the lubricant environments listed in Table 1.

Experiment	Average thickness	Average centerline warpage	Thickness of damaged layer	Total # of defects between 2 and 100 μm
1	602 μm	17 μm	60 μm	6.1×10^2
2	593	19	55	3.3×10^2
3	596	30	55	4.4×10^2
4	593	11	60	12.0×10^2
5	585	16	70	10.8×10^2
6	597	20	65	7.9×10^2

DISCUSSION:

LIU: You mentioned that the out-of-plane vibrations do have major affects on the depth of damage. Do you see any distribution changes of damage depth from the point of entrance, where you start cutting the wafer, to where you finish cutting the wafer? I would imagine that the out-of-plane vibrations would be different.

KUAN: Yes, that is a good point. All the data I show you is data obtained from the center of the wafer. Besides, we got a very good correlation between the surface observation which indicated the vibration amplitude and the depth of damage.

FRIZELL: The oil that you were using flashes at approximately 150°F. Therefore, in the temperatures that you are working at, your oil loses its lubricating ability rather quickly. What you are getting with your results was the fact that nitrates are a very good cooling agent, that's true.

I want to know how you connect with the charge and what you think this accomplishes for you, I still don't see how it accomplishes anything.

KUAN: We apply the positive or negative potential on the crystal during the sawing, and what I tried to say is that the potential either changes the frictional property between the saw blade and the crystal surface or it changes the polarity of the ion so that it effects the chemomechanical effect.

FRIZELL: What ratio of these products did you use to water?

KUAN: In the Kleenzol B we just use it as an ideal solution. The KleenKool is a concentrated fluid and we dilute it with 80 parts water.

LANE: This dielectric oil, is it a commercial cutting fluid?

KUAN: Yes.

N82 23659 D9

INFLUENCE OF FLUIDS ON THE ABRASION OF SILICON BY DIAMOND

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ABSTRACT

Silicon wafers ((100)-p-type) were abraded at room temperature in the presence of acetone, absolute ethanol and water by a pyramid diamond and the resulting groove depth was measured as a function of normal force on the diamond and the absorbed fluids, all other experimental conditions being held constant. The groove depth rates (depth of groove/s) are in the ratio of 1:2:3 for water, absolute ethanol and acetone, respectively, for a constant normal force. The groove depth rate is lower when the normal force is decreased. The abraded surfaces were examined by scanning electron microscopy. The silicon abraded in the presence of water was chipped as expected for a classical brittle material while the surfaces abraded in the other two fluids showed ductile ploughing as the main mechanism for silicon removal.

INTRODUCTION

Abrasive cutting and grinding is currently being used in the solar photovoltaic industry as one method to produce large area sheet silicon. Silicon ingots are sliced into wafers by: (1) inner diameter wafering, (2) multi-blade wafering using a slurry and (3) multi-wire wafering using a fixed abrasive. These methods rely on abrasive wear for cutting by the motion of diamond impregnated wires, abrasive wheels or silicon carbide slurries in water or an oil-based fluid carrier. Although abrasive cutting is used extensively, the basic mechanisms for abrasion, i.e., the interaction of the cutting tool and the silicon and the effects of the fluid in the process are still not well understood. An understanding of this process could lead to improvements in abrasive cutting technology and have a significant impact on the successful utilization of silicon for photovoltaics since this part of the processing represents ∿ 30% of the cost of photovolatic cell production [1].

It is well-known that besides lubrication and effects on the motion of the cutting tool, fluids can influence the surface mechanical properties of non-metals [2]. Fluid adsorption has been known to affect the surface hardness of non-metals. However, there is no general concensus as to the cause for the effect and no satisfactory model has yet been proposed [3]. The relation of fluid adsorption to the abrasive wear of semiconductors has not been investigated.

In this paper we present experimental results for the abrasion of a single crystal (100)-p-type silicon wafer by a pyramid diamond in three fluids. The experimental apparatus in essence is a simplification of the currently used silicon wafering methods discussed previously. It was of interest to evaluate the effects of abrasion rate on changing fluid environments, force on the abrading pyramid diamond and depth of damage and type of debris generated in the abrasion process. The abraded surfaces were studied by scanning electron microscopy (SEM). The results are interpreted in terms of fluid adsorption and its effects on surface mechanical properties of silicon.

EXPERIMENTAL PROCEDURES

Polished silicon (100)-p-type, three-inch diameter round wafers (sheet resistance 9-16Ω-am) were abraded at room temperature by a pyramid diamond while the fluid environment and load (F_n) on a pyramid-diamond were varied. A schematic of the experiment is shown in Fig. 1. The silicon was rotated past the stationary pyramid diamond at a speed of 0.56 rps. Sets of grooves were formed by varying the time of abrasion and F_n and only one fluid was used per wafer. The surface of each slice and the debris was examined by SEM and the depth of the groove vs. abrading time was determined. Polished cross sections of the wafer, which included the grooves, were etched for $\sim$ 2 min. in a Sirth etch to determine the depth of damage.

RESULTS

Representative SEM micrographs of the surfaces of the silicon wafers abraded in the presence of (a) water, (b) absolute ethanol and (c) acetone are shown in Fig. 2. The normal force, F_n, was 62 g and the abrading time was 1.8×10^3 s, all other variables being held constant. As can be seen, the groove surface appears brittle (a), ductile (b) and a mixture of the two (c). The depth of the groove vs. abrading time is shown in Fig. 3. As can be seen, the depth increases as a function of time and the rate is greater when absolute ethanol and acetone is used as compared with water. The rate of groove depth formation increases in the ratio of 1:2:3 for water, absolute ethanol and acetone, respectively, when F_n was 62 g. The rate decreased when F_n was lowered to 42 g.

A cross section of a wafer showing cracks emanating from the groove bottom is shown in Fig. 4. The cracks are sharp, extended for a significant distance into the wafer and are oriented along (110).

The debris expelled during the abrading process is shown in Fig. 5. The surface of the silicon in 5(a) has debris deposits some of which show sharp cleavage facets of the type observed in brittle fracture of ceramic materials. The debris shown in (b) also has these same features--sharp cleavage facets.

DISCUSSION

As seen in Fig. 3, the groove depth vs. abrading time is significantly influenced by the fluid in contact with the silicon surface. In addition, the following was also observed: (a) the depth also varied with F_n as expected and with mixtures of acetone and distilled water [4], (b) no significant differences could be detected in the debris shape when the fluid was changed, (c) the SEM micrographs clearly show that the mechanism for silicon removal changes when the fluid environment is changed; the surfaces abraded in the presence of acetone and ethanol have a similar morphology to abraded metals [5] and (d) there appears to be an incubation time in the wear rate. Considering that all experimental conditions remained constant except for changes in fluid and F_n, the above can be modeled as adsorption of the fluid on the silicon surface and the effect of adsorption on surface hardness.

Rabinowicz and co-workers [6] derived a relationship for abrasive wear by a rigid conical asperity carrying a load L and slidng through a distance S. The expression relating L to the material hardness p and geometry of the cone is

$$L = p \cdot \pi/4 \cdot W^2$$

where W is the diameter of contact of the cone. The groove area A_g, which is the projected area of the penetrating cone in the vertical plane, is given by

$$A_g = \tfrac{1}{4} \cdot W^2 \cdot \tan\theta = \frac{L \tan\theta}{\pi p}$$

where θ is the slope angle of the cone measured from the plane of the surface. Thus when the cone moves through a distance S, it will sweep out a volume V given by

$$V = \frac{L \cdot S \cdot \tan\theta}{\pi p}$$

Substituting $S = t(\omega r)$, $V = 2\pi r A_g$, $\omega = 0.56$ rps, $\theta = 62°$ and $L = 62g$, where t is the abrading time and r the radius of the abraded groove, the hardness can be expressed as

$$p = (6.1/A_g)\left(\frac{kg}{mm^2}\right)$$

The hardness p is therefore related to the groove geometry and the slope of the groove depth vs. time with all other experimental conditions being held constant. Since the fluid environment influenced A_g, then consequently the surface hardness is also affected. Using the above equation we find that the fluid adsorption changed the surface hardness of the silicon in the ratio of 1:0.5:0.3 for water, ethanol and acetone, respectively.

The effect of fluid adsorption on hardness of silicon have previously been reported by Ablova [7] who observed a surface softening by adsorption of water. Westbrook and Gilman [8] also found a softening (up to 60%) in silicon when indentations were carried out in the presence of a small potential between an indenter and the silicon surface. Some recent results of Yost and Williams [9] showed a minimum in hardness for n- and p-type silicon with concentration NaCl and $Na_4P_2O_7$ for a maximum in the negative zeta potential which was interpreted to mean that the hardness change with zeta potential is related to the surface charge and the influence on the charge carrier concentration at the surface. The surface charges were thought to interact with charged kinks at dislocations. Recently Cuthrell [10] has expanded on the adsorption model by relating the drilling rate of glass to the dielectric constant of the fluid in contact with the surface. The dissociation of the fluid into singly and multiply charged ions (as evidenced by the dielectric constant) was found to correlate with drilling rate. Applying these ideas to the abrasive wear of silicon in our case, the slope of the groove depth which varies as 1:2:3 for water, ethanol and acetone, respectively, compares with the dielectric constants which vary in the ratio of 1:1.2:3.8 for these same fluids. Although the correlation does not appear good, the variation is in the right direction and additional experiments are under way to test this hypothesis.

Cracks at the bottoms of the grooves were evident and the length of the cracks were also related to the type of fluid in contact with the surface. Although it was expected that the number and length of subsurface cracks should be smaller for the ductile mode wear groove, this was not found to be the case. Similar results of subsurface cracking was observed in MgO and explained by dislocation interactions resulting from a redistribution of resolved shear stresses during sliding. It was speculated that the internal cracks do not have a direct influence on the increase of wear [11] in that case but a correlation does exist in our results of abrasion of silicon.

SUMMARY

The results of this study may be summarized as follows:

(1) Fluid environments in contact with (100)-p-type silicon affect the wear rate. The rate varies proportionately as 1:2:3 for water, ethanol and acetone, respectively, for a conical diamond abrading silicon at room temperature.

(2) The deformation mode changes from brittle to ductile when the fluid is changed.

(3) The abraded debris is not noticeably different when the fluid environment is changed.

(4) Subsurface cracks are present at the bottoms of the abraded grooves. Their length is also affected by the fluid environment.

(5) The surface hardness of silicon is influenced by fluid adsorption and there appears to be a correlation of the groove depth with the dielectric constant of the fluid.

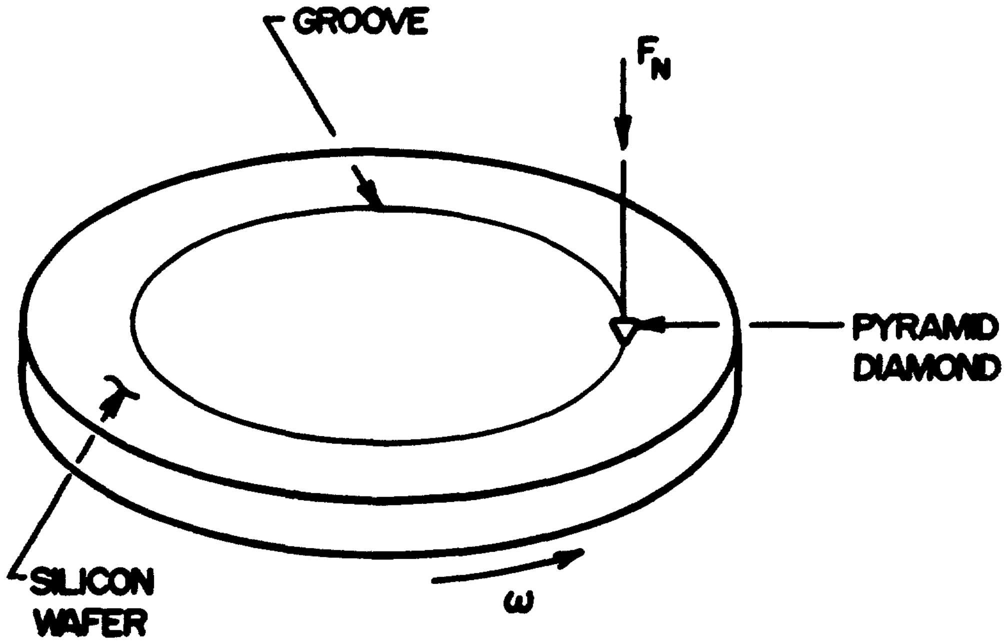

Fig. 1. A schematic representation of the experiment for abrading silicon by diamond. Grooves are produced on the silicon wafer and the groove depth is measured as a function of time, fluid environment and normal force on the diamond. The surface of the silicon is examined by scanning electron microscopy (SEM) for mode of silicon removal.

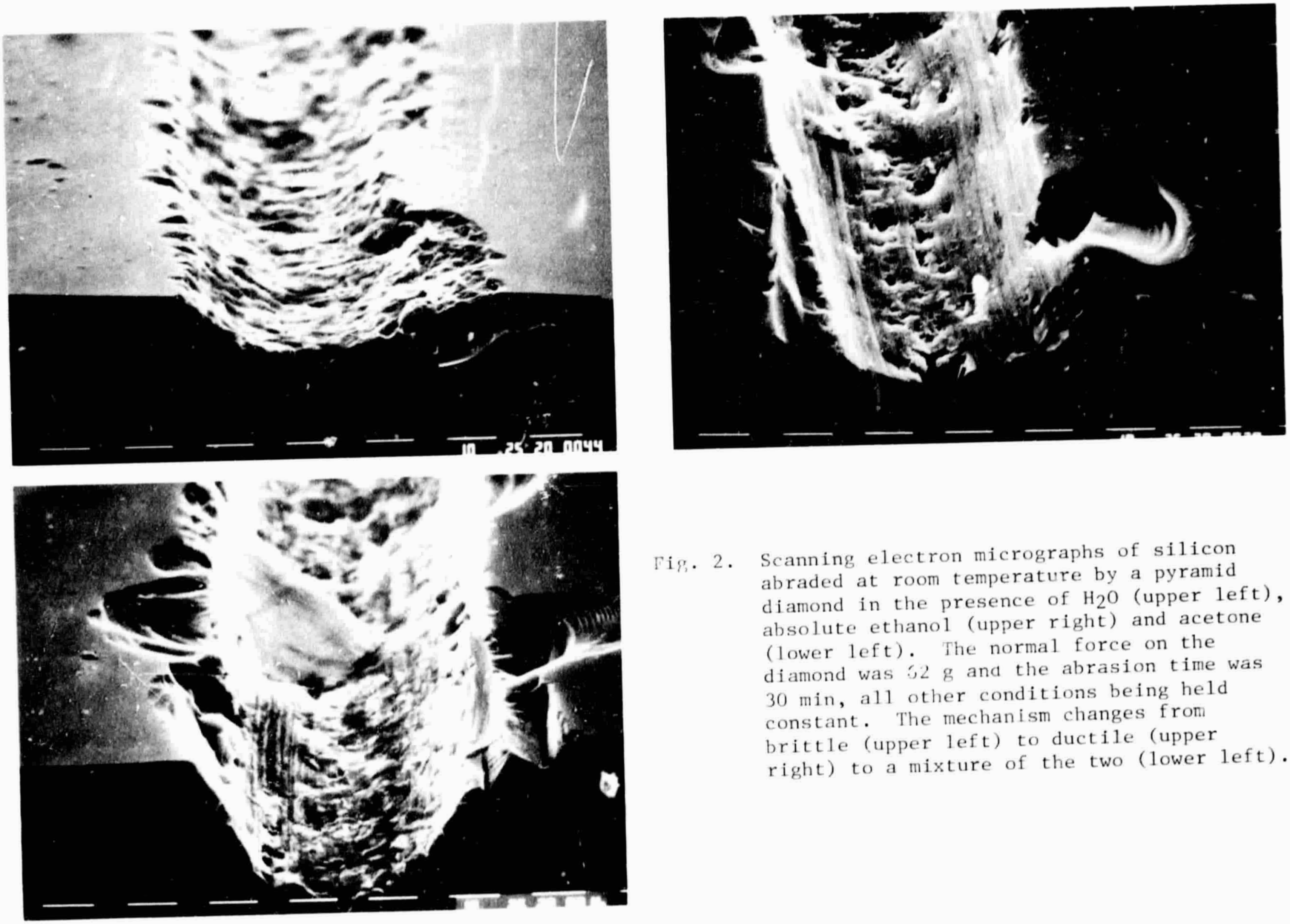

Fig. 2. Scanning electron micrographs of silicon abraded at room temperature by a pyramid diamond in the presence of H_2O (upper left), absolute ethanol (upper right) and acetone (lower left). The normal force on the diamond was 52 g and the abrasion time was 30 min, all other conditions being held constant. The mechanism changes from brittle (upper left) to ductile (upper right) to a mixture of the two (lower left).

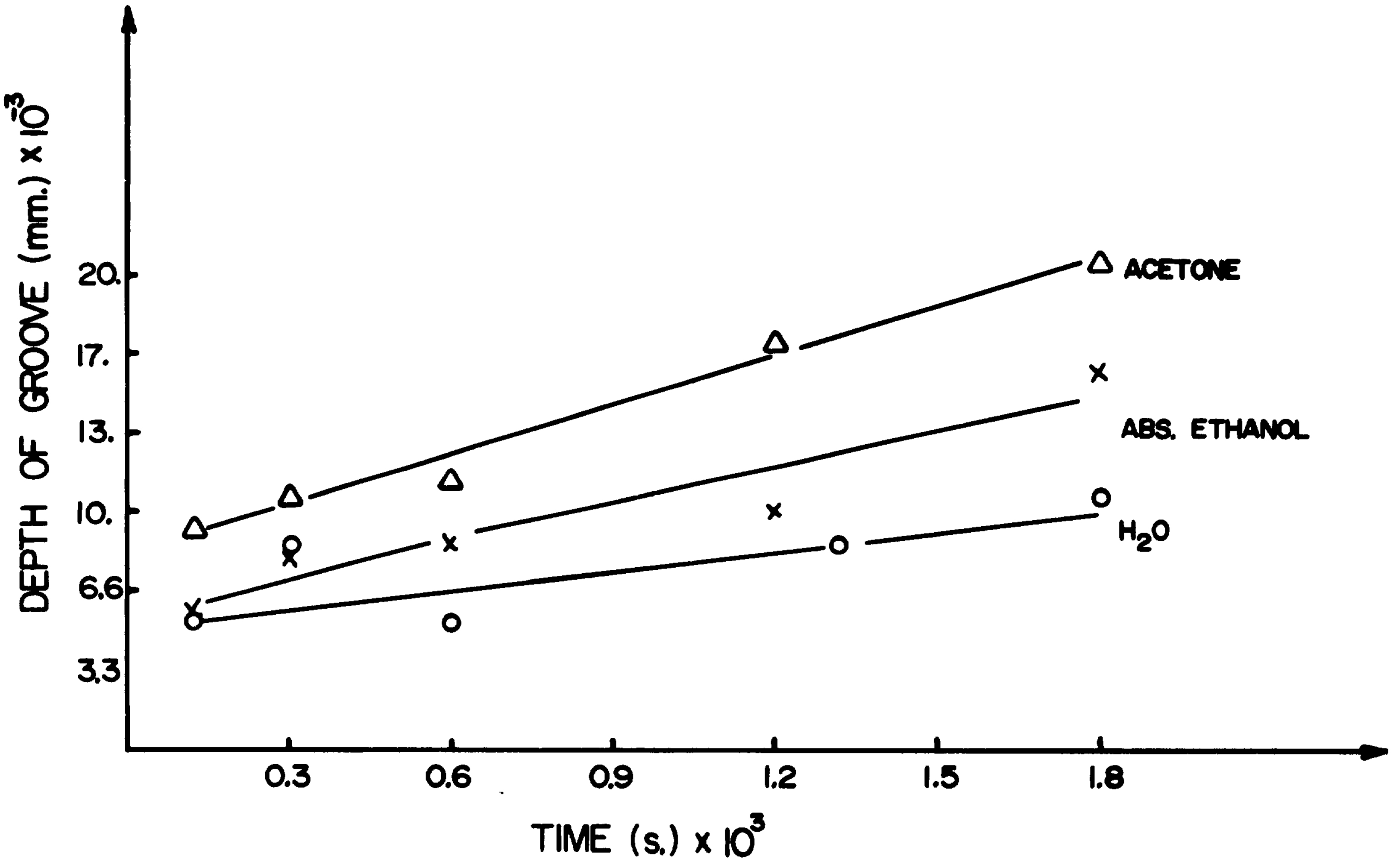

Fig. 3 The depth of the groove (mm x 10^{-3}) in silicon formed by a pyramid diamond at room temperature vs. abrasion time (s). The fluid environment was varied. The normal force was F_n = 62 g.

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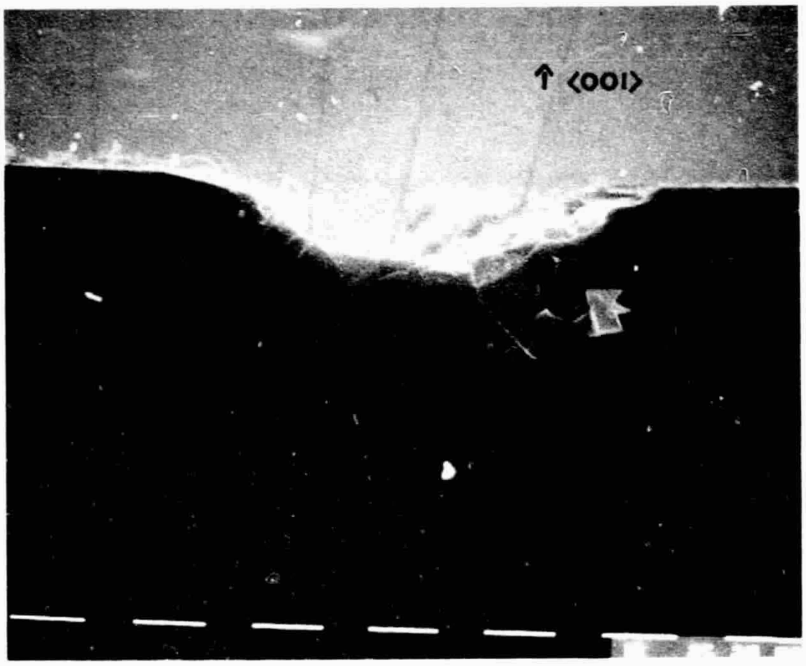
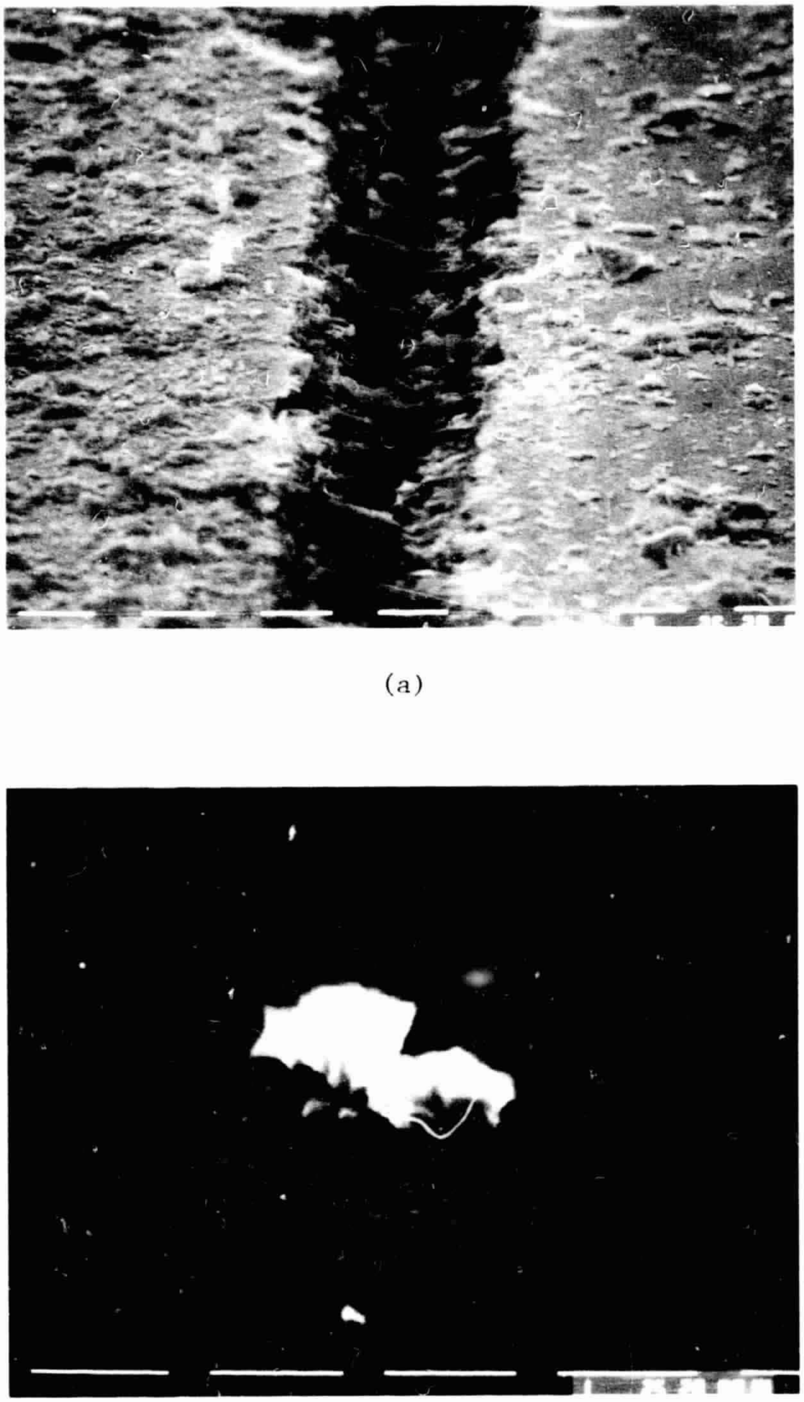


Fig. 4 SEM micrograph of a cross section of a silicon wafer with cracks emanating from the groove bottom. Conditions were: $F_n = 62$ g, distilled water and 600 s abrading time.



(a)

(b)

Fig. 5 SEM micrographs showing debris expelled during the abrading process conditions were: 75% acetone, 25% distilled H_2O, abraded for 30 min. with $F_n = 42$ g (a) and isolated debris generated under 100% acetone (b).

REFERENCES

1. Department of Energy/Jet Propulsion Laboratory, Low-Cost Solar Array Project, Project Report 16, DOE/JPL-1012-51, Sept. 1980.

2. Rehbinder, P. A. and Shuchukin, E. D., Prog. Surf. Sci. 3 (2), 97 (1972).

3. NATO Advanced Study Institute on Surface Effects in Crystal Plasticity, R. Latanision and J. T. Fourie, Noordhoff-Leyden-1977. Proceedings of a NATO Advanced Study Institute, Hohegeiss, Germany, Sept. 5-14, 1975.

4. Danyluk, S. and Reaves, R., to be published.

5. Shetty, R. H., Kossel, T. H. and Fiore, N. F., "Wear of Materials, 1981," Int. Conference on Wear of Materials, ASME (1980).

6. Rabinowicz, E., Dunn, L. A. and Russell, P. G., "Wear," 4, 345 (1961); E. Rabinowicz, "Friction and Wear of Materials," John Wiley and Sons, New York, 1965.

7. Ablova, M. S., "Soviet Physics - Solid State," 6, 2520 (1965).

8. Westbrook, J. H. and Gilman, J. J., J. Appl. Phys., 33 (7), 2360 (1962).

9. Yost, G. H. and Williams, W. S., J. Amer. Cer. Soc., 61 (3), 139 (1978).

10. Cuthrell, R. E., J. Mat. Sci., 14, 612 (1979); R. E. Cuthrell, J. Appl. Phys., 49, 432 (1978).

11. Sugita, T. and Hasegawa, T., J. Mat. Sci., 13, 1471 (1978).

DISCUSSION:

FRIZELL: How could you maintain, with normal ambient relative humidity, the identity of your acetone or your ethanol, both of which are terribly hygroscopic?

DANYLUK: That is a very good point. We have been very careful to do our experiment with fresh acetone and fresh ethanol. We open a fresh bottle, we put the fresh fluid on the silicon surface when we do the abrasion and within half an hour there is a possibility of H_2O absorption. I don't know how much that would be, though.

GALLAGHER: Do you think the fact that in one case you used a noncompressible fluid, water, and the rest of the time you use something that is compressible, could have made a difference in the actual force that you were seeing?

DANYLUK: We have tried to keep all of our experimental variables constant. That means that we don't vary a normal force at all. We essentially keep our pyramid diamond loaded, we just simply remove our slice and insert the next slice. The only changes that we have made in the results that I have been reporting are changes in fluid environment.

GALLAGHER: I guess my question should have been, how did you apply that force? Was it a dead weight?

DANYLUK: It is a dead-weight force, yes.

DYER: Since the abrasion process is mainly mechanical all of the time, I think we ought to keep in mind that this is a mechanical thing and were looking at the possibility of an environment influencing whatever the mechanical affect is. You have a stress field under a point source like that point load. You can even get a picture of that stress field or an idea of the picture of it from books on photoelasticity. It is very complicated, but the general shape of the stress field far away from the point is fairly well known, according to the principle of St. Venant.

Did you measure the friction difference between the water and the acetone and the alcohol? If there is a frictional difference, then that tangential force, if it is substantial, can have two different effects. First, it actually changes the magnitude of the entire stress field. You showed a large effect of going from 42 grams to 62 grams, so that if you had to push on it a little more hard with one tangentially than you did with the other, then you would essentially be increasing the basic size of the stress field. In addition to that, you would be increasing the tilt forward of that field. As you know from looking at the pictures in Frocht or some photoelasticity book, the sum of the two forces, the tangential and the vertical, if you take that vector, then the center of symmetry of that stress field is exactly along that axis. So you essentially tilt the stress field forward and change the things that stress fields do, either cracking or abrasion.

DANYLUK: Our rotation speed was 0.56 rps. So we are essentially at a very slow speed of rotation in the silicon. I think what you are referring to is basically more of a dynamic effect of a changing stress field. I don't think that we are in that regime with our experiment.

WOLF: After seeing the pictures of your grooves, and hearing of your experimental setup, I am wondering how much the bounce of the diamond could have been and how the different fluids could have provided different lubricating quality so as to alter the amount of bounce you might get as you pull the stylus along the groove.

DANYLUK: Well, we haven't measured the bounce, but we are at 60 grams. Our diamond is instrumented to record an acoustic signal. You can obviously hear a difference between the water and the acetone and the ethylene. There is probably some bounce occurring. When we looked at the ethanol grooves, there were some gouges at the bottoms of the grooves that lead us to believe that there may be some bounce occurring. I don't think that is a predominant effect in these experiments.

FRIZELL: Could it be that your lubricants evaporated more rapidly with the ethanol and the acetone than with the water?

DANYLUK: The surface is totally immersed in the fluid.

FRIZELL: Except that at the point of the diamond you got to those temperatures where you are evaporating more acetone than water.

N82 23660 D/10

THE USES OF MAN-MADE* DIAMOND IN WAFERING APPLICATIONS

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The continuing, rapid growth of the semi-conductor industry is requiring the involvement of several specialized industries in the development of special products geared toward the unique requirements of this new industry. The Specialty Materials Department of General Electric has often accepted the challenge of developing a specialized manufactured diamond to meet various material removal needs. The area of silicon wafer slicing has presented yet another challenge -- and it is being met most effectively. Before discussing how MAN-MADE diamond can be useful in slicing wafers, a look at the history, operation, and performance of MAN-MADE diamond is in order.

The History of MAN-MADE Diamond

Natural diamond was first found in India. Later, much larger deposits were found in South Africa and other countries on the African continent, like the modern Zaire, Ghana, and Sierra Leone. In more recent times, the Soviet Union has emerged as a major supplier of mined diamond, and very recent discoveries in western Australia show considerable promise.

In 1951, a project was started by scientists at General Electric who recognized that industry would need more stable reliable sources for diamond. Diamond, as the scientist knew, was a form of carbon, the same material that composes graphite. The GE researchers felt they could create diamond by compressing and then heating the graphite structure. They knew they would have to design equipment that would exert tremendous forces of heat and pressure great enough to change the atomic structure. The change would have to be powerful enough to form the characteristic three dimensional covalent bond that gives diamond its unmatched hardness.

They developed apparatus capable of producing and containing very high pressures and temperatures that could be controlled for adequate time periods and could be reproduced.

But innovative apparatus was only part of the solution. It was discovered that a catalyst was also necessary for the transformation to take place. With this discovery, all the pieces fell into place. In 1955, General Electric announced that they had, in fact, manufactured real, non-artificial diamond in the laboratory. It passed all the tests. It scratched natural diamond, it would not dissolve in acid, oxidized at high

*Trademark of General Electric Co., USA.

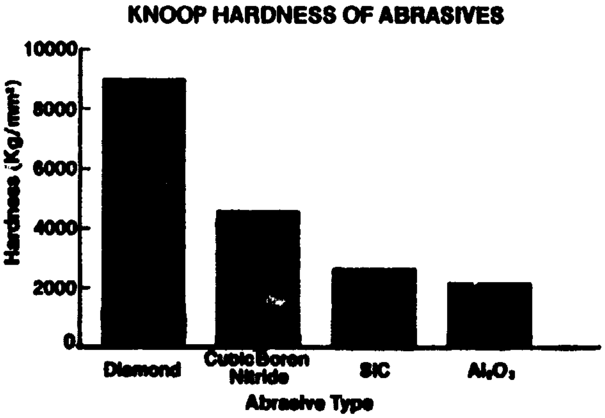
temperatures as mined diamond does, and passed x-ray diffraction patterns identical to natural diamond. GE went on to make other important contributions and discoveries about the nature and formation of diamond. For example, they discovered that the catalyst could be any one of a variety of metals, the carbon used as a starting material affected the character of the diamond formed, and temperature differences could produce diamond crystal color varying from black when manufactured at low temperatures through dark green, light green, yellow and white at the highest temperatures. Color is also affected by the presence of non-carbon atoms in the diamond crystal.

General Electric has even demonstrated the ability to synthesize a variety of gem size and gem quality stones.

For a wide number of reasons that will be discussed later, manufactured diamond has been rapidly growing in popularity ever since its introduction in 1957. It is now used almost five times more often than mined diamond in industrial applications and still growing steadily.

Why Use MAN-MADE* Diamond?

MAN-MADE diamond has properties such as hardness, abrasion resistance, compressive strength and thermal conductivity that make it a logical choice over conventional abrasives for many applications.



(Fig. 1)

The Knoop hardness test (Fig. 1) is a standard method for measuring the hardness of exceptionally hard and brittle materials and individual grains and particles. It is an indentation test. and thus, is regarded as a true test of the relative hardness of materials. It can readily be seen here that diamond far surpasses the conventional abrasives in hardness.

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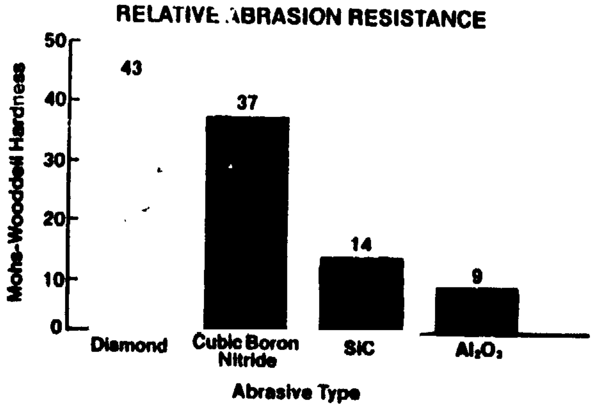
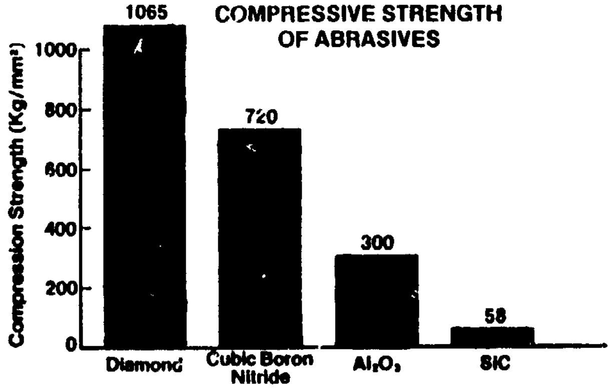
(Fig. 2)



The relative abrasion resistance (Fig. 2) calls for some explanation. Note that the vertical scale on the chart is labelled "Mohs-Woodell Hardness". However, the Mohs-Woodell hardness determination is the result of "rubbing" materials together; thus the values obtained are essentially measures of relative abrasion resistance instead of hardness. The important point, of course, is that diamond is significantly more abrasion resistant than either aluminum oxide or silicon carbide.

(Fig. 3)



The high compressive strength value (Fig. 3) of diamond is expected in light of the atomic structure of diamond. Essentially each crystal is composed of carbon atoms arranged in face-centered lattices forming interlocking tetrahedrons and also hexagonal rings in each cleavage plane. Each carbon atom in the crystal is surrounded by four other carbon atoms lying at the corners of a tetrahedron. These four atoms are connected by covalent bonds to the original carbon atom. In turn, each of the four corner atoms is connected to four other carbon atoms, including the original, by covalent bonds. This pattern persists throughout the entire diamond crystal so that each crystal is one giant molecule, accounting for its hardness. Therefore, in order to break the diamond crystal, many covalent bonds must be broken. This requires a large amount of energy.

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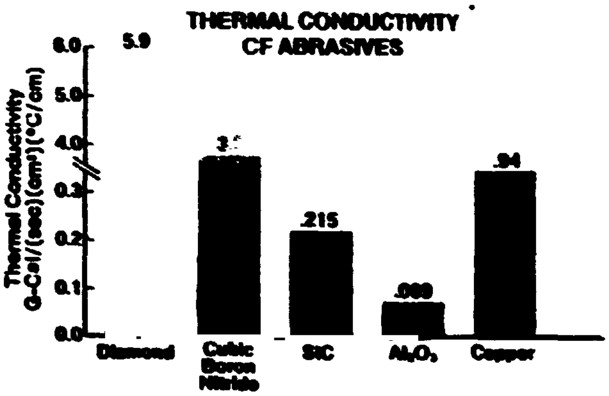
(Fig. 4)



The high thermal conductivity of diamond (Fig. 4) is an advantage for material removal applications. Heat generated during the operation is rapidly dissipated through the superabrasive material into the grinding wheel or tool thus reducing the risk of thermally damaging the workpiece material. A characteristic of great importance when slicing silicon wafers.

How Does MAN-MADE* Diamond Work?

When using a tool impregnated with MAN-MADE diamond, each abrasive particle on the periphery of the tool contacts the workpiece, acting as an individual cutting tool and removing a minute chip, or particle, from the surface of the material being ground. In addition to its hardness characteristic, it is important that a diamond have good sharp cutting edges with which to remove material. In time, these cutting edges could be worn smooth making the diamond less effective unless the proper kind of diamond is utilized. This is where a MAN-MADE diamond, tailored to a specific application becomes so beneficial. One of the benefits of MAN-MADE diamonds in this type of application is that they are designed to micro-fracture. That is, before their cutting edges become too worn they actually break away exposing new, sharper cutting surfaces to maintain the good free-cutting characteristics of the tool.

A combination of these MAN-MADE diamond characteristics and the process by which material removal is accomplished leads to a cutting tool with excellent performance. This shows itself by a longer tool life experienced over conventional abrasives, a higher stock removal capability, the ability to hold and maintain much tighter tolerances on the workpiece, and a much higher degree of productivity.

One final characteristic that sets MAN-MADE diamond apart from mined diamond and other abrasives are the strict set of quality control procedures that each shipment of diamond must pass before being delivered. Over 15 product tests are conducted on each shipment of GE diamond before leaving our plant. Some of the key tests that GE demands to maintain a consistently high quality diamond are tests used to measure a diamond's toughness, bulk density, size, and appearance. The first is the test of toughness.

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The term friability is used to refer to an impact strength measurement which is conducted on diamond products. At GE, we refer to this parameter as our products' Toughness Index. This refers to a test which measures the resistance to impact fracture of the crystal when it is subjected to a controlled duration of destructive ball milling.

Bulk density testing is a test which is an ANSI standard in the United States. Of the two tests in common use, GE uses ANSI B-74.4, because of the greater degree of accuracy it yields due to the use of very large test samples.

Size testing is based on the existing ANSI and FEPA standards for the size of diamond grains. It is interesting to note that both of these standards were developed on the basis of work done at the Specialty Materials Department of GE. Only costly, precision electroformed screens are used in this test.

In addition to a wide number of other tests, a visual examination is given to each batch of diamond to be sure that crystal size, shape, color, and other physical characteristics are consistent with all other shipments of that product.

As you can now well understand, a MAN-MADE* diamond which can be grown, sized, and tested to meet a specific application need is the very type of product needed in a field of such growing sophistication as the semiconductor industry. Furthermore, in light of the recent natural diamond shortage and with the prospect of continued disruptions in the supply of mined diamond, it appears as if the goals of that original GE research team in providing a more stable and reliable source of diamond are becoming even more critical to industry today.

How Is MAN-MADE Diamond Being Used?

A brief look at some of GE's existing MAN-MADE diamond product families will illustrate how they have been tailored for specific applications.

RVG - The earliest GE product offering, is composed of very friable, irregular crystals most frequently used with a nickel or copper coating which totally covers the entire exterior surface. This diamond is designed for use in resin or vitreous bonds and used when processing cemented tungsten carbide, carbide-steel combinations, cermets, and diamond or cubic boron nitride compacts tools.

MBG - A medium tough to tough regular crystal which ranges in color from yellow-green to light yellow and almost white. This product is aimed for use in metal and plated bond applications and is used for processing glass, ceramics, ferrites, plastics, fiberglass and other materials.

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MBS - This product is composed of tough, blocky cubo-octaheydral crystals with predominantly smooth faces. Generally the crystals are transparent or translucent and range in color from light yellow to medium yellow-green. Designed for metal bond applications and used in processing stone, concrete, refractories and other highly abrasive materials.

Micron Powders - A product made up of blocky crystals generally less than 60 microns in size. It is available in either a diamond graded or ungraded form or BORAZON* CBN. Micron Powders are used as a loose abrasive or for lapping and polishing in slurries or compounds and has been tailored for use in processing dies, ceramics, stone, metallurgical specimens, gemstones and other metals, and more recently has been successfully used in silicon dicing blades.

BORAZON CBN - (Cubic boron nitride) - These crystals vary from sharp, irregular shape to strong, blocky shape with the color varying from black through translucent orange-brown. BORAZON CBN was developed in 1956 by General Electric specifically for the processing of steel, cast irons, ferrous nickel, cobalt base alloys, and stainless steel.

Within each of these major product groups, separate product offerings have been developed for even more specialized applications making the total number of GE diamond product types well over 200, with many more to follow.

Some of these products are currently being used as a silicon wafer slicing diamond while development work is being done on MAN-MADE diamond specifically tailored for this application. But, before turning our attention to silicon wafer slicing with MAN-MADE diamond, let us first examine the types of requirements that would be made on such a product.

The Slicing of Silicon Wafers

Silicon Wafer Slicing makes some very specific demands upon the slicing saw that should be addressed before considering the type of blade to use.

A major problem encountered with blades is the excessive heat generated at the point of cut. This heat build-up results in a degradation of the quality of the cut due to the possible disintegration of the abrasive material used.

Of the major sources of heat build-up, coolant starvation is the most common. The rotating blade acts as an air pump creating a high velocity air blanket between the blade and the work. This blanket of air prevents coolant from reaching the point of the cut adequately, causing the blade to cut dry.

A second cause of heat build-up is the loading of the cutting edge with silicon, causing galling and burnishing of the wafer surface.

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This gives rise to a second consideration - the prevention of thermal damage to the silicon wafer. Care must be taken in choosing the proper slicing blade or the temperature build-up at the point of contact could be excessive enough to create thermal cracks in the surface of the water.

Minimal kerf loss is also important to the wafer manufacturer who is trying to achieve the highest number of wafers from an ingot. Kerf losses of 10-12 mils are presently considered the lowest obtainable for cutting semi-conductor grade wafers. Even this kerf amounts to a 30-40% loss of the silicon at the sawing step.

The process of obtaining a flat wafer with no taper or bow, starts at the sawing operation. If the wafer is sliced as flat as possible and with little damage from the saw blade, subsequent lapping and polishing operations can be simpler and less costly. If the sawing operation is not properly executed, wafers will be produced which cannot be connected or which will break on further processing.

A final consideration that is essential to accurate slicing lies in the performance of the balde within the sawing equipment itself. Critical to making a good cut is having a blade that is vibration free, and a system which does not produce retrace damage when the blade is retracted from the workpiece. The latter becomes extremely important as the size of the wafer increases, requiring larger blades and greater throws.

MAN-MADE* Diamond for Silicon Wafer Slicing

MAN-MADE diamond products are successfully being used for slicing silicon wafers, but we at GE, are continuing to investigate system improvements. We are currently developing a silicon wafer slicing diamond that will significantly improve on the current method of wafer slicing. This MAN-MADE diamond has been specifically tailored to solve the problems of slicing silicon by exhibiting the following characteristics.

We originally discussed the elevated temperatures experienced at the silicon cutting interface. Our diamond is engineered to give quality performance at high temperatures. Such a characteristic is essential for the slicing operation due to the elevated temperatures discussed earlier. MAN-MADE diamond remains stable for several hundred degrees above the point that most bonds would break down. As an example, temperatures were measured at the tool/workpiece interface when dry grinding a high alumina ceramic material with diamond electroplated pins. These temperatures were approximately 300°C at maximum, far below any of the critical temperatures for the common electroplating bond. In addition, most wafer slicing is done wet, and special coolants are now available to prevent starvation thus alleviating the severity of any temperature problem even more.

Thermal damage was a second concern of wafer slicing operations. Our diamond has been designed with physical properties to eliminate thermal

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damage. An application utilizing the proper coolant and the appropriate type and mesh size of diamond will cause the crystal to fracture in such a way so as not to contribute to heat build-up. Tests have shown that the proper MAN-MADE* diamond produced considerably less chipping on the surface of a silicon wafer than did a similar application with mined diamond.

Kerf loss is an economic concern in slicing wafers. Use of GE diamond in a slicing saw will provide for the thinnest possible saw blade. By merit of the fact that the wafer slicing diamond is developed specifically for an electroplated application, the plating process provides the capability of making a blade to the desired thickness required for minimal kerf loss.

The next generation of VLSI circuits will require operation near the limits of resolution of optical photo-masking processes. As mentioned earlier, ultraflat wafers and masks will be required, among other things, to achieve high yields in these critical applications. It has been estimated, for example, that a one-to-one projection printer capable of reproducing one micron lines over the entire wafer will require wafer surfaces flat to within three microns. The main device for assuring as flat an initial cut as possible is to hold the blade in tension enough to prevent vibration or rubbing, which occurs when the blade wanders excessively from a straight cutting path. The proper type of adhesion between MAN-MADE diamond in a plated bond and the core of the blade is what is necessary in order to be able to withstand the extreme stress exerted on the blade during the mounting process prior to slicing.

Finally, there is little that the diamond abrasive can directly contribute to the minimization of the blade vibration and retrace damage. However, blade manufacturers continually review the basic diamond properties and with their practical experience they anticipate any changes in diamond properties which occur to specific bond and blade manufacturing techniques. As he is well informed of the diamond properties, blade manufacturing procedures, and the application details of the silicon wafer slicing operation, he can optimize the overall slicing performance.

Conclusion

As we have seen, General Electric has historically been able to manufacture a diamond that has been specifically designed for one particular application. We have seen this in the case of RVG for tungsten carbide grinding, MBG products designed for glass grinding, EBG, a diamond designed specifically for electroplated application, and many other examples.

Currently, blade manufacturers have taken these existing product lines and have designed silicon wafer slicing blades around them. This has been done by combining their knowledge of the industry with that of blade manufacturing.

A second alternative that GE is offering is to continue the practice of their development of a new product designed specifically for one application--in this case that application is silicon wafer slicing. Product development

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is currently underway to come up with a diamond specifically for sawing silicon wafers on an electroplated blade.

In the final analysis, a proper combination of General Electric Diamond Engineering technology and the expertise of the blade manufacturer can and will continue to provide an array of superior slicing products suited to meet the ever growing needs of the semi-conductor industry.

WIRE-BLADE DEVELOPMENT FOR FIXED ABRASIVE SLICING TECHNIQUE (FAST) SLICING*

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ABSTRACT

A low-cost, effective slicing method is essential to make ingot technology viable for photovoltaics in terrestrial applications. The Fixed Abrasive Slicing Technique (FAST) is a new slicing process which combines the advantages of the three commercially developed techniques. In its development stage FAST has demonstrated cutting effectiveness of 10 cm and 15 cm diameter workpieces by slicing 25 and 19 wafers/cm respectively. Even though significant progress has been made in the area of wire-blade development it is still the critical element for commercialization of FAST technology. Both impregnated and electroplated wire blades have been developed; techniques have been developed to fix diamonds only in the cutting edge of the wire. Electroplated wires show the most near-term promise; hence the emphasis has been placed on this approach. With plated wires it has been possible to control the size and shape of the electroplating--this feature is expected to reduce kerf and prolong the life of the wirepack.

INTRODUCTION

The Fixed Abrasive Slicing Technique (FAST) makes most ingot technologies viable for photovoltaic applications. Compared with current wafering methods --Internal Diameter (ID), Multiple Blade Slurry (MBS) and Multiple Wire Slurry (MWS) processes--the FAST approach offers the potential of lowest add-on cost (1). FAST uses diamond fixed on wires in a multiple-wire pack configuration for slicing silicon. This new technique was made feasible by developing a method for making bladepacks with equal wire spacing and tension and a higher speed reciprocating slicer. The development of FAST is being discussed in another paper at this conference (2). At the present time a preprototype slicer designed for FAST slicing is being optimized. Significant progress has been made in the area of wire blade development but it is still the critical element for commercialization of FAST technology.

For any ingot technology to be cost effective for photovoltaic applications, it has to be combined with a low-cost slicing method. Kerf loss and ingot utilization (kerf plus slice) are major considerations in silicon sheet cost. An economic analysis (3) of silicon slicing has indicated that the ingot utilization considerations limit the cost reduction potential of the ID technology. This analysis also showed that the expendable materials costs, slurry and blades, dominate the wafering costs of MBS. Demonstration tests (4) of MWS method has shown that lowest kerf widths are obtained with wire slicing. However, the cost of the wire is even more than the slurry costs, thereby increasing the expendable materials costs of MWS even more than the MBS process.

In FAST a pretensioned, fixed-diamond, multiple-wire pack is reciprocated similar to the MBS process to slice through the workpiece. The multi-wire FAST approach combines the economic advantages of ID, MBS and MWS techniques. Expendable materials costs are low as in ID slicing, capital equipment and labor costs are low as in MBS slicing, and material utilization is high as in MWS wafering.

ADVANTAGES AND REQUIREMENTS OF FAST WIREPACKS

Aside from the economic advantages, there are technical advantages of using multi-wire FAST approach:

(1) Due to the symmetry, wires do not torque the wafers after slicing as in the case of flat blades; this allows for less clearance and, therefore, reduced kerf width.

(2) In case of wire breakage only two wafers contacting that wire are lost.

(3) The diamonds fixed on the wire prevent wire wear, hence wire and abrasive cost is minimized.

(4) No fatigue problems occur because wire is not wrapped around rollers.

(5) Wires are cheap to fabricate to a higher dimensional accuracy and uniformity.

(6) No corrosion problems occur since the wires are nickel or copper plated.

(7) Wires can be pretensioned to higher stresses.

(8) Wires do not buckle under high feed forces.

(9) Slicing is carried out under low feed forces resulting in low surface damage.

(10) Wafers produced show no edge chipping problems.

The essential requirements of wirepacks used for FAST slicing are:

(1) The wires must be clamped to prevent slippage and must be with equal tension and spacing in the bladepack.

(2) Wire core must have high yield strength and modulus for minimum deflection.

(3) Diamonds must be fixed on wire with high, uniform concentration.

(4) Prevent erosion of the matrix holding the diamonds.

(5) Diamonds must exhibit long life and high cutting rates.

(6) Wire diameter must be minimum to reduce kerf.

(7) Minimized wander for accurate slicing.

(8) Prevent corrosion between the matrix holding the diamonds and the core material.

In the above tabulation the first requirement is related to fabrication of wirepack and the rest relate to properties of wire, matrix and procedures for fixing diamonds onto wires. Simple fabrication procedures have been developed which give the wires equal spacing and tension with no problems of cumulative errors. After evaluation of various core materials (5) a selection was made to use high strength steel, stainless steel and tungsten. High strength steel and stainless steel wires were selected based on high yield strength and tungsten on the basis of its high modulus. Most of the work was carried out with a 5 mil (0.125 mm) tungsten wire because of its high modulus and corrosion resistance.

Two approaches were pursued in fixing diamonds, *viz.* impregnated wires and electroplated wires. In the former case diamonds were impregnated into a soft copper sheath on the core wire, whereas in the latter case diamonds were fixed by electroplating.

IMPREGNATED WIRES

Commercially available impregnated wire (6) was 5 mil (0.125 mm) stainless steel core with a 1.5 mil (37.5 µm) copper sheath impregnated with 45 µm natural diamonds. Slicing with this wire showed that cutting effectiveness was lost within approximately 0.25 inch depth of cut. Examination of the wires showed considerable diamond pull-out. Electroless nickel plating of these wires reduced the diamond pull-out considerably. It was found that nickel plating thickness of 0.3 mil (7.5 µm) produced best results; a nickel layer of 12.5 µm was sufficient to bury the diamonds. A wafering experiment of a 10 cm diameter silicon workpiece with 114 parallel wires spaced at 19/cm with these wires showed an average slicing rate of 2.33 mils/min (0.059 mm/min) and produced a 96.5% yield.

Impregnation techniques developed within Crystal Systems showed that it was possible to impregnate diamonds in the cutting edge of the wires only in an area less than the bottom half circumference of the wires. Figure 1 shows a cross section of such a wire. Natural diamonds of 45 µm size were impregnated into a 1.5 mil (37.5 µm) copper sheath on a 5 mil (0.125 mm) stainless steel core wire. A 0.3 mil (7.5 µm) electroless nickel layer was plated after impregnation. Slicing tests using wirepacks with diamonds impregnated in the cutting edge only improved the average slicing rate to about 3 mils/min (0.075 mm/min) and reduced the kerf. This approach also allowed use of 60 µm diamonds without significantly adding to kerf. The advantages of diamonds in the cutting edge only are:

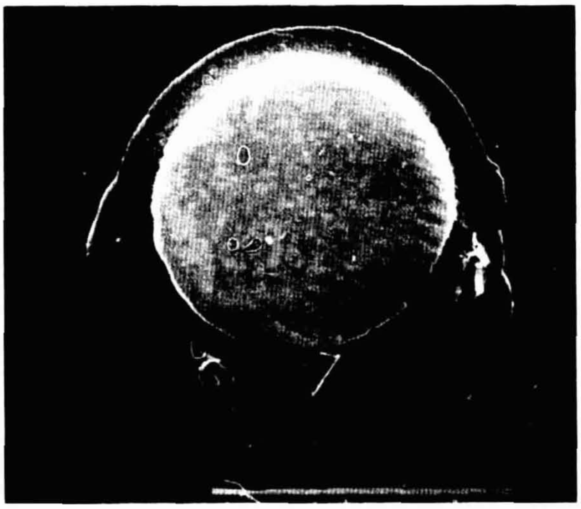

Fig. 1. Cross-section of wire with diamonds impregnated in cutting edge only

(1) Lower kerf.

(2) Use larger diamonds.

(3) Ability to add more than one layer with marginal increase in kerf.

(4) Minimize degradation of guide rollers in the FAST slicer.

(5) Better seating of the wires in the grooved guide rollers.

(6) Improved accuracy of slicing because of absence of diamonds on the sides of the wires.

(7) Minimize wire wander when diamonds in the cutting edge are somewhat "dulled".

Even though significant progress has been made with impregnated wires considerable effort has to be devoted towards achieving high concentration of diamonds with good uniformity and preventing diamond pull-out during slicing.

ELECTROPLATED WIRES

At the start of this program electroplated wires were not commercially available. Initial work was carried out in cooperation with various plating vendors.

Choice of Core Wire

It was found that the core wire used as a substrate was very important to achieve plating with a good bond between the nickel matrix and the core substrate. Plating on steel caused embrittlement which resulted in considerable wire breakage during slicing. Difficulties in cleaning procedures prior to plating of tungsten necessitated the use of a thin nickel flash on the core wire prior to use as a substrate. Figure 2 shows the longitudinal and cross-section of electroplated wires using (A) a copper flash and (B) a nickel flash on tungsten core wires. It can be seen that the longitudinal sections show a high concentration of diamonds. Examination of the cross-sections shows corrosion problems in the copper flash layer which is not existent in the case of the nickel flash wire. No such problems were evidenced in plating directly onto a stainless steel substrate (Figure 3). Emphasis was placed on using nickel flash tungsten core 5 mil (0.125 mm) in diameter; recently procedures were developed in plating copper-flash, high-strength steel wires without embrittlement problems.

Choice of Diamonds

With fixed diamond it is very important to establish a speed-pressure relationship at the diamond tip for effective slicing. Rocking of the workpiece in FAST increases the pressure by decreasing the contact length; however, the diamond type and size needs to be optimized. Both natural and synthetic variety are available. In the synthetic type the choice is blocky, explosively formed, EDC, Man-Made (7), etc. The various varieties also include tough and friable; while the former stand up to slicing conditions without breakdown, the latter breaks down and exposes new surfaces for higher cutting rates. Under similar conditions of slicing to date the natural diamonds gave better results than the blocky type. An SEM of the two varieties is shown in Figure 4.

Besides the diamond type a choice has also to be made for diamond size. The larger particles are desirable for long life and higher cutting rates;

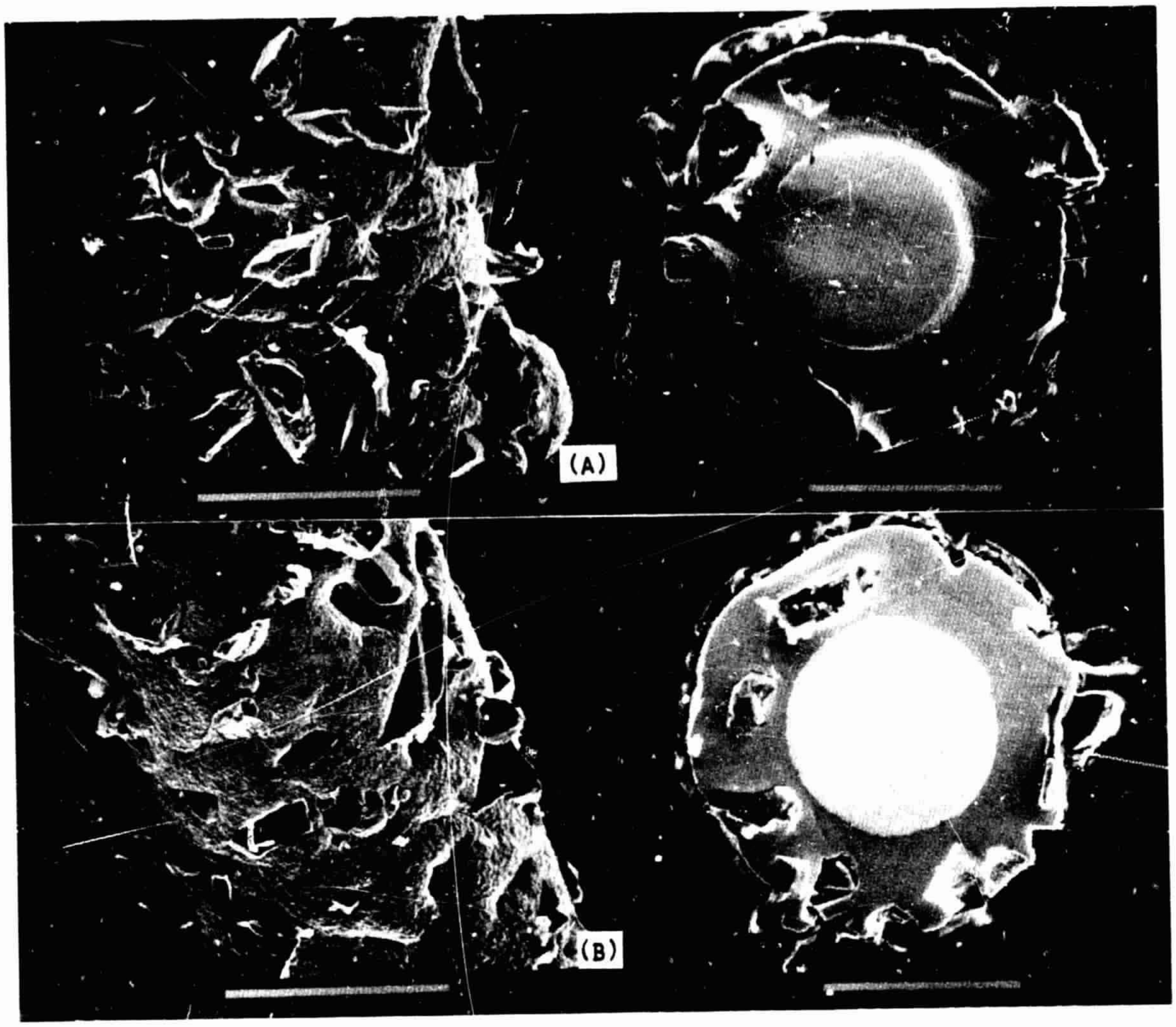

Fig. 2. Longitudinal and cross-section of electroplated wires using tungsten core with (A) copper flash and (B) nickel flash

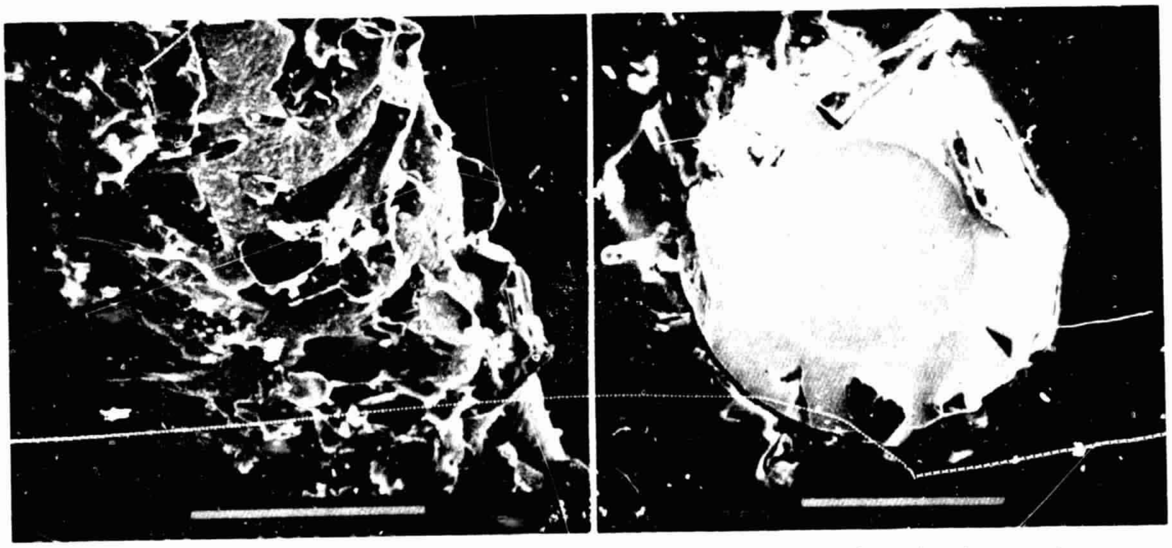

Fig. 3. Longitudinal and cross-section of an electroplated wire using stainless steel core

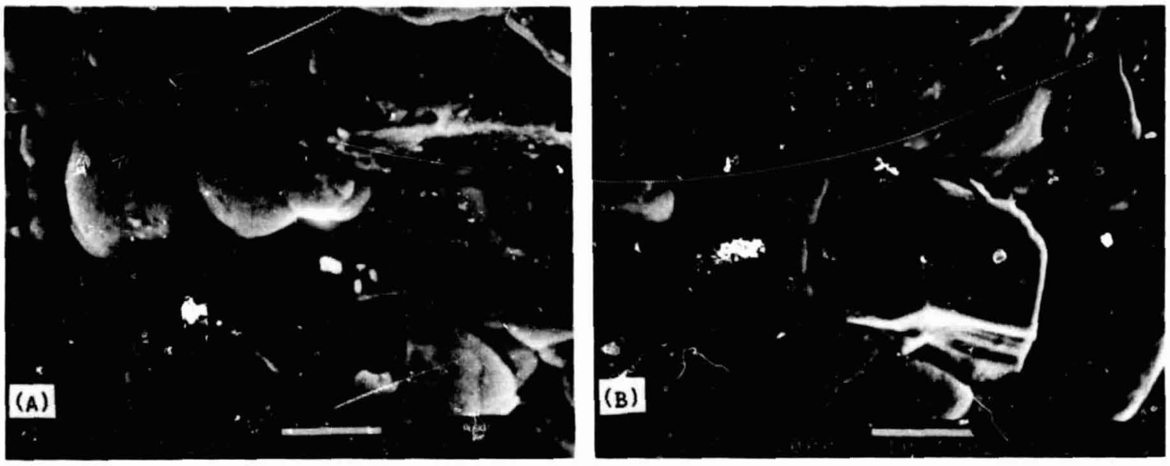

Fig. 4. SEM examination of electroplated wires with (A) natural diamonds showing sharp edges and (B) synthetic diamond showing blocky characteristic

however, they have larger kerf. The choice in particle size is, therefore, limited to the 22 µm to 60 µm range. Effective slicing has been demonstrated for the entire range with diamonds electroplated over the entire circumference. The lowest kerf of 6.2 mils (0.157 mm) was achieved with 22 µm diamonds. Best material utilization by slicing 25 wafers/cm on 10 cm diameter silicon was demonstrated by using 30 µm diamonds. The longest life wafering three 10 cm diameter ingots with the same wirepack has been with 45 µm size. Very limited experiments have been conducted with 60 µm diamonds plated over the entire circumference because the large kerf makes it impractical to slice 19 and 25 wafers per cm of silicon length with a 10 cm diameter workpiece.

With larger diamond particles or when low concentration is achieved by electroplating,the swarf generated during slicing tends to erode the matrix thereby pulling off diamonds from the wires. The concentration of diamonds to prevent erosion has to be such that the inter-particle distance is less than the size of the particle. Electroplating of wirepacks with 45 µm diamonds and small amounts of 30 µm and 15 µm diamonds has shown improved slicing effectiveness. The larger diamonds tend to slice and the smaller ones act as fillers to prevent erosion of matrix. This condition can be achieved by using screened rather than micronized diamonds. Examination of the swarf has shown the mean particle size to be about 0.5 µm and is not dependent on the size of diamonds in the range studied.

ELECTROFORMING

In order to effectively slice silicon for photovoltaic applications the wirepack fabricated should combine (i) low kerf, (ii) high density of spacing of wires, (iii) high slicing rate, (iv) long life of the wirepack and (v) high yields during slicing. The first two criteria are possible by using small diamonds; however, for the next two criteria larger diamonds may be desirable. For example, where 45 µm diamonds were plated all over the circumference of the wire, the minimum kerf achieved was about 8 mils (0.2 mm), whereas it was 6.2 mils (0.157 mm) with 22 µm size In impregnated wires where diamonds were impregnated only in the cutting edge of the wires a compromise was arrived at where larger diamonds could be used without significant increase in kerf. Techniques were developed where diamonds were electroplated in the cutting edge only and, therefore, benefits could be derived by using larger diamonds and maintaining a low kerf.

Masking of the wires during electroplating produced a flat top surface of the wires which did not seat in the guide rollers and, therefore, caused wire wander. Techniques were developed at Crystal Systems to electroplate diamonds and nickel in a form of desired shape and size, *i.e.*, electroform the plating. Figure 5 is three views of a wire rotated 120° where diamonds are electroplated by the electroforming technique. Figure 6 is a cross-section of a wire which was electroplated preferentially in a 60° V-groove. Under these conditions larger size diamonds can, therefore, be electroformed in any desired shape and size. If smaller diamonds are used plating only on the cutting edge allows more than a single layer of diamonds to be plated and the kerf width can still be controlled to the desired size.

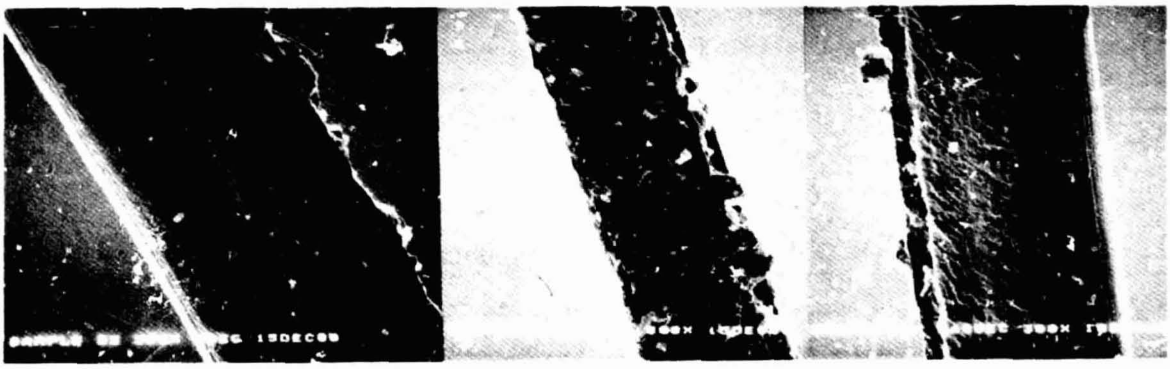

Fig. 5. Three views of an electroformed wire showing preferential plating on cutting edge only

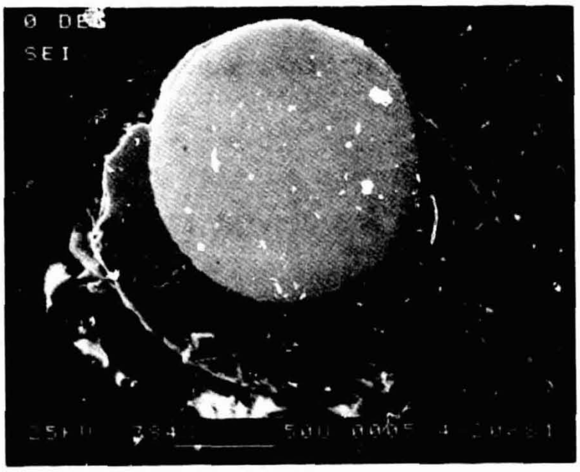

Fig. 6. Cross-section of an electroformed wire with plating in desired shape and form

RESULTS

The feasibility of using FAST for photovoltaic applications has been demonstrated. Wire-blade development has been found to be critical to commercialization of FAST. Control of the diamond plating on wires has shown effective slicing of 10 cm diameter silicon ingots at 25 wafers/cm with 224 wires in a wirepack at an average slicing rate of 3.03 mils/min (0.077 mm/min), and over 99% yield (2). It has been shown that the slicing rate is a strong function of the reciprocating speed of the bladehead; average cutting rates of 5.7 mils/min (0.145 mm/min) have been demonstrated. Wirepack life of wafering three 10 cm diameter silicon ingots has been shown. Effective slicing of 10 cm x 10 cm and 15 cm diameter cross-section ingots has also been carried out.

Electroforming techniques have been demonstrated on individual wires. Tooling for performing these tests on wirepacks has recently been received in-house; it is expected that this approach will increase the life of the wirepack considerably as well as optimize other slicing parameters.

REFERENCES

1. H. Goldman and M. Wolf, DOE/JPL 954796, Quarterly Report, November 1978.
2. F. Schmid, M. B. Smith, and C. P. Khattak, Proc. JPL/LSA Project Wafering Workshop, Phoenix, AZ, June 1981, to be published.
3. K. M. Koliwad, M. H. Leipold, G. D. Cumming and T. G. Digges, Jr., Proc. 12th IEEE Photovoltaic Specialists Conf., Baton Rouge, LA (1976).
4. C. P. Chen, "Multi-Wire Slurry Wafering Demonstrations," DOE/JPL Publ. 78-37, February 22, 1978.
5. F. Schmid and C. P. Khattak, ERDA/JPL 954373, Final Report (Phase I), December 1977.
6. Laser Technology, Inc., No. Hollywood, CA.
7. EDC and Man-Made are trademarks of DeBeers and General Electric Company, respectively.

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[*] Supported in part by the LSA Project, JPL, sponsored by DOE through agreement with NASA.

DISCUSSION:

GALLAGHER: I have a question for IBM. I'm intrigued with the fact that you did get the results you did by applying the potential to the workpiece itself. Do you think it would be possible in real time to measure the out-of-plane vibration, and instead of using the dc potential as a function of time, using a rectified and variable ac potential wherein you could either vary the frequency, and/or vary the potential?

KUAN: I think the point of applying a dc potential is to enhance the absorption of ion species and if you apply the dc potential I don't think you would observe any effects. I agree that it would be nice if we could observe directly the amplitude of blade vibration, but it is very difficult to do so. So that is why we observed instead the surface morphology and the kerf size, which sort of indirectly gauge the vibration amplitude.

GALLAGHER: Do you do this (notice the kerf difference) in real time as you are cutting, or do you do it after the fact?

KUAN: After--but those are the features that were created during sawing.

DYER: It seems to me that if there is a potential, that is between the crystal and the blade, and if the slice is the most flexible thing in the whole business, there would be an opportunity for the slice to be either attracted to or repelled from the slot and this might be, in fact, just as large an effect as we're considering the Zeta potentials, etc. In other words, it would be a mechanical effect related to the one that was mentioned earlier today by Dr. Chen, on the flexure away from the crystal. I would suggest that you consider that as a possibility in your explanations. Also, you were saying that it was generally agreed (and I know this was stated by Meek & Huffstutler) that the out-of-plane blade vibration was the main damage mechanism. I certainly agree that there are times in the life of a saw in which this is the case, but he also stated that since the contact forces were the greatest at the bottom of the slot, then it is not consistent that the main damage mechanism is the out-of-plane contributions to the contact stresses. It would be, more than anything, the increases in the contact stresses in the cutting direction. I offer that for your consideration.

KUAN: For your first comment, I think that there is an attraction of the saw blade if you apply a dc potential. We do observe that the scratches on one side are larger and deeper than on the other side of the blade when you apply the potential and we got a negative effect if you applied a negative potential. For your second comment, I think that in our case it is the out-of-plane vibration because we got a good correlation between the depth of damage and the surface scratches. Of course, the non-circularity of the hole also contributes.

BOUJIKIAN: In some of the discussion we had here today and also Prof. Danyluk's presentation, we saw several evidences that there was plastic deformation in the cut in the silicon itself. This also was discussed by Prof. Werner, about the existence of very high temperature at the point of cut. I know for a fact, there have been several papers, by many companies, on thermal damage. It is ironic that General Electric people brought up thermal damage in the cut, which, in my opinion, is much more severe than the vibration damage. I have been in the abrasive diamond-blade-business for 20 to 22 years. I would like to make a statement that General Electric really saved this diamond-abrasive industry by developing the industrial diamond. It was one of the real discoveries of the century if not the only one as far as the diamond-blade industry is concerned. However, there have been several studies (including General Electric, at their facilities over in Auburn years ago, through the direction of Tuzio and Ernie Raderman, etc.) that without any question there is a definite breakdown at high temperature with synthetic diamond compared to the natural diamond. In your speech, you referred to heat-treating it at 1100°C. You used the word "controlled." If you take your diamond and put it in even 1100°C in open air for half an hour you will end up with a bunch of black junk. I don't want to make the assumption that the GE diamond is actually, in terms of toughness, hardness and structure, superior to natural diamond. The only main factor is in ID slicing because temperature is more of a factor than anything else in that particular application. You did not address anywhere in your speech a comparison with the natural diamond in ID slicing. I would like to know why.

FALLON: To clarify a number of the points that were brought up: 1100°C is a test that we conduct to determine the thermal toughness index. It's one that we have been doing for years and we don't seem to reduce our diamonds to little black stubs by doing it to 1100°C. As regards the temperature breakdown, all I can do is again go back to the fact, mentioned earlier today, that bonding systems break down at 700°C, so if you have a diamond that can withstand 5000°C it doesn't really matter, if your bond is going to go at 700° anyway. We made no comparison, or try not to refer to any comparison with mined diamonds because depending upon test conditions, mined diamonds will be better than man-made diamonds, or man-made will be better than mined; they will be equivalent. The important point is the fact that man-made diamond is consistent. You will get the same diamond today that you get two years from now. This is not true with mined diamonds.

WERNER: First, I think you are absolutely right that the big advantage of man-made diamonds is that the characteristics and the properties are much more consistent. On the other side, especially in ID sawing, so far the natural diamond is preferred to the synthetic one. I would like you to comment a little more on what General Electric is doing at the moment to lift the synthetic material to the same performance level as the natural one. Second, a comment: the heat flows through the tip of the diamond and then is distributed in the much greater volume of the diamond. Therefore, the transition temperature from the diamond into the bond is several hundred degrees lower and the nickel layer never gets a temperature up to 700°. The maximum temperature that I would expect to occur in the nickel layer is maybe 150-200°, so your argument that the nickel fails before the diamond fails is completely wrong. Another misconception is the air cushion you referred to in the circumferential vicinity of the wheel. That cushion does not really exist. There are a few atoms going around with the wheel but the mass of this layer of air is much too small to prevent a fluid from getting into contact with the wheel. The real effect is that where a drop of oil or water gets into contact with the fast-spinning wheel it is vaporized. It all of a sudden is distributed in millions of little particles and therefore you have to apply a tangential stream onto the surface. You can only achieve that if you get the liquid out under high pressure and have matching velocities between the spinning wheel and stream of the coolant. In order to overcome the so-called air cushion layer it was recommended to increase the pressure to go through it. What really happened was that you sped up the velocity of the liquid to match the velocity of the grinding wheel. All the derivations, all the conclusions from this air-cushion model with regard to increasing pressure are right, but in designing special spouts and nozzles there has been a lot of misconceptions, and the wrong things have been recommended due to that. In ID sawing, the main setback is that the liquid does not automatically flow into the contact zone even if you apply it with higher pressure.

FALLON: Concerning the fact that right now the industry seems to be leaning more toward natural diamond, especially on the ID saw blades, I think this is a holdover from the fact that electroplating in general used to have natural diamond as the preferred source. Within the last year and a half we have perfected our electroplating product, EBG, standing for Electro Bonding Grinding. We have perfected our electroplated product to the point where it is, in the worst cases, comparable to the natural diamond. We are seeing more and more activity in this product line. I think it is indicative of the type of success that we have had in finally perfecting a diamond that can be used for electroplated applications.

WERNER: One further comment, you see that even where you have a resin-bond system where the maximum temperature is 350 to 400 surface degrees, and with diamond as an abrasive, if you would exceed that temperature it would just fall apart. But we know it stands pretty well if you have the right coolant conditions. With a metal matrix of nickel, you can expect basically lower temperatures because the nickel as a metal leads away the thermal energy faster than resin does. There are bond systems where you have a metal and resin at the same time. The Norton Aztec wheel is an example of that. Here they say it works that well because there are metal particles that contact each other so the temperature has a way to flow out of the contact zone and the measured temperatures in those cases are never higher than 300°, so I have reason to assume that they will not be higher in an ID saw either.

LIU: I have heard a lot about the cutting edge, plating of diamonds onto the cutting edge, etc. For the illumination of those of us who are less familiar with the process, could we hear more details about this process?

SCHMID: There is no question that plating plays a very important role in cutting effectiveness. The plating hardness can be adjusted. Certain types of plating give you a very hard bond. What is good for us is not necessarily good for ID. For example, our wire does have some flex to it, and so if you have a very hard bond you can initiate cracks in it that can propagate into the core wire itself. That is a condition that you really would not want. You would want a softer plating that would not do that. The other thing I didn't talk about to any extent is whether you are using screened diamonds or micronized diamonds. Micronized diamonds will give you a much narrower spread of particle size, but it may not protect the bond. By using screened diamond, you can protect the bond. There will be certain diamonds that will be exposed; others will be not exposed but will protect the bond itself. There has to be compatibility with the diamond and the plating. One of the big developments is the man-made diamond that will now allow for effective plating of the diamond itself. The natural diamond for some reason has been a good one to plate and the man-made one was impossible until they worked out procedures to do that. It is important that the bond is resistant to erosion (which you can help by selection of the diamond particles), to corrosion, and that sort of thing.

BOUJIKIAN: Nickel electroplating is relatively simple. You can control it any way you want in hardness, softness. When you talk about hardness in nickel it is not a chemical hardness, it is stress hardness. The more impurities you get or some electrolytes will cause more internal stress than others.

LIU: Do you think that development of this actual cutting-edge technology is pretty much in hand, or are further developments necessary?

BOUJIKIAN: The proof of that is that the ID diamond blade almost never wears, and anybody in here who uses it can testify on that: on 95% of all diamond blades that are discarded from the machine, the diamond is still on. At least a large percentage, if not over 50%, is still on. TI has one hanging on the wall that says 84,000 cuts came out of it. The life of the blade is built into it, but all other factors involved in extracting or using it have to be accomplished. One is the core material. If we can find a core material that is chemically hardened instead of plastic-deformation-hardened, then that will solve many problems connected with it. But it is not available. I saw a gentleman from Uddeholm this morning over here and I have been keeping in contact with him for the last 15 years. They make hardened or chemically hardened rolled steel up to 6 inches wide, and that is it. If we can get a breakthrough in that area where you can get a core material that would stand the tensioning stresses we will have a big breakthrough.

(To T. S. Kuan): I want to know why the thermal damage was not addressed, only vibration damage or mechanical damage was addressed.

KUAN: These cracks usually range from 10 microns, 20 microns up to 100 microns, in front of the blade edge, so at that position I believe that the temperature is rather low. I think that the small effect probably is not important in terms of propagation of cracks, that is, what we describe as the saw-damage mechanism. I said that the plastic deformation is not important because I did not observe any dislocations in the damaged structure. Probably it is because the temperature never reaches 600°, at the contact point.

SCHWUTTKE: You have to look at the situation of how the wafer user judges the wafer quality. Once the wafer has been sliced, the damage is removed by using different polishing techniques, so a semiconductor engineer is using a wafer that contains residual mechanical damage, a crack tip. Polishing produces a flat wafer, so if you have damage, the polishing would remove this anyhow. We are much more concerned that a wafer contains residual damage. This is what is killing the semiconductor wafer.

KOLIWAD: My question is to Drs. Danyluk and Kuan, on the Zeta potential variations with respect to using different chemical environments. The Zeta potential variation and the softening observed in cutting has actually been documented for ceramic cutting--aluminum oxide, for example, where there is beautiful work. When you are cutting, the wafer surfaces are really not virgin silicon any more. I don't have any knowledge of any studies done on Zeta potential on real silicon surfaces. I wonder whether you are influencing the potential of oxide formation and softening the oxide instead, if in fact there is an oxide, and you are affecting the absorption of ionic species on an oxide, or whether it would be better if you add some oxidizing agents to your solution in addition to whatever lubricants or temperature environments you are using?

DANYLUK: First, I would like to say I don't believe the Zeta potential measurements have much to do with the mechanisms that we are talking about. Most of the Zeta potential measurements are done on crushed silicon. My opinion is that the crushing process itself affects the Zeta potential measurement that is used in a description of the space charges. These space charges, which are essentially what Dr. Kuan is talking about and which I am implying exist at surfaces, essentially exist at surfaces that start out being electrically charged. For example, dislocation cores are electrically charged but the overall surface is electrically neutral. The problem then comes in as to what the space-charge region has to do with the cutting phenomena. I believe that it has got to do with the Debye-Huckle length of the space-charge region. If it is big, then it has one affect and if it is small, it has another affect.

KUAN: There are basically two theories to interpret the lubricant effects. One is the Rebinder effect and one is the Westwood mechanism. I personally believe that the Westwood mechanism is more important in our case because all of these propagations of dislocation occur several microns underneath the surface, whereas the Rebinder effect talks about the event occurring exactly at the surface plane, which is not directly related to our case. I would like also to comment about the formation of oxide. Under such high cutting rates, I think that the formation of oxide probably is not important, although the formation of oxide does occur in certain cases where the metal is being cut under some kind of lubricant.

DANYLUK: When you expose virgin surface of silicon, that is precisely what the absorption problem is. Absorption is the initiation of the oxidation. I think that essentially we are talking about the same mechanism, the very early stages of oxide formation.

MULTIBLADE TECHNOLOGY

Chairman: R.L. Lane, Kayex Corp.

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INTRODUCTION

LANE: When I learned that I would be chairman of this session, I decided I would do a little homework on Multiblade Slurry Sawing. First, to learn how to say it, and second, because I didn't think I know very much about it. After spending a few hours with the literature and reading JPL reports, I decided I was absolutely correct; I know nothing about it. What I decided to do was to present to you, for about five minutes before we start, some of the things that I uncovered in my brief research.

It was pointed out yesterday that slicing with ID sawing is truly a grinding operation. Dr. Peter Gielisse of the University of Rhode Island some years ago developed a classification for abrasive machining, and broke it up into three different classifications. He talked about bonded abrasive machining, contained abrasive machining, and free-abrasive machining (BAM, CAM, and FAM). These three methods relate to the way the abrasive is forced against the workpiece by the action of the cutting tool (Table 1). BAM, or bonded abrasive machining, can be equated to the standard ID slicing, as we learned yesterday. The diamond is bonded, typically in a nickel matrix. The individual grains are dragged and pressed against the silicon at high speeds and pressures. Such high speeds tend to minimize the forces on the blade, and are best provided that the resulting flash heat can be removed adequately. The FAST technique that Fred Schmid has been talking about is also a bonded abrasive method although, in this case, I believe that the speeds are considerably slower and the pressures are considerably lower, and that appears to relate to the damage. Apparently, with silicon, a water coolant is the primary cutting fluid in production environments, although we have heard some indication that oil coolants might be possible.

In CAM, contained abrasive machining, on the other hand, the abrasive is in a paste form or a loose form, and is applied to the tool. It becomes embedded in the tool, so the tool becomes charged with this abrasive. This is quite common in the optical industry where generation of optical flats or lenses uses this method. It's sometimes called "lapping" in optical circles. Again, Fred Schmid has worked with bonded abrasive, I believe, where he has worked with impregnated wires. In this case, the abrasive is held into the workpiece, but not as strongly as with fixed abrasive. It tends to move somewhat, but it is carried along with the tool. In this case, it's usually very fine abrasives; 5 to 10 microns are the largest grain size used typically.

Table 1. Abrasive Machining

Bonded	(BAM)	ID wafering FAST
Contained	(CAM)	Diamond lapping
Free	(FAM)	MBS, MWS

In FAM, free-abrasive machining, the abrasive is carried in a vehicle and held between a very hard work tool and the workpiece, which in our case is silicon. The abrasive grains roll between the tool and the material to be cut. Silicon carbide is generally used as an abrasive, although alumina is sometimes used in flat-lapping the silicon. In the silicon wafer industry, lapping is always considered to be FAM, free-abrasive machining, and not contained abrasive machining. I am not aware of any contained abrasive applications. Obviously, with a multiblade slurry saw, this is the method. In my brief studies I learned that maintaining the abrasive film between the work tool and the workpiece is all-important. That must be maintained. A certain minimum concentration of abrasive is needed to maintain this film. Also, if the abrasive concentration is too high, apparently one can get multiple layers of abrasive that then do not cut as well. The lower limit of particle size in this particular method seems to be 5 to 10 microns. If you go smaller in size, it reverts back to the contained abrasive. The particles are pressed into the workpiece and begin to move along with it, causing a totally different mechanism of cutting.

I ignored the contained abrasive because we're not using it in silicon, and tried to come up with some of the major differences between the bonded abrasive method that we talked about yesterday, and the free-abrasive method that we're going to talk about today.

Professor Wolf has certainly done a much more thorough job of this, in his talk yesterday, but I'd like to just briefly go through some of the things that I looked at.

The speed of removal is obviously very rapid for the bonded abrasive. (Table 2) It's very slow for the free abrasive. However, it's relatively easy to gang up free-abrasive blades, and as we learned yesterday, if someone can invent a way to gang up ID blades, I guess it's all over for the free abrasive;

Table 2. BAM vs FAM

	BAM (ID)	FAM (MBS)
Speed of Material Removal (Per Blade)	Rapid	Slow
Removal Action	Slicing, cutting	Rolling, crushing
Tool Speed (ft/m)	≈3000	100 to 400
Localized Temperature	Warm	Cool
Sub-surface Damage	≈1/5 grit size	≈1/2 grit size
Minimum Kerf (Production)	0.25 mm (0.010 in.)	0.25 mm (0.010 in.)
Minimum Wafer Thickness (100 mm)	0.43 mm (0.017 in.)	0.25 mm (0.010 in.)
Slices/cm	15	20

but I don't think that's going to happen. The throughput of a particular piece of MBS equipment is very competitive with ID. As I said, the removal action appears to be sliding and cutting for the bonded abrasive, and rolling for the crushing mechanism for the free abrasive. I would like to learn more about the mechanism of dirt removal in this. Perhaps some of our speakers can address that question.

The tool speed is greatly different. Three thousand surface feet per minute for ID, give or take a few hundred. An order of magnitude less for the free abrasive. One must ask the question "How can this be speeded up? How can we get the tool speed up and maintain the abrasive film?" The temperature, which may relate to damage, is different for the two. We've talked about the flash temperature of the bonded abrasive. Obviously, the free abrasive is a cool method.

Regarding the last four items: I found much disagreement in the literature I surveyed. So, I stood back 10 feet, and I said I think that's about what the consensus is in the literature.

I tried to describe what I thought were typical production-type parameters for these, so if you disagree with the minimum kerf or the minimum wafer thickness for the free-abrasive method in a production mode I'd like to hear about it today.

I've found a number of references in the literature to damage, and I was totally confused. You'll see tremendous discrepancies here (Table 3). Look at the lap diamond--that is a contained abrasive method. You'll see the damage is quite low. Silicon-carbide free abrasive is compared directly with silicon-carbide paper, which is a bonded abrasive, and the free abrasive gave more damage for a given grit size. This seems to be in general agreement with the literature. The multiblade slurry data comes from the Varian Associates, Inc., report and the diamond-wire data comes from the Crystal Systems, Inc. reports. In FAST, the grit apparently is well embedded in the matrix, so its effective diameter is less. That may be the simple-minded way of reasoning why the damage is less. But certainly, the nature of cutting and removal is quite different between the two methods.

The point was made at the meeting yesterday that in wafering, we can't put our problems on to other technologies. We can't push them back into the ingot technology, we can't push them forward into the wafer technology. We have to address the problems in slicing; otherwise we don't make progress in the system cost. So, for example, if the method of slicing requires some very special shapes or sizes of ingot, that is a disadvantage (Figure 1). Likewise, if the process creates tremendous damage and cannot slice thin wafers, or it adds more cost to the wafer, then it is also a problem.

Table 3. Damage

Material	Abrasive	Particle Size Max (μm)	Grit Size Designation	Depth of Damage (μm)	Reference
Si	Diamond (OD)	62	220	12.5	1
Si	Lap Diamond Paste	0.9	-	3	1
Si	Lap Diamond	15	-	3.5	2
Si	Lap Diamond	30	-	5	2
Si	LAP SiC	25	400	10	2
Si	LAP SiC	25	400	15	2
Si	Lap SiC	25	400	10	3
Si	Lap SiC	62	220	65	3
Ge	Lap Al_2O_3	12	-	3 - 3.5	4
Ge	Diamond (ID)	62	220	8.0 ± 0.7	4
Si	MBS	30	600	10 - 15	5
Si	Diamond Wire	45	-	3	6

Note: See References 1 through 6.

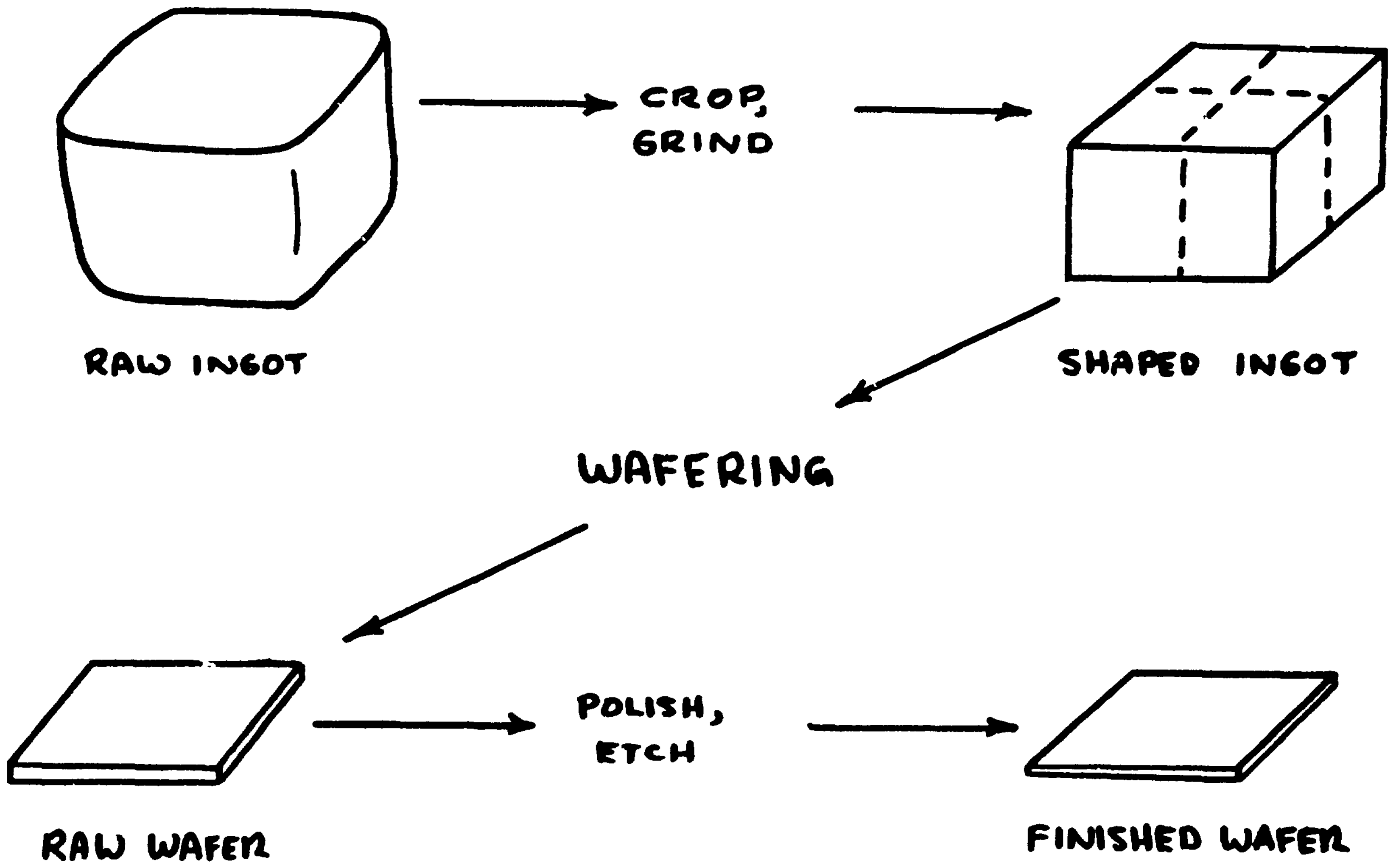

Figure 1. Shaping an Ingot

REFERENCES

1. Saccocio, E. J., and McKeown, W., "Saw and Polishing Damage in Silicon Crystal by X-Ray Topography," J. Applied Physics, 38, pp. 2702-2704, May 1967.

2. Stickler, R., and Booker, G. R., "Surface Damage on Abraded Silicon Specimens," Philos. Mag., 8, pp. 859-876, 1963.

3. Pugh, E. M., and Samuels, L. E., "Damaged Layers in Abraded Silicon Surfaces," J. Electrochem. Soc., 114 (12), pp. 1429-1431, 1964.

4. Knudsen, J. F., "Depth of Saw and Lap Damage in Germanium," Advances in X-Ray Analysis, 7, ed. Mueller, W., Mollett, G., and Fang, M., Plenum Press, New York, pp. 159-173, 1964.

5. Fleming, J. R., Holden, S. C., and Wolfson, R. G., "Slicing of Silicon into Sheet Material," Final Report, Contract No. DOE/JPL 954374-10, Low-Cost Solar Array Project, Jet Propulsion Laboratory, September 21, 1979.

6. Schmid, F., and Khattak, C. P., "Heat Exchanger--Ingot Casting/Slicing Process," Final Report, Phase I, Low-Cost Solar Array Project, ERDA/JPL 954373-77/4, Jet Propulsion Laboratory, 1977.

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DESIGN AND USE OF MULTIPLE-BLADE SLURRY SAWING IN A PRODUCTION ATMOSPHERE

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WHAT IS MULTIPLE BLADE SLURRY SAWING?

Since there are many arrangements, designs and uses of these saws, the best approach to the understanding of the mechanics is to consider the process or technique. This consists of arranging multiple bands of steel in a frame and reciprocating the frame with the bands in contact with a workpiece, while simultaneously applying abrasive at the point of contact. As a result of this arrangement, the blades wear slots in the workpiece and, if the process is carried on long enough, the blades progress through the piece resulting in several parts or wafers. An early use of a device employing this technique was the dressing of large quarry block into smaller, flat building stone or into tomb stones. This is commonly called "loafing" in reference to the similarity between the workpiece as cut and a sliced loaf of bread.

WHAT SUB-SYSTEMS ARE REQUIRED?

The basic parts required to saw are:

A. Blade Frame. This component carries the steel blades, keeps them in proper spacing such that the slices will be uniform one to another and of even thickness, and in the case of the stone saws, imparts the reciprocating or oscillating sawing action.

B. Drive System. This system is the motive power into the saw and includes the prime mover, speed reduction, and conversion from rotary to reciprocating motion.

C. Travel Guide. The blade frame must traverse in a straight line in relation to the blades and it is the guide system that establishes the travel line.

D. Feed. As previously mentioned, the blades and the workpiece are brought into and kept in contact while the sawing action progresses. It is the function of the feed system to apply and maintain this contact.

E. Feed Guide. As with the travel guide, the feed guide must raise the workpiece, or lower the blade frame, as the cut progresses such that the cut remains in the plane of the blades.

F. Abrasive System. This system must mix, transport and gather the abrasive slurry for re-use and must do so in a very efficient manner. The working parts of the machine must be completely protected from the abrasive, lest the parts operate with abrasive on them and experience high and abnormal wear.

Multi-blade sawing existed in this crude stage up until the mid 1950's with few attempts to establish the technique as a precision process. It was the advent of the electronic grade silicon that prompted the design and construction of a precision multiple blade slurry saw (MBS) and the patenting of a technical breakthrough which made the precision possible.

Grover Hunt, who designed the multiple blade power hacksaw, came into the problem as no stranger to material processing. He was a principal character in the cast of pioneers in the Carlisle based crystal industry and, as such, knew first hand the problems of sawing thin fragile parts.

The basis for the patent, No. 3,079,908, and the breakthrough to precision was in the blade frame construction and the holding and tensioning of the blades in the frame. In the Hunt machine the blades are spaced apart with solid spacers and the ends squeezed with compression bolts such that the blade to spacer friction is initially low enough to allow the blades to slip and equalize. Then the compression bolts are tightened such that the friction is high enough to resist high tension, 80% of yield, which is put into the blades by the blade frame.

After designing and building the saw, many attempts were made to saw silicon with the device. The success of these attempts was limited and the emphasis was put on multi-blade quartz slicing. Several units were built and sold as the "Berkshire" Machine until the patent rights were sold to Norton Co. and then to Varian. The machine gained a substantial foothold in the quartz industry, but never proved out in the electronic grade silicon wafering industry.

In the last 5-8 years a Swiss Company, Meyer & Burger, has been marketing a similar saw in the U.S. and has taken some necessary steps to increase the precision of the saw. In addition, several new designs have very recently appeared on the market since the original Hunt patent coverage has expired. Various attempts have been made to address the requirement of each sub-system.

DESIGN PROBLEMS AND EXISTING SOLUTIONS

The requirements of the blade frame on a modern precision machine have become much more stringent. The blade frame must resist gigantic loads for the size, upwards of 100 tons without appreciable twist. It must be relatively lightweight so that the mass loading during reciprocation is low, if in fact the designer opts to drive the frame. Provision must be made to adjust the absolute track and to also adjust the blade pack for parallelism.

The available blade frame design alternatives are to make the frame massive to resist warpage and either limit the stroke speed or fix the blade frame and reciprocate the workpiece, to use the original system as patented by Hunt, or to use the frame within a frame concept as does the Meyer & Burger.

The requirement on the drive system is simple and straight forward, without any weight or size constraints. It is to deliver the power to the reciprocating member with a reliable and trouble free system. The real problem is the reversing load through the Pitman Arm, (if one resorts to the classical steam engine drive) to the Drive Pin and back through the speed reduction to the motor.

Both of the saws presently in use have Pitman Arm type drives, or connecting rod ties to a flywheel. This gives the classical sinusoidal velocity to the blade frame (work table in the case of a P. R. Hoffman machine) and therefore, sinusoidal force in the drive system. This reversing load is very hard on a worm gear reducer, and P. R. Hoffman has therefore precluded this problem by using a three stage "V" belt reduction.

The travel guides must be as true as possible, since the target for blade alignment is .0002" or less. Inaccurate ways produce wide kerf and broken parts. The problem is not in getting the ways true but keeping them so. Both Varian and Meyer & Burger, as previously mentioned, reciprocate the blade head. They guide the head with an inverted "V" way and a flat; classical grinding machine design. This is a very acceptable way to attack the problem. The ways, being cast iron, can be hand scraped to very accurate tolerances and form an easily lubricated surface on which to slide the blade frame. The problem is twofold. One, the ways are difficult to protect and when contaminated with grit they rapidly lap out of line. Secondly, in the case of a Varian machine as well as some of the newer designs, the scotch yoke type drive places an off-center load on the head which must be countered by side loading in the travel guides. This gives rise to preferential wear which quickly destroys the true "track" built into the way system. P. R. Hoffman and Meyer & Burger have both precluded this off-center loading by placing a slider, steam locomotive style, between the rotating member and the connecting rod. The ways of the slider accept the off-center load and will wear. This will not affect the tracking however, since care in connecting the slider to the blade frame precludes a moment transfer. P. R. Hoffman does not use a hand scraped "V" and flat ways since we have elected to reciprocate our work table. We have used preloaded ball bushings and precision ground round ways. These have proven to be true to within 50 microinches over full stroke.

The basic requirement for the feed pressure system is accuracy. When the operator selects a feed force, it must be the same today as last week. Most everyone uses air pressure cylinders to push the work into the blades; Meyer & Burger use hydraulics. The problem with the direct method is friction and change in friction with temperature. Therefore, every effort must be made to keep down the friction. Using low friction cylinders or bellows type cylinders, and keeping the feed guide system well lubricated and as free as possible are acceptable approaches to the solution of this problem.

In the design of the feed guide the tracking requirements on the guide are as stringent as on the travel guide and the same approach has been used. Meyer & Burger use the hand scraped double "V" with adjustable gibs. This is a very acceptable arrangement but, since we have found round ways and ball bushings accurate enough for travel, we likewise found the die-set feed system more than adequate. As with the travel guides, grit contamination in this system is catastrophic.

In designing the abrasive slurry flow system, as discussed throughout, one must recognize that grit contamination is disastrous and therefore the shielding must be 100% efficient. The other functions of the system, mixing and delivering the abrasive slurry, are important considerations, but not nearly as critical.

EXPLORATION OF FUTURE DESIGN IMPROVEMENTS ON THE P. R. HOFFMAN SAW

We have concentrated our design efforts on the elimination of internal stresses and pounding due to load reversal, and feed inaccuracies due to friction as we recognize the solution of these two problems should provide the greatest dividend. The obvious solution to the load reversal problem seems to be to store the slow-down energy in some device, such as a spring or tank of air, and use it to supply the inertial start-up at the stroke start. We have tested such an arrangement using the spring system, but have found spring noise and guide slide defeated the system. Work in this area is still underway.

Feed inaccuracies do exist in most machines we have seen and the most promising arrangement proposed to date seems to be using the pnuematic or hydraulic cylinders as a servo device only, and sensing the blade pressure either at the chuck or on the blades. In an arrangement such as this, the best bet might very well be using hard feed (screws, racks, wedges, cams, etc.) in place of the cylinder feed. P. R. Hoffman is investigating this system also, and should have a protype on our saw in the middle future.

USE OF MBS IN PRODUCTION

Familiarity with the various design considerations and problem areas presented above will enable the reader to identify the key controls necessary for satisfactory operation of the MBS saw in production. In setting up the saw for a wafering run, the operator must take care to properly install the blade package so that proper alignment and blade tensioning are achieved. Appropriate adjustment of vertical feed pressure at the start, and maintenance of proper pressures throughout the run, are essential to achieving good wafer quality. Other factors contributing to wafer quality are slurry vehicle and abrasive ratio, slurry volume and delivery system, and vehicle, abrasive and blade specifications. It will be found that specification of these last factors is dependent on the material being wafered and the desired finished wafer specifications.

TYPICAL MATERIAL WAFERED BY MBS PROCESS

Materials which are suitable for MBS wafering include silicon, germanium, crystalline and fused quartz, crown and flint glasses, ferrite, tantalates, niobates, carbides, ferrous and non-ferrous alloys, ceramics, and various crystalline and amorphous specialty materials used in optical and electro-optical applications. The MBS process has been utilized at P. R. Hoffman Co. (for approximately 8 years) to wafer piezoelectric quartz crystal blanks and many of the various materials listed above. During this period, well over one million production saw hours have been logged.

GENERAL PRODUCTION CONSIDERATIONS

The transition to MBS from traditional O.D. diamond blade slicing was justified by the savings resulting from minimized kerf losses, minimized sub-surface damage, and improved surface quality off the saw. These benefits allowed wafering much closer to finished thickness specifications, which provided better material utilization and the elimination of some intermediate processing operations.

The maximum allowable size of the workpiece to be wafered is, ot course, dependent upon the clearance available through the blade frame. On most of the equipment available, workpiece width is limited to 6 inches and available depth of cut is approximately 6 inches. Note that depth of cut capability does vary significantly depending on machine manufacturer. Working length of the workpiece can vary from roughly 7 inches on the Varian saw to 9 inches on the P. R. Hoffman saw. This length is also limited by the desired wafer thichness to be produced. Sawing of very thin wafers allows enough blades to be stacked in the blade frame to result in tensioning load requirements which exceed the capacity of the frame.

Although it is not necessarily representative of the limits of the MBS process, the following presentation of MBS production parameters experienced in the ongoing production activity at P. R. Hoffman Company is intended to enable the reader to assess the applicability of the process to his current or future slicing requirements. Along with our traditional production of piezoelectric quartz crystal blanks, we manufacture several custom optical components and provide slicing service to various industries which further process wafers of most of the above listed materials.

Using the MBS process, wafers of .015" thickness to greater than .300" are routinely produced from materials ranging from .090" diameter to over 5" in diameter. Typical quartz crystal blanks range from .350" square to .750" x 2" rectangles. Due to standardization of blade thickness and abrasive particle size to satisfy other production constraints, the vast majority of our wafering is accomplished at a kerf loss of .013" per wafer. Various combinations of available blade and abrasive materials are utilized to result in kerf losses ranging from .0055" to .017" per wafer. Typical thickness tolerances are ±.002" and tapering is generally held to between .0005 " and .001" per inch of cut depth.

The reduced sub-surface damage and improved surface finish (typically 15 micron RMS) of wafers produced by MBS have proven advantageous in our production of optical parts. Traditional optical production technique has been to wafer materials as much as one-eighth inch greater than desired finished thickness on conventional fixed diamond cut-off equipment. The parts are then finished via a series of blocking and successively finer grinding and polishing operations. Use of MBS for wafering allows slicing much closer to finished thickness and elimination of the cost and handling losses associated with the several intermediate processing steps. In some cases, MBS wafered materials cam immediately enter the final polishing operation. In addition, the improved materials utilization becomes significant because many optical materials are extremely expensive.

Because the workpiece is mounted to some type of fixture, which is in turn affixed to the chuck of the MBS saw, critical orientation of the workpiece can be accomplished away from the saw and maintained through the use of precision mechanical transfer devices. In quartz processing, the major faces of a wafer must be held to specific angular orientations with respect to various crystallographic planes. In some cases the tolerance on this specification can be as small as plus or minus 15 seconds of arc. Typically the MBS process can yield 100% of product within a ±3 arc-minute tolerance and better than 90% within ±2 arc-minute tolerance.

WAFERING OF SILICON FOR SOLAR CELLS - THE JPL LOW-COST SOLAR ARRAY PROJECT

P. R. Hoffman Company is currently under contract to Jet Propulsion Laboratory in support of the Low-cost Solar Array Project. We are to provide testing and development which will result in optimization of both the MBS process and the design of the MBS saw. The goals of this project will not be realized without vast improvement in the state-of-the-art MBS technology.

In the past, solution of technological problems in the production environment has been accomplished empirically. Some attempts have been made to develop mathematical models of the various micro-systems of the process in an effort to identify a practical solution to the various problems involved in successfully producing the large diameter, extremely thin silicon wafers dictated by the project goals. In many instances the theory thus developed has hot been supported by production test results. The ability to wafer 6 inch diameter ingots at 25 wafers per centimeter of ingot length is essentially a problem requiring improvements in machine design and process control. The foregoing discussion has indicated where these improvements must be effected.

The second area of concern, and certainly not secondary in importance, is the over-all reduction of process costs. Major improvements must be made in the process cutting rate and the utilization of consumable materials. Significant increases in cutting rate will result in reduced capital investment due to the reduction of the number of machines, and therefore floor space, required to produce a unit area of silicon "sheet" material. Additionally, labor costs would be somewhat reduced, power consumption would be lessened, and all costs generally related to the physical size of the production facility would be lowered.

The cutting rate is, of course, affected by many dependent and independent variables of the process. The testing being conducted by P. R. Hoffman is intended to establish the effect of these several variables on the cutting rate (and quality of the product), establish the optimized process parameters, and thereby define the design improvements required. As an example, it is known that higher relative blade speed (oscillation) results in improved cutting rates. However, maximum speed is limited by the mass of the moving saw components and various constraints of the drive systems. This identification of optimum operating speed will result in definition of necessary design improvements.

Much of our research effort will be directed toward identification of less costly consumable materials and the extension of their useful life. Currently, blades can be used for only one wafering run through a 4 inch diameter ingot and the abrasive slurry has a maximum life of two wafering runs at best. We are attempting to identify less expensive blade materials and/or materials which will not wear as readily due to the abrasion which exists as the basis of this process. Research of methods to reclaim vehicle and abrasive material is currently under way. Future research will include attempts to use water as the basic slurry vehicle.

In summary, it is recognized that the current state-of-the-art MBS technology must be significantly improved if the LSA project goals are to be attained. While alternative wafering systems have been developed and vastly improved in recent years, MBS has seen little technological advancement. We at P. R. Hoffman believe that major improvementsare not impossible. Although MBS will never be the answer to every wafering requirement, we are confident that economical production of wafers to LSA project specifications will be achieved in the not-too distant future.

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KINEMATICAL AND MECHANICAL ASPECTS OF WAFER SLICING

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1. Definition of Variables

a = Stroke length [mm]

b = Width of workpiece [mm]

C = Concentration of abrasive grains in lapping suspension [mm^{-3}]

c = Maximum value of tool wear contour [mm]

d_K = Average grain diameter [mm]

e = Maximum value of vertical stroke [mm]

l_k = Length of contact zone between tool and workpiece [mm]

n_s = Stroke frequency [s^{-1}]

P_K = Average force per active grain [N]

p' = Specific blade load [N/mm]

r = Stroke ratio [–]

t = Cutting time [t]

v = Lapping or slicing speed [mm/s]

v_K = Velocity of contact point between tool and workpiece [mm/s]

2. Introduction

Slicing of silicon wafers by means of multiple-blade slurry sawing offers a great potential for increased productivity, as demonstrated in several analytical und practical investigations performed in the USA and Europe /1,2,3/. In order to realize the combined goals of higher productivity and reduced slicing cost, two main prerequisites have to be met first: the construction of a high-efficiency slurry-saw machine and the functional description of the technological fundamentals of this particular lapping process.

In the paper, some recently achieved results concerning the technological fundamentals of slurry sawing will be presented. First, a new concept of the specific material removal process and the related kinematic and geometric contact conditions between workpiece and saw blade are described. Based hereon, the result of a functional description of the slurry sawing process is presented, expressing the main process criteria, such as infeed per stroke, specific removal rate, specific tool wear, and vertical stroke intensity, in terms of the dominating process parameters, such as stroke length, width of workpiece, stroke frequency, specific cutting force and slurry specification.

The derived process models contribute to an improved understanding of the slurry sawing process, and provide a means for improved machine tool design and optimized selection of sawing conditions. This is demonstrated in the final part, comparing practical test results with the analytically derived process models.

3. New View on Material Removal in Slurry Sawing

Conventionally, the process of material removal in lapping is understood as a micro-chip formation process, where abrasive particles stick to the tool and are dragged over the work surface, thus removing material by ploughing, scratching and regular chip formation. Recent findings, however, show clearly that this kind of a real chip formation process never occurs really in a well controlled lapping operation. In the contrary, such an event results in an undesired scratch on the work surface, which is normally regarded as an indication for an inferior working result. The real material removal process in lapping is based on a rolling action of the abrasive particles in the gap between workpiece and lapping tool /4/. This is generated by the relative motion between tool and work surface and is supported by the lapping fluid, which forms a linear velocity field characterized by a constant degree of shearing. As a consequence, the abrasive grains do rotate even if they are not in contact with the tool and/or work surface, as demonstrated in Figure 1. As a result of this rolling action, the edges of the irregularely shaped

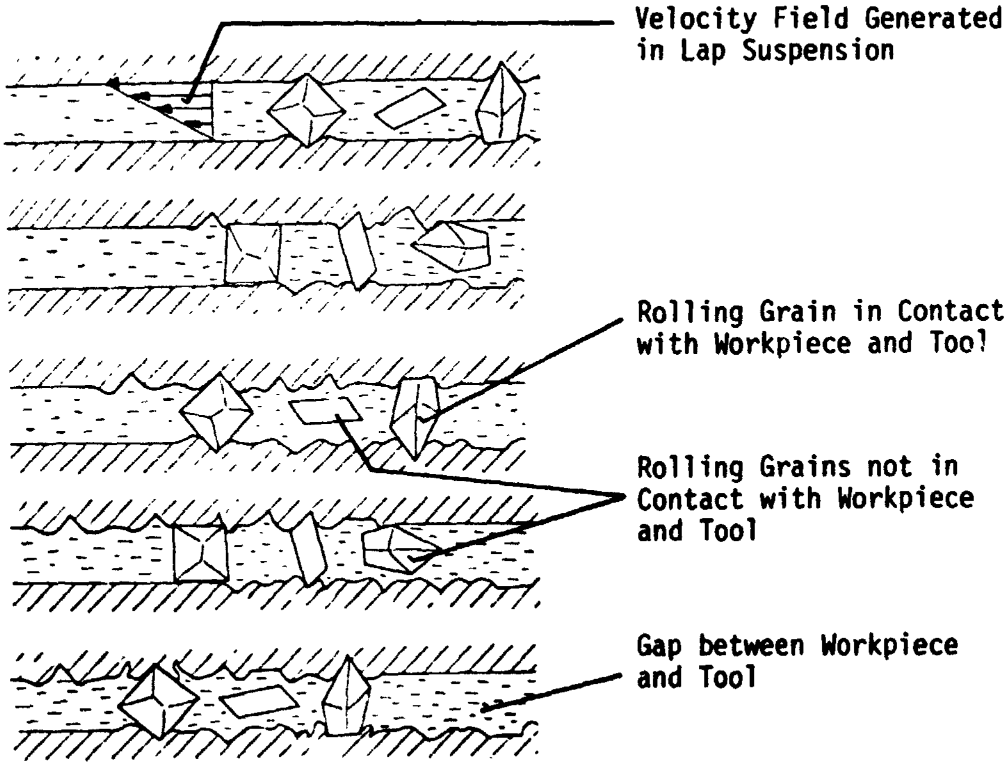

Fig. 1: Principle of grain rotation and material removal in lapping /4/

grains penetrate into the work surface at an extremely high rate. For example, a slurry with a concentration of $C = 10000 \text{ mm}^{-3}$, a lapping speed of $v = 500$ mm/s and a 30% grain participation factor results in 1.5 million impacts of grain edges per second and per square millimeter on the work surface.

In the case of ductile materials, like steel and superalloys, these impacts lead to a high degree of plastic deformation in the respective surface layer of the workpiece. As a consequence, the deformability of the material is reduced and the hardness is increased, both effects based on the principle of strain hardening. With ongoing impacts and deformations, the yield strength of the material is exceeded locally, and as a result small work particles of irregulare geometry are seperated from the work surface and removed out of the working area by the lapping fluid. With impact rates as high as demonstrated above, material removal rates in lapping can reach values comparable to precision grinding processes.

In case of rigid-hard materials, such as ceramics, carbides, and silicon, the micro-mechanics of the material removal process in lapping is even simpler. While the individual grains roll over the work surface with no tendency for plastic deformation at all, compressive stresses are induced into the work surface, which locally exceed the limits of strength of this particular material. As a consequence, flake-type of particles break loose from the work surface with no repetive plastic deformation involved. Due to the rigid character of the penetration and seperation process, the volume removed from the work surface by an individually impacting edge might be larger than the actual volume of penetration of the abrasive edge into the work material.

One specific characteristic of the lapping process is, that the tool is also subjected to the micro-impacts of the abrasive grains, and thus shows a certain loss, too. This tool wear can be reduced by selecting saw blades with favorable properties, such as high degree of elastic deformability, low strain hardening capability, and high yield strength.

In the case of slurry sawing of silicon material, the tool should have a sufficient capability for elastic/plastic reaction. Due to the rigid interaction between work material and abrasive grains, the impact forces need to be damped by means of an elastic/plastic interaction between grains and tool material. Otherwise, the reactive forces on the grain edges themselves would be too high, and would result in an exessive grain wear.

Utilizing this novel concept of material removal in lapping, it is possible to define the numer of impacts N_r per unit of work surface and time by multiplying the concentration C with the lapping speed v /3/:

$$N_r = K_1 \cdot C \cdot v \qquad [\text{mm}^{-2} \cdot \text{s}^{-1}] \qquad (1)$$

Assuming a quasi-proportional relation between the average force P_K per active grain and the amount of material removed per edge impact, the total amount of material removed per unit of work surface and per unit of time results to:

$$V_r = K_2 \cdot P_K \cdot N_r = K_3 \cdot P_K \cdot C \cdot v \qquad [\text{mm}^3/\text{mm}^2/\text{s}] \qquad (2)$$

In this function, which is used later for deriving the process model functions for slurry sawing, the proportionality factor K_3 is valid only for a given combination of work material, tool material and abrasive material, as well as the particular specification of the lapping suspension used. Recent investigations show, that the volume of material removed per edge impact does, in reality, not increase exactly proportionally with the average load per grain, but rather shows a slightly degressive increase. The implications of this nonlinear behavior are of secondary importance and will not be taken into further consideration in the context of this paper.

4. Kinematic and Geometric Conditions of Contact between Workpiece and Blade

Figure 2 represents the basic geometric and kinematic conditions of the slurry sawing process. The individual saw blade is moved back and forth with the varying speed $v = f(x)$, the stroke length a, and the stroke frequency n_s, cutting into a block of work material with the width b. As a result of the varying cutting speed, the resulting blade wear is uneven versus the length of contact. At point A (upper part of Figure 2), the slicing speed v is at its maximum ($v = v_{max}$) and so is the blade wear. At point A" (lower part of Figure 2), the maximum stroke position is reached and the related slicing speed becomes zero ($v = v_{min} = 0$), and in accordance with this the blade wear is zero, too. As a result, a quasi-elliptic wear profile is formed in the tool. This geometric deviation from the original straight tool profile bears dramatic consequences for the whole process, as a similar curved profile is generated in the work surface, exposing a stronger curvature versus its entire extension than the tool profile. Actually the two mating profiles are congruent, because they are bound to have identical tangents in their respective points of contact.

Most important for the understanding of the slurry sawing technique, and in strong contrast to the conventional concepts, is that tool and workpiece actually have a point contact rather than a line contact versus the total work width as formerly assumed.

There are two other specific characteristics of the slurry sawing process, which can be derived from Figure 2. The first one is related to the fact, that the contact point (A, A', A") moves with the speed v_K opposite to the actual motion of the blade indicated by the blade speed v. The second characteristic refers to the vertical motion the blade is forced to make, while the blade contour works its way up on the contour of the workpiece. This vertical stroke is indicated by the vertical blade speed v_e and represented by the maximum vertical stroke length e valid for the extreme positions of the saw blade. In essence, the vertical stroke phenomenon is the reason for the dynamic instability of the slurry sawing process and causes major process disturbances especially at high stroke rates and cutting speeds. As a consequence, measures to compensate or minimize this effect are essential for high-efficiancy slurry sawing processes.

From Figure 2 the following functions concerning the basic geometric and kinematic relations of slurry sawing can be derived:

a) Maximum vertical stroke e:

$$e = c \cdot \frac{a}{a+b} \quad [\mathrm{mm}] \tag{3}$$

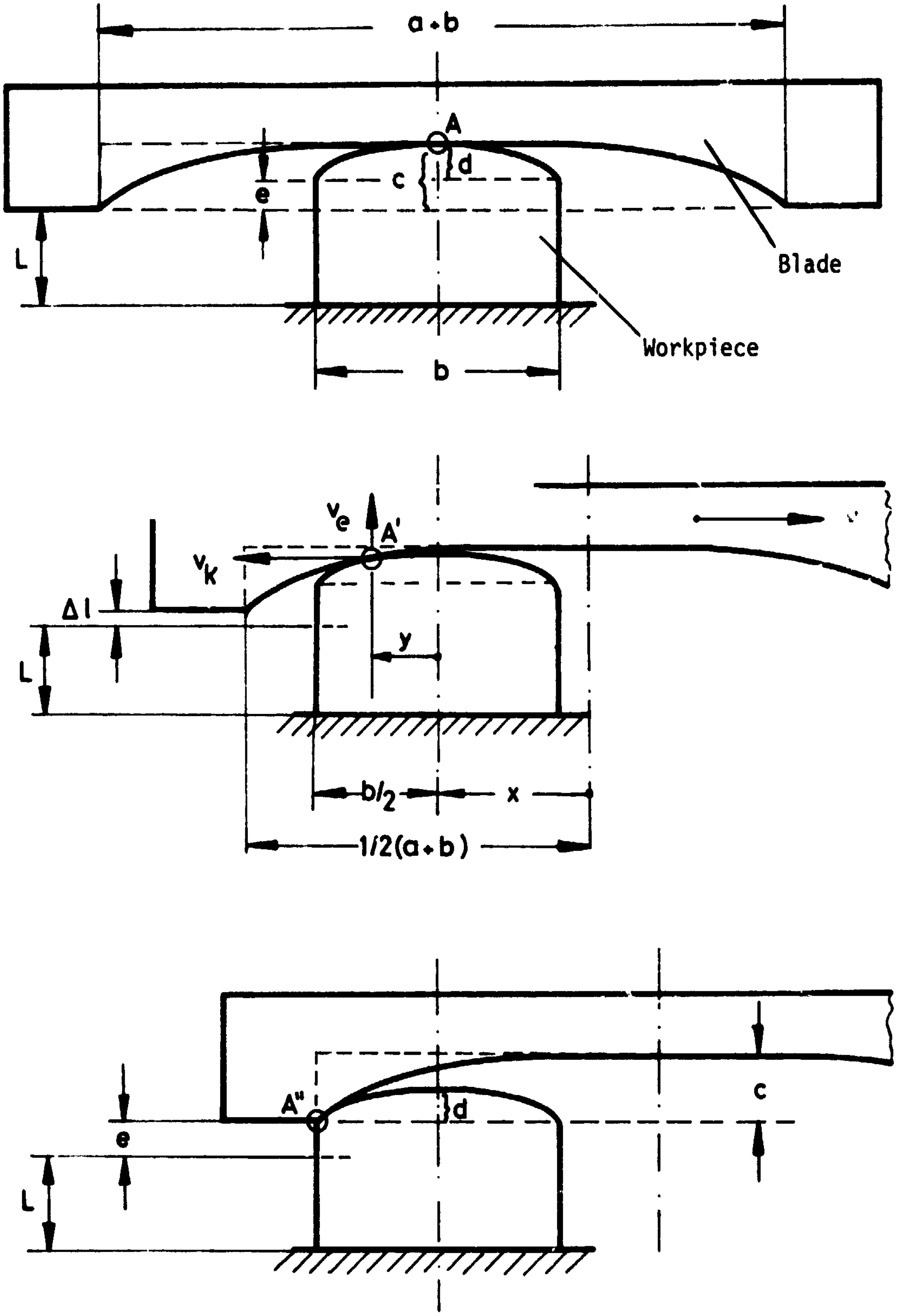

Fig. 2: Representation of geometric and kinematic conditions of the slurry sawing process /3/

b) Velocity of contact point v_K as a function of the simultaneous cutting speed v:

$$v_K = v \cdot \frac{a}{b} \qquad [\mathrm{m/s}] \qquad (4)$$

c) Ratio between maximum blade wear c and maximum workpiece contour d:

$$\frac{c}{d} = \frac{a+b}{b} \qquad [-] \qquad (5)$$

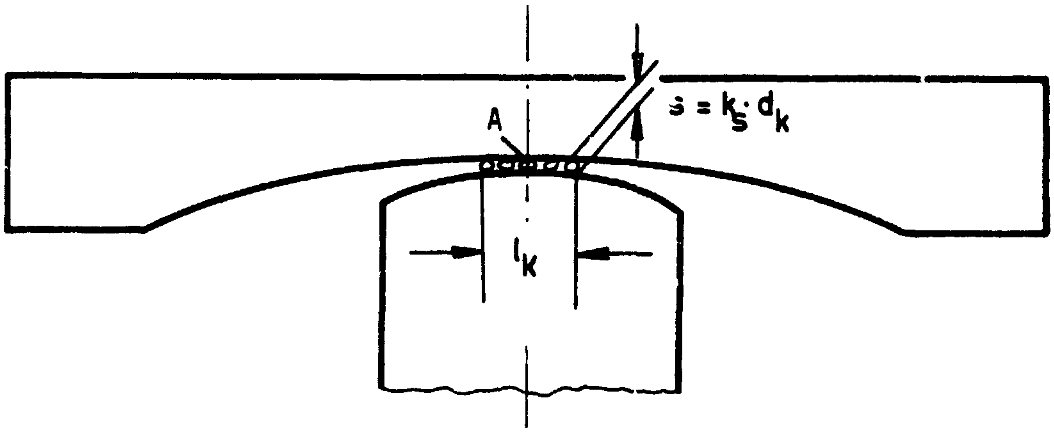

Fig. 3: Actual contact conditions between workpiece and saw blade

The actual contact conditions between workpiece and blade are such that active grains are distributed around the theoretical point of contact A covering a confined width of contact l_K (Figure 3). Based on certain assumptions regarding the grain distribution and the average depth of penetration of cutting edges into the tool and work material /3/, the contact time t_K for which any point of the work surface is subjected to the lapping action results to:

$$t_K = \frac{l_K}{v_K} = \frac{l_K}{v} \cdot \frac{a}{b} \qquad [\mathrm{s}] \qquad (6)$$

Further analytical investigations have been carried out to describe the actual width of the contact zone l_K, revealing that it is a complex function of the average grain diameter d_K, the cutting force P' per unit of blade width, the stroke frequency n_S, the cutting time t, the stroke length a, and the width of the workpiece b. This, however, will not be dealt with here, as l_K is cancelled out in the concourse of the analytical derivation of the process models, based on the grounds of the already mentioned linear relationship between average force per grain and average material removed per edge impact /3/.

5. Functional Description of Process Criteria

Based on the geometrical and kinematical fundamentals of the slurry sawing process described above in brief, the following functions related to the main operational process criteria have been derived in a recently finished study /3/:

a) Depth of cut per stroke of saw blade:

$$f_e = K_f \cdot \frac{P'}{d_K^{\alpha}} \cdot \frac{a}{b} \qquad [\mathrm{mm}] \qquad (7)$$

b) Feed rate:

$$f = f_e \cdot n_s = K_f \cdot \frac{P'}{d_K^{\alpha}} \cdot \frac{a}{b} \cdot n_s \qquad [\mathrm{mm/s}] \qquad (8)$$

c) Specific removal rate:

$$Z' = K_f \cdot \frac{P'}{d_K^{\alpha}} \cdot a \cdot n_s \qquad [\mathrm{mm}^2/\mathrm{s}] \qquad (9)$$

d) Maximum blade wear:

$$c = K_v \cdot \frac{P'}{d_K^{\beta}} \cdot n_s \cdot t \qquad [\mathrm{mm}] \qquad (10)$$

e) Ratio between material removol and blade wear ($r = a/b$):

$$G = K_g \cdot d_K^{\beta-\alpha} \cdot \frac{r}{r+1} \qquad [\mathrm{mm}^3/\mathrm{mm}^3] \qquad (11)$$

f) Maximum vertical stroke:

$$e = K_v \cdot \frac{P'}{d_K^{\beta}} \cdot n_s \cdot t \cdot \frac{r}{r+1} \qquad [\mathrm{mm}] \qquad (12)$$

The feed rate f and the specific removal rate Z' show a proportional increase versus specific cutting force $P' = P/b_S$ (P = total force load per blade, b_S = width of blade), stroke length a and stroke frequency n_S. The influence of the average grain diameter d_K on these two process criteria is not clearly decided and depends on the actual positive or negative volue of the respective exponent α. On the other hand, the grain concentration C of the lapping suspension does not appear to have an influence on these and the other process criteria in the context of the presented analysis. This result is again based on the assumed linear relationship between average force per grit and average material removed per individual edge impact. However, practical tests indicate, that there is indeed an optimum grain concentration for given operational process conditions. As a consequence, this specific relation will be checked further, including the application of a non-linear relationship to describe the material removed per individual edge.

Another result is more obvious, proving that the specific removal rate Z' is independent from the effective width b of the workpiece. This actually means, that for a given set of cutting conditions, the volume cut per unit of time is always the same, independent from the actual width of the workpiece.

Similar structures as derived for feed rates and removal rates have been obtained for the process models concerning the wear related process criteria such as maximum blade wear c, abrasive ratio G, and the maximum vertical stroke e. The last two criteria show a strong dependency of the stroke ratio

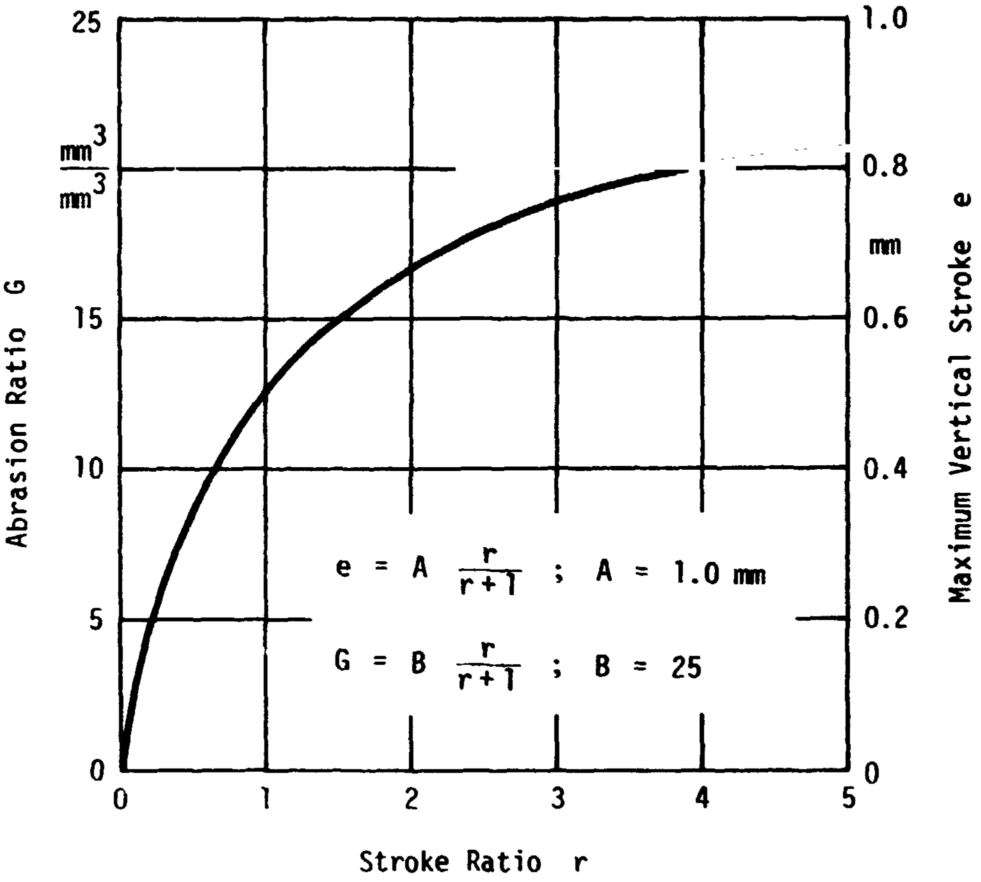

Fig. 4: Qualitative representation of abrasion ratio and vertical stroke versus stroke rate

r = a/b (a = stroke length, b = width of workpiece). The respective functions are displayed qualitatively in Figure 4, showing that the G-ratio improves degressively with increasing stroke ratio r. As a result, tooling cost are decreased, and productivity in form of increased removal rates could be improved, too. On the other hand, however, the disturbing vertical stroke e is increased at the some rate versus r, indicating that counteractive measures to reduce the intensity of e is an important requirement in case of higher stroke ratios. The same is true for higher stroke rates n_s, as the vertical stroke intensity increase proportionally with n_s. The abrasive ratio G, on the other hand, is independent from n_s, because both, the removal rate and the wear rate increase at the same rate versus n_s, and thus this influence is cancelled out.

6. Comparison between Analytical Results and Practical Tests

Slicing test performed in the USA reveal a promizing accordance of the derived process model functions with the test results /1/. In Figures 5 to 8 recorded abrasion rates and cutting rates, which are in fact identical with the specific romoval rate Z' defined above in equation (9), are plottet ver-

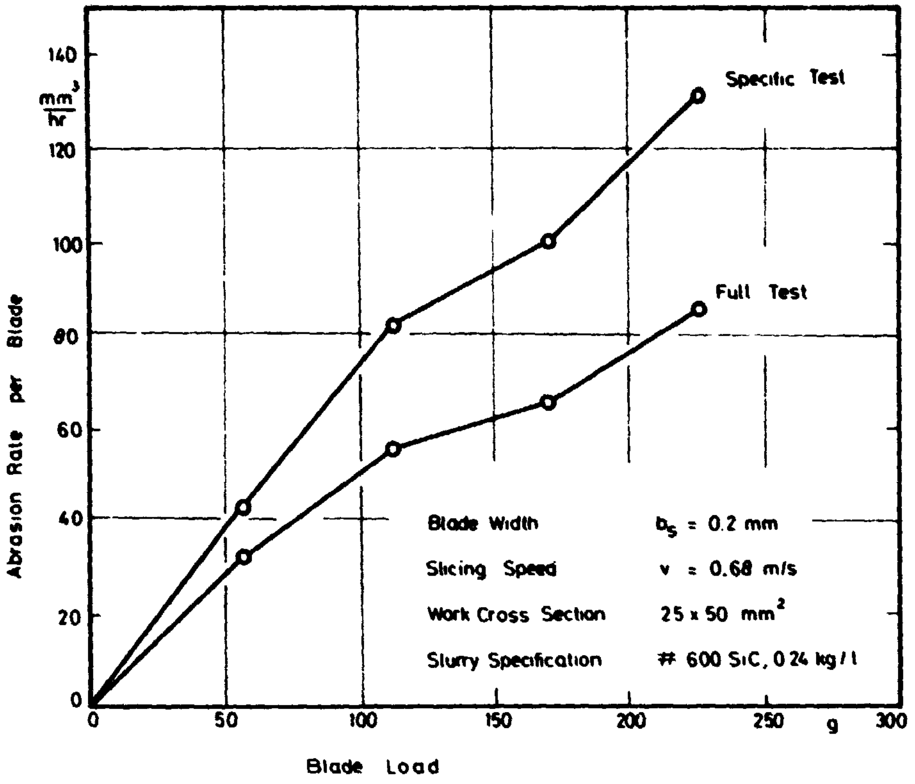

Fig. 5: Abrasion rate per blade versus blade load in slurry sawing /1/

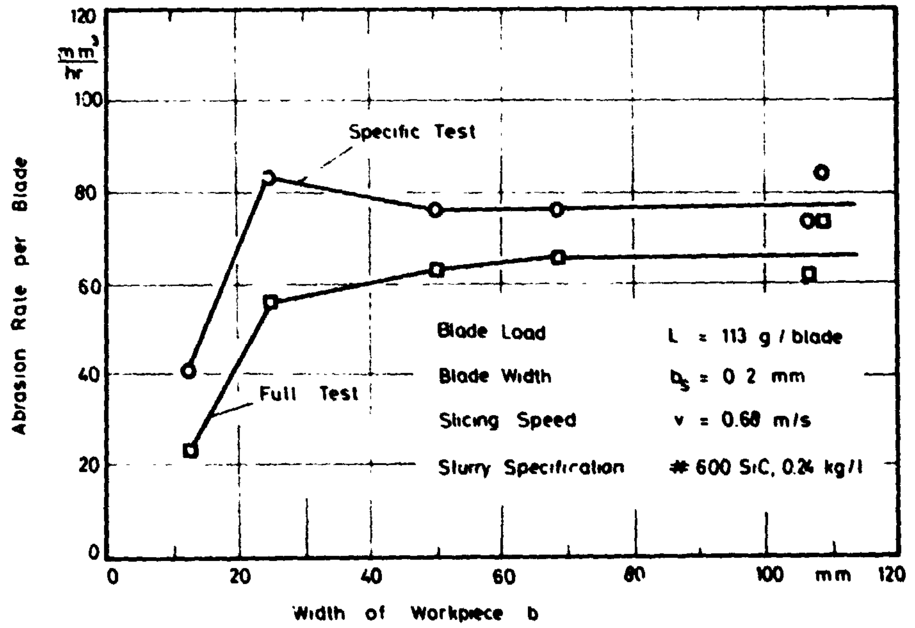

Fig. 6: Abrasion rate per blade versus width of workpiece in slurry sawing /1/

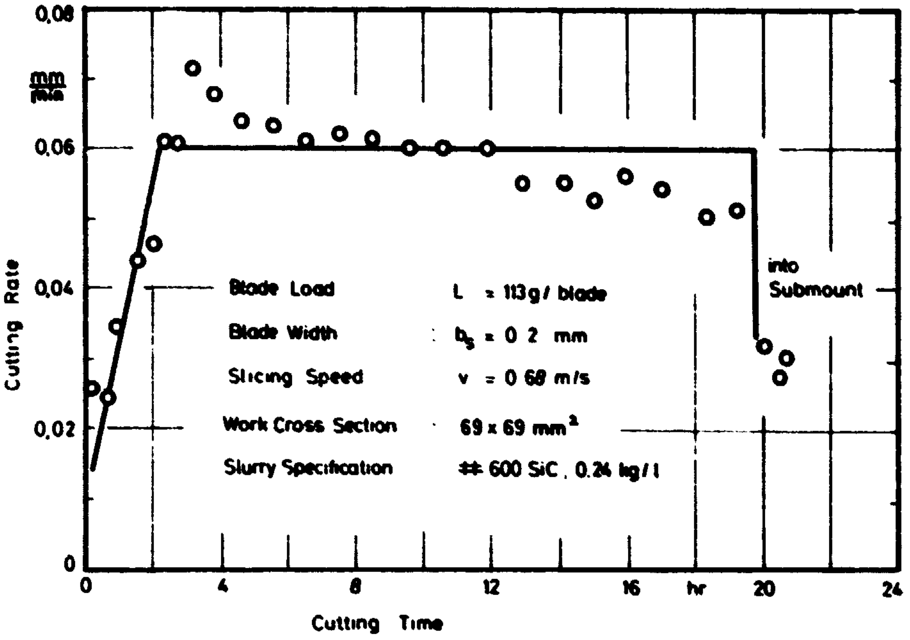

Fig. 7: Cuttig rate versus cutting time in slurry sawing /1/

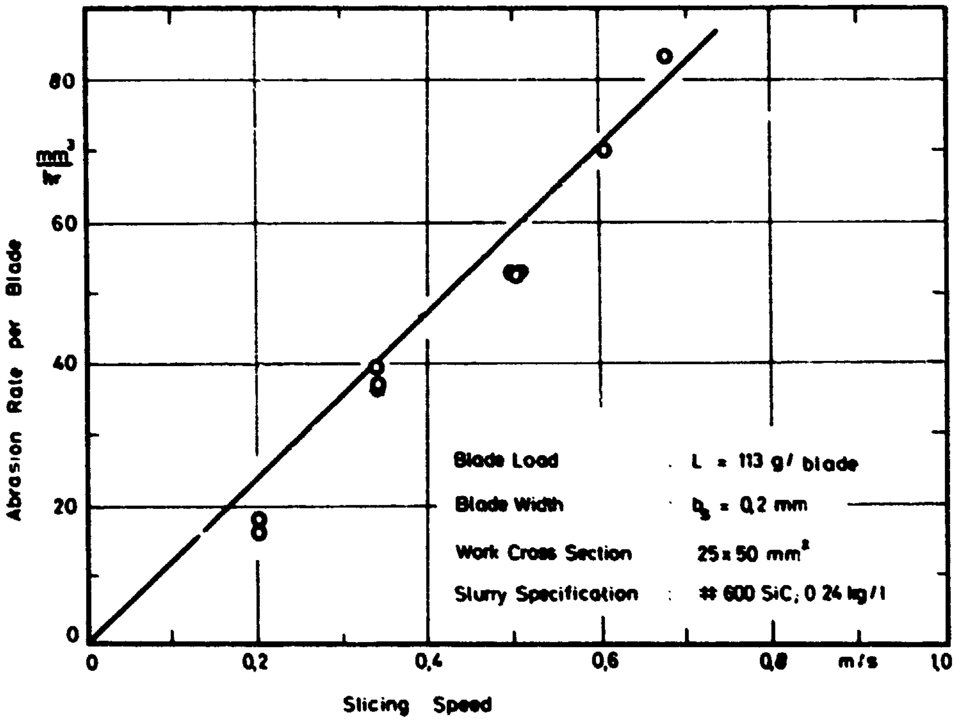

Fig. 8: Abrasion rate per blade versus slicing speed in slurry sawing /1/

sus various process parameters. Figure 5 shows clearly the almost proportional increase of the material removal rate versus the blade load, while in Figure 6 the independence of the removal rate from the width of the workpiece is demonstrated. Only at a small width of less than b = 20 mm, the recorded removal rates drop, most probably because of an improper generation of the work contour. The quasi-constant removal rate versus cutting time becomes evident from Figure 7. In the beginning of the slicing process, the removal rates are lower due to the fact that the proper contours of tool and workpiece are not established yet. With increasing cutting time, however, the mating contours develop gradually, and at the same time the removal rates increase until the optimum, steady-state of operation is reached. In the tests cited, a slight decrease of the removal rate was observed at steady-state conditions instead of the expected constant behavior. Further investigations of the slurry sawing process, which will be carried out as part of a major practical research program, are scheduled to decide whether this declining tendency is a general characteristic of the process based on geometrical and/or mechanical deviations, such as tool wear and work contour changes, or whether the observed behavior occured on the grounds of an unidentified disturbancy. Finally, a very clear tendency is demonstrated in Figure 8, proving the exactly proportional increase of the removal rate versus the slicing speed, which on the other hand is identical with an increasing stroke rate a at a constant stroke length b.

7. References

/1/ Holden, S. C., Fleming, J. R., Slicing of Silicon into Sheet Material, Series of Quarterly Reports, ERDA/JPL Contract No. 954374-77/5, 1977-1979.

/2/ Sirtl, E., Regler, D., Moritz, A., Process for Multiple Lap Cutting of Solid Materials, USA Patent, No. 4 187 827, Febr. 1980.

/3/ Werner, G., Grundlagen der Prozesstechnologie des Trennlaeppens, Research-Project, Bremer Institut fuer Angewandte Strahltechnik (BIAS), Bremen, West Germany, 1981.

/4/ Martin, K., Neuere Erkenntnisse ueber den Werkstoffabtrag beim Laeppen, Fachberichte fuer Oberflaechentechnik, Bd. 10, No. 6, 1972.

DISCUSSION:

SCHMID: Your model is very interesting. When I first got into this, I was using the slurry saw and was using blades with fixed diamond on the bottom. And, in fact, it would not cut. If it had any kerf length at all, it would not cut. What I did was to make a step-block, which was a 1/4-inch, 1/2-inch, 3/4-inch--varying kerf lengths, to see how effectively it would cut for those particular kerf lengths, and it cut fairly well in the 1/4 inch. Once I hit the half-inch, it almost stopped dead--this was with sapphire--and from that I came to the idea of rocking. I could never really understand why there was a significant difference between cutting with a diamond, the fixed abrasive, as opposed to the loose abrasive, and I think your model explains that very nicely.

WERNER: Yes, it exactly explains it. If you have some kind of line contact, your removal rate is very low. The main reason is that the contact between work and tool is too long, and so the distribution of the load over many thousands of grits results in a too small load per grit and nothing happens. Only if the contour is such that your real contact lengths between the tool and the workpiece is small enough, does the process work.

SCHMID: It might be interesting to try a step-block. I did this with sapphire, and saw, in fact, the 1/4-inch, I was able to physically cut with it. There was movement. It would be very interesting to try the same kind of experiment with silicon to see what, in fact, is that contact length for the particular load that you're using.

WERNER: You could increase your load, theoretically. But as it begins to buckle, you never get to that high total load. But the load per grit is high enough for cutting action to start.

JACKSEN: Considering, with slurry saws, the problem of this buckling process, how would you feel about raising pressure to increase cutting rates? Consider that the contact area's being so small would result in dramatically increased kerf sizes as the parts started to get either some vibration or some extra motion in the non-desired edge. That is, is there some point in tension, which would be optimum considering the 80% elongation?

WERNER: There is an optimum relation between the stroke lengths and the work widths. That is roughly in the vicinity of 1:1. That means that stroke lengths and work widths should be the same. Now, about the contour in your blade, the work contour is just twice as long as the work width is. If you would increase the stroke length, which has some advantages, then you would weaken your blade with respect to the danger of buckling. And, therefore, you would rather reduce the stroke length and have also a smaller blade length, and increase--instead of that--the stroke frequency. So it helps very much to speed up the process, if you can increase the load. It helps also to increase the stroke length. It helps to increase the frequency. But there are constraints that are given by the system and by the machine. And that is exactly what we are now dealing with to find the optimum conditions of these partly contradicting influences of the process parameters. There is some kind of optimum set of working conditions. For that we need a better machine.

QUESTION: What do you feel the optimum speed of sawing could be from this system if you optimized it?

WERNER: Actually, the answer is as fast as possible. I would like to have a machine that can go up to 200 meters per minute, maximum speed. You see the speed goes from a maximum value to a minimum one.

QUESTION: You're talking about speed of reciprocation, or speed of sawing? I didn't understand.

WERNER: Speed of sawing and the in-feed velocity. I think it is possible, one day, to arrive at such speeds that you can cut through a 10-x-10-centimeter, or 4-x-4-inch, ingot in less than an hour.

QUESTION: They are doing that now with diamonds, sawing ID, are they not?

WERNER: Yes, but one wafer after another. Here you have the same speed for 300 wafers at the same time, so that results in less than 10 seconds per wafer.

QUESTION: But you also have a changing parameter in this system. That is, your blade is changing shape as you're sawing. Does not that variable give you a headache in the single-point forces that you're talking about?

WERNER: Not in the shape itself, but in the accumulation of the compounding forces at the end. You come to a point, especially if you have long strokes, where you have a disadvantageous kind of wear profile. You have a wear profile that is straight and then suddenly breaks off. So you have a very strong component force at the end. If you have smaller strokes, and faster ones, then your wear profile is more smooth, and you don't experience this problem so much. However, in time, these disturbing forces grow, and you come to an end where you can no longer continue to use your blade system. The best is just to use one blade for one cut, and then throw it away and put another set of blades in.

QUESTION: The shorter the stroke, the worse the problem is with the removal of the slurry, and with heat buildup.

WERNER: That's clear. Because if you reduce your stroke lengths to zero, what do you have? Nothing. Actually, your contact point--let's say you have 1- or 2-millimeter stroke length--then your point of contact is switching, going from one side of the workpiece to the next at the stroke rate; however, the real rolling action, because of the small relative motion between work and tool, is very very small, and it approaches a zero removal rate

HEIT: There was reference made to an enrichment in the concentration of the slurry as it passed into the work area, the specific pressure section. You mentioned that it almost doubled from 10,000 grains per cubic centimeter to 20,000 grains per cubic centimeter. Is there any speculation at this point as to why that is happening in the slurry? We have slurries that are used in fuel treatment, which behave somewhat along those lines, when they have to be forced through narrow apertures. There's a distortion in their weight percent.

WERNER: You see here the speed of the centerpoint of my grain is half. So it is in tune with the speed of the liquid, while here, that point of the cutting edge, has exactly the speed of the workpiece and so does the speed of the outmost layer of the liquid. Here that point of the particle has a speed of zero because it sticks into the workpiece, and so does the liquid in contact with the workpiece. Now, you see that results in the fact that average speed of the particles is half of the speed of my lapping tool. But the concentration in the gap is twice the concentration of the particles in the free suspension. Just because they are forced to go through this gap, which is roughly the average size of the grain diameter. Because, in a free distribution, you never have them all aligned in one little gap and line, but rather, if I had a model of the free suspension here, I would have a concentration that could be put into a gap double as big as this gap, but the same number of grains, actually. Forcing a liquid with solid particles into a small gap, nearly as small as the diameter of grit itself, results in a condensation and an increase of the concentration of the grit in the fluid.

WOLF: Does that mean speeding up the fluid velocity?

WERNER: You are right. Actually, the fluid that was here may that result in a compression of the fluid. But I think we have to find out what the answer is here. But we have grains in the gap, I'm sure, and you have also the lapping component, because that is not only necessary for getting the particles in rotation, but also for getting the debris out. If you did not have a liquid vehicle here, we never could get the silicon particles out of this gap and it would clog pretty fast.

MORRISON: I wonder what the practicality of continuous or periodic blade dressing would be to overcome the problem of stroke shortening for excessive blade wear. People shorten the stroke, and therefore shorten the bladelife, when the rounding wear becomes excessive. Is blade dressing one alternative to stroke shortening?

WERNER: Blade dressing to remove contamination. But changing the curvature is a problem because there is such a delicate equilibrium between the working conditions and the right profile, that any dressing process would disturb this equilibrium and would result in a reduction of the removal rate. But it is an interesting point to think about blades with fixed abrasive having the right contour. Of course, that is such a natural view to put on this problem, we are trying that and it seems to work very well. If we start with a straight blade with diamond particles, we have a rather slow process, especially if the workpiece develops a straight flat contour too. It comes to an end and we cannot just put the pressure on. It's like a sawing process with a very wide workpiece. However, if we just have a little concave contour on the tool, it works very good.

BOSOMWORTH: You started your talk with a comment that you thought that shortly there would emerge some techniques that came close to meeting the solar cell goals. I'd like to invite you to comment further on that ... you've certainly gone through some fundamental things here that would speed up multi-wire cutting. Are we, in your opinion, going to see some machines in the near future that are greatly improved, and where are they going to come from?

WERNER: **I'm sure that we'll see some machines emerging both in the multiple blade slurry area and also with wires.**

JACKSEN: **How about the silicon carbide particles breaking down and perhaps causing your cutting rate to decrease, because the particle sizes are starting to get smaller? I ask that in the context not only of silicon but of fused silica, which is my main interest.**

WERNER: We did not experience that over a period of 30 hours. Over this time, there was no deterioration visible with regard to the average shape and size of the silicon carbide grains. If we see that, over a time, constant stroke lengths bear problems, we could think about reducing gradually the stroke length by 2% or 3% and avoiding the pounding effect at the very end of the stroke. However, there's no machine available on the market at the moment, where you could gradually reduce stroke lengths in process.

LYNAH: Our machine has infinitely variable stroke lengths. We can program it--it's not normally done, but it can be programmed to change the stroke length as it is sawing.

LANE: You have told us it appears that the process works best with the curvature. Are you saying that if we could magically make a machine that has perfectly flat blades and maintains them, that we'd have slow cutting? Is it a force problem?

WERNER: If you want to have a straight tool, you can rock the workpiece and then you have this difference in curvature, and by that, a point contact. It is, basically, an inherent characteristic of the process, which of course depends on the force of the millions of impacts of the grains on the tool and the workpiece. And then, it stretches in the blade over a greater length, and this length is the width of the workpiece plus the stroke length, while the contour in the workpiece is just confined to the width of the workpiece. So you are bound to have a smaller curvature in the tool, and a contour with a larger curvature in the workpiece.

LANE: The problem I have in understanding this is that in wire sawing the wire bends. We have conformity and contact through a very long arc, and that still cuts.

WERNER: Yes. It cuts because of the high speed. And it's not a rolling process, nor a scratching process. And if you would look into how many diamonds on a wire really cut, you would be amazed how small this number is. Actually, the slurry wire saw system can only improve from these relatively low cutting rates. If the angle of contact between the workpiece and the wire is larger--that means go round 180 degrees--and pull it down, then you can increase cutting width. I don't know whether somebody is trying that, but it requires a different kind of machine too. First you have to have an idea, and understanding of the process, and then you have to try to do it. But what was done over the past few years, was just try something without an idea. And that was the reason why the progress was small. Maybe I'm biased because I'm working in this area. I favor the multiblade slurry technique because with regard to the difficulties related to the machine, to the tool, and all that, it seems to be the least compilation of problems. But with wires, you have a lot of other difficulties. Wire is very small, it can break, you have to guide the wire, and as it goes out of contact, it takes slurry with it. You see, if you can achieve a better result with a slurry saw, then I think at least the people involved in this business would forget the wire saw. On the other side I am very much interested in following up progress on these wire saws.

In the ID sawing process, if the workpiece does not rotate, of course, you have a line contact over the total contact length, the total width of the workpiece. And for the kind of heavy total load, between the tool and workpiece, you need bonded abrasives and you need a very rigid cutting edge. That's the main reason why it is done internally. OD sawing would not be possible, at least not easily, by that method, because the total contact forces between the blade and the workpiece are too high and such a thin saw blade would buckle.

WALLITT: What if you rocked the work while you were doing it?

WERNER: You see, I have to point in one direction always. And the big advantage of a slurry saw is that you can indeed cut up to 300 or more wafers at the same time. So even if the cutting time, for one cutting process, is an hour or two, the resulting average cutting time for an individual wafer is a few seconds. 10-15 seconds. It's very difficult, at least if you go to a larger cross section of your ingots, to achieve that, as we heard yesterday, with an ID saw. However, I want to make another statement. The ID sawing system, especially if it is further improved, is a very good cushion to rest on as long as other techniques are not available or fail. And I am pretty sure that if a high-efficiency slurry technique were to come through, the ID sawing and tool manufacturers would not sit back and just give up. I think then some of the possibilities they have to further increase their removal rates and decrease the cutting cost would be tried out. You can see the same kind of competition between processes in other fields too. And very seldom is one process completely wiped out when another one comes up that does a little better.

SCHMID: A little while ago you made a comment that when you're rocking with fixed-diamond abrasive, the number of particles that actually are in contact with the work is very small, far smaller than you would expect. This is something that we are trying to achieve, to minimize the actual contact point, so we can achieve high pressure at the diamond tip. What makes you feel that number of contact points is minimal?

WERNER: A shadowing effect. You see, if you have a saw blade, let's take a bandsaw where theoretically the blade goes down vertically and you have cutting edges all aligned at the same line, theoretically only one can cut. So you need a certain distribution of cutting edges in a small field. In a normal bandsaw operation, not more than a tenth, or even less of the teeth, really cut. That goes on until the one that protrudes most is worn away, and then that which follows next, at a certain position, takes over the cutting. That is true for grinding too. Especially in this plunge ID process. It is possible that on the whole circumferential area of the wheel, from the many thousand grits only a few hundred are, at a certain point of time, really cutting. And that explains why the tool life is so high, in my view. So the number of engaged edges in grinding, and I dealt with that problem in conventional grinding very much, is much smaller than you think. With the wire sawing process, where you have this problem of getting enough normal force on your edges, one way out is to have fewer of them really working, and taking the load off a certain length of the wire.

SCHMID: Yes. Rocking it. And the other thing, of course, is that by going to a finer particle size, we saw a much more effective cutting action. By going to a finer particle size, the number of contact points is going to be increased substantially.

WERNER: It always helps to know how many edges in a microchip formation type of process are in real contact with the workpiece. In most of these processes it is very unclear. We have very little means of calculating or measuring the real number engaged. If you understand the process well, that understanding might also force you to give up.

SCHMID: Yes. The other thing that you can do to minimize your number of points in contact to increase the pressure is in fact to have a larger rocking angle, which will minimize the curve.

WERNER: Yes. The end cutting speed helps also. You can, to a certain extent, overcompensate this deficiency of low forces by a higher speed.

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CORROSION INHIBITORS FOR WATER-BASE SLURRY IN MULTIBLADE SAWING

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ABSTRACT

In the JPL Low-Cost Solar Array (LSA) Project, the use of a water-base slurry instead of the standard PC oil vehicle was proposed for the multiblade sawing (MBS) silicon wafering technology. Potential cost savings were considerable; however, significant failures of high-carbon steel blades have been observed in limited tests using a water-based slurry during silicon wafering. Failures have been attributed to stress corrosion. Plans were developed to improve blade performance by adding a corrosion inhibitor to the slurry.

A specially designed fatigue test of 1095 steel blades in distilled water with various corrosion-inhibitor solutions was used to determine the feasibility of using corrosion inhibitors in water-base MBS wafering. Fatigue tests indicated that several corrosion inhibitors had significant potential for use in a water-base MBS operation. The fatigue life of blade samples tested in these specific corrosion-inhibitor solutions were found to exhibit considerably greater lifetime than those blades tested in PC oil.

INTRODUCTION

In the Low-Cost Solar Array (LSA) Project, the use of high-carbon steel blades (with a water-base slurry) for the multiblade sawing (MBS) technique has been proposed. This cutting-base system can reduce the cost of silicon ingot wafering significantly. Until now, PC oil, fully hardened 1095-steel blades and silicon carbide abrasive have been used for MBS ingot wafering. The PC oil, cutting abrasive and blades are "expendables" in the MBS technique. Short working lifetimes of these materials have made this slicing technique costly.

Significant failures of high-carbon steel blades have been observed in limited tests (Reference 1) using a water-based slurry during silicon wafering. These blade failures were determined to have been attributed to stress corrosion. Plans were developed to improve steel-blade performance by adding a corrosion inhibitor to the slurry.

A specially designed fatigue test of 1095-steel blades was developed to determine the feasibility of using corrosion inhibitors in water-base MBS wafering. Sample blades were fatigue-tested in distilled water with various types and amounts of corrosion inhibitor solutions added.

Results of failure analyses on saw blades from water-based slurry wafering, fatigue and corrosion-inhibitor testing on 1095 high-carbon steel blade samples and present and future test plans are summarized below.

FAILURE ANALYSIS OF BLADES

The typical fracture surface of a saw blade that failed in service during water-based-slurry silicon cutting action is shown in Figure 1. Corrosion products were observed on the fracture surface and intergranular fracture features were noted near the original cutting edge (Figure 2). This type of fracture surface suggested stress corrosion, a mechanism probably induced by an oxygen concentration cell effect (Reference 2), residual blade tensioning load and cyclic cutting loads. Considering these factors, a more descriptive term for the failure mechanism is corrosion fatigue. The concentration-cell effect can usually be seen on steel surfaces, resulting from a water-drop interaction.

In environments where oxygen concentration is variable, oxygen-deprived areas become anodic to oxygen-rich areas. In-service blade cracking was found to have started at the cutting edge of blades near the worn-unworn blade boundary (Figure 3). This failure site is located at the wetted-nonwetted interface on working saws. Thus oxygen surface concentration is most variable in this area on a blade where fully aerated cathodic areas drive corrosion in air-deprived areas.

To improve the service life of 1095 high-carbon steel for MBS wafering, slurry solutions carrying corrosion inhibitors with the potential of preventing or minimizing oxygen concentration-cell effects were proposed for evaluation. Inhibitors can (1) interfere with cathodic oxygen reduction on iron surfaces by maintaining a layer of absorbed oxygen on the surface or (2) passivate the steel by forming a stable surface oxide. Oxygen-scavenger or anode-cathode inhibitors (absorbed oxygen effect) were selected for blade-screening tests.

METALLURGICAL-MECHANICAL EVALUATION OF BLADE MATERIAL

A quantitative chemical analysis was made on sample blade material; the results are presented in Table 1. Chemical analysis indicated that the blade material was indeed 1095 high-carbon steel.

Metallographic examination of a cross-section sample of a blade was made. A photomicrograph of the blade material is shown in Figure 4. Spheroidal cementite particles were found to be uniformly sized and distributed, which indicated a fully hardened steel blade.

Hardness and standard tensile tests also were performed on the blade material. Rockwell hardness (Rc) was approximately 56. Yield and ultimate tensile-strength values for reduced-section samples were 242×10^3 lb/in.^{2} and 260×10^3 lb/in.^{2}, respectively (Table 2). These were the average values from five tests.

FATIGUE TESTING OF BLADES

To determine the feasibility of using corrosion inhibitors in water-base MBS wafering, a specially designed fatigue test of 1095-steel blades was developed. The width of blade samples for fatigue tests was reduced to control failure location. Blade thickness was 0.0086 in. and original width 0.250 in. The typical configuration of a blade sample and fractured blade sample are shown in Figure 5.

Fatigue-test loading conditions are give in Table 3. The mean load applied to the samples was approximately 70%, ≈200 KSI, of determined yield stress, similar to the blade tensioning load in actual blade packs. The minimum and maximum fatigue stresses were considered to be comparable with the loading range on a blade during MBS sawing. The controlled-test environment (aqueous fluid) was applied to the test sample by enclosing it in a silicone-sealed plastic bag, as shown in Figure 6.

Baseline fatigue test results of 1095-steel blade samples in PC oil, water and air environments are given in Table 4. Considerable improvement was seen in fatigue resistance from water to PC oil and again from PC oil to air.

Seven corrosion inhibitors were selected for fatigue-test evaluation and screening. Specific inhibitors tested included:

1. Cortec VCI-309. This product combines contact and volatile corrosion inhibitors to protect the metal surface. Use over 57°C (135°F) should be avoided. Continuous exposure to temperatures above 40°C (104°F) can result in a 40% reduction in lifetime protection.

Typical Properties:

Vapor pressure at 70°F (mm Hg)	0.0007
Solubility at 70° g/100 g solvent	
in H_2O	10.0
in slushing oil (SUS 65)	<3.0
Appearance	white crystals

Recommended concentrations of VCI-309 for water or aqueous systems range from 0.5% to 2.5%.

These types of inhibitors (VCI, volatile corrosion inhibitors) are amine salts. For analysis of this compound, a sample of VCI-309 was hydrolyzed in dilute hydrochloric acid. The extracted organic acid was identified by infrared analysis to be benzoic acid. Benzoic acid is a relatively strong organic acid that volatizes with steam and sublimes at about 100°C. The amine was considered to be propylamine or hexyldiamine with an equivalent weight by titration of 177. The pH of a 1% solution was 6.3 and the conductivity was 0.0020 mho/cm, indicating ionization.

2. Wrico H-1015. This product is designed for corrosion control and scale retardation in recirculating cooling systems. It is used when pollution-control regulations require a treatment containing no heavy metal regarded as pollutant. Wrico H-1015 is a blend of organic inhibitors with molybdate, polymer, phosphonate and a specific inhibitor for non-ferrous metals. It is a straw-colored mobile liquid weighing 9.8 lb per gallon. Maintenance of 75-400 ppm of treatment is recommended.

3. Wrico H-7654. This product is classified as a non-heavy-metal inhibitor to replace chrome, zinc and phosphate formulae. It is a blend of organic inhibitors that include tolyltriazole. It has a high stability with respect to chlorine and can be used over a broad pH range. Wrico H-7654 is a light-brown liquid with a drummed pH of 12.4.

4. Wrico H-7888. This product is used as an inhibitor in open, recirculating cooling systems. It is a blend of chromate, trizaole, phosphonate and organic additives. It can provide good stability at low chromate levels. Vendor literature describes it as being totally compatible with both non-oxidizing bromides and chlorination programs. Wrico H-7988 is a brown liquid with a drummed pH of 11.9.

5. Penechrome 17. This product is designed for a broad range of water recirculation applications. Penechrome 17 is a dark-brown mobile liquid of zinc chromate and hexavalent chromium, with organic additives. It has a pH of 3.9 in a 1% tap-water solution. Temperature exposure below 0°F will solidify it.

6. Leco. Rust-inhibiting compound, Part No. 811-108. Recommended dilution of this purple liquid is 1 part to 150 parts water.

7. Water-soluble oil. "Pigeon milk," used in machining operations.

The fatigue life of 1095-steel blade samples in the corrosion-inhibiting water-base solutions cited above (using preselected inhibitor concentrations in three tests each) are given in Table 5. Blade fatigue life in PC oil is included in Table 5 for comparison. Four of the seven corrosion inhibitors were found to have potential for water-base slurry MBS wafering application: Wrico H-1015, Wrico H-7654, Penechrome 17 and water-soluble oil. The fatigue life of blade samples in these solutions was found to be greater than that in the PC oil.

The inhibitor concentrations used for initial tests was relatively high. Optimization of inhibitor concentration has continued by use of the fatigue test. Table 6 gives the optimized concentration of inhibitors found so far. Although the optimization listed in this table is not final, the corresponding cost per gallon of MBS vehicle is given (abrasive cost is not shown). The cost of PC oil per gallon is shown for comparison in Table 6. Fatigue-test results for two different inhibitor concentrations and three inhibitor types are compared in Table 7. Reducing inhibitor concentration levels by an order of magnitude from those values shown in Table 5 caused significant reduction in fatigue life.

Wafering Tests

Silicon wafering tests using aqueous-based slurry systems are planned. Further optimization efforts are expected to provide adequate SiC abrasive slurry suspension and lubricity (to minimize blade drag). The addition of methyl cellulose, a water-soluble gel, for abrasion suspension, has been contemplated.

Two Varian 686-type multiblade saws have been renovated, installed and operated at JPL. Four demonstration or learning wafering runs have been made on one machine using standard PC oil and 400- or 600-grit SiC abrasive. Prepinned blade packs of 100, 43, and 25 blades have been used with 8-mil-thick blades and 14-mil spacers. Wafering yields have ranged from about 60% to 90%. The other laboratory saw has been instrumented with closed-loop linear variable differential transformer controls and load transducer for blade-head operation control and readout. This machine will be used for alternative slurry-system research.

CONCLUSIONS

Fatigue test of high-carbon steel blades in several corrosion-inhibitor and water solutions indicate that four solutions have significant potential for water-base slurry MBS wafering application. The cost of these corrosion inhibitor and water solutions is significantly lower than that of PC oil, which is the vehicle presently used in MBS wafering systems.

REFERENCES

1. Holden, S. C., and Fleming, J. R., Slicing of Silicon into Sheet Material, Eighth Quarterly Report, Varian Associates, Lexington Vacuum Division, DOE/JPL 954374-78/1, April 3, 1978.

2. Uhlig, H. H., Corrosion Handbook, John Wiley, New York, 1948.

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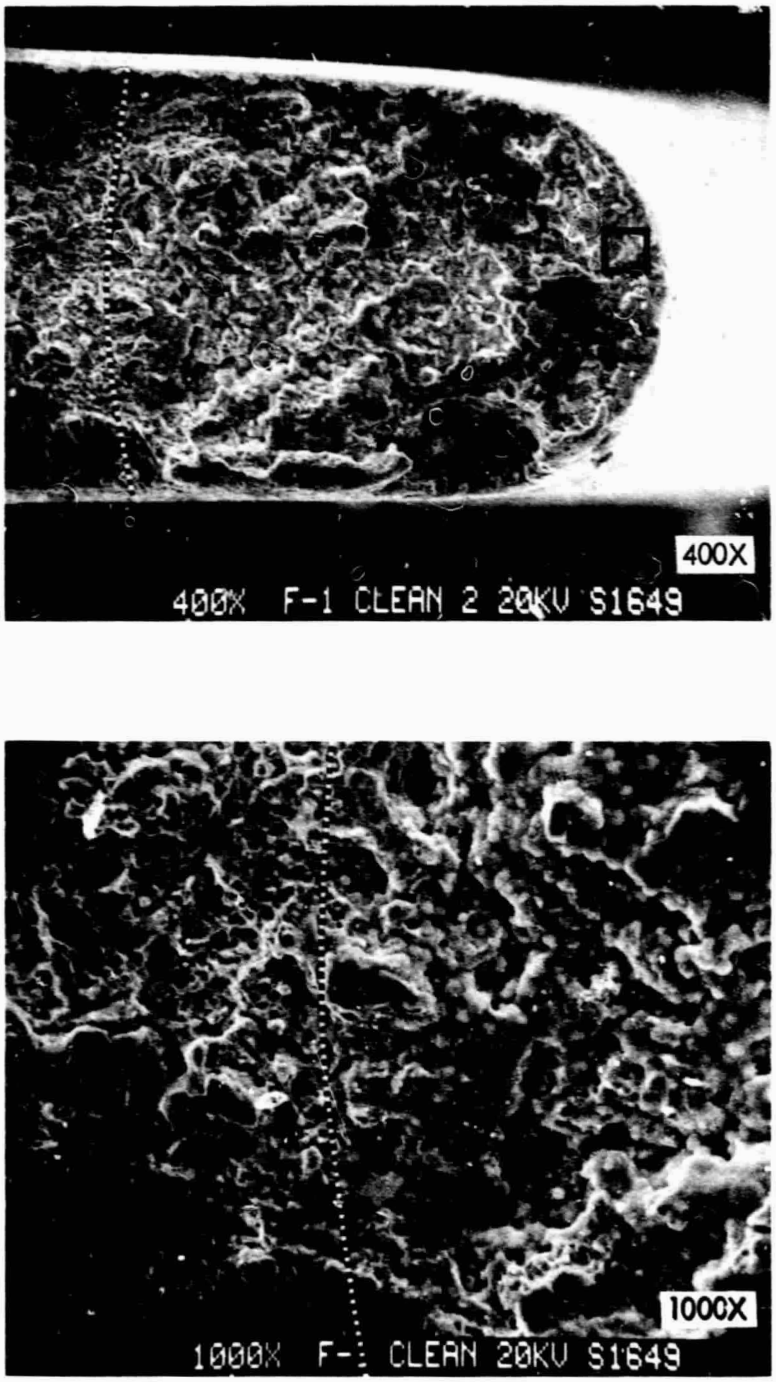

Figure 1. Scanning Electron Micrographs of Sample F-1. Corrosion-Product-Covered Area can be seen to the Left of the Dashed Line in 1(b).

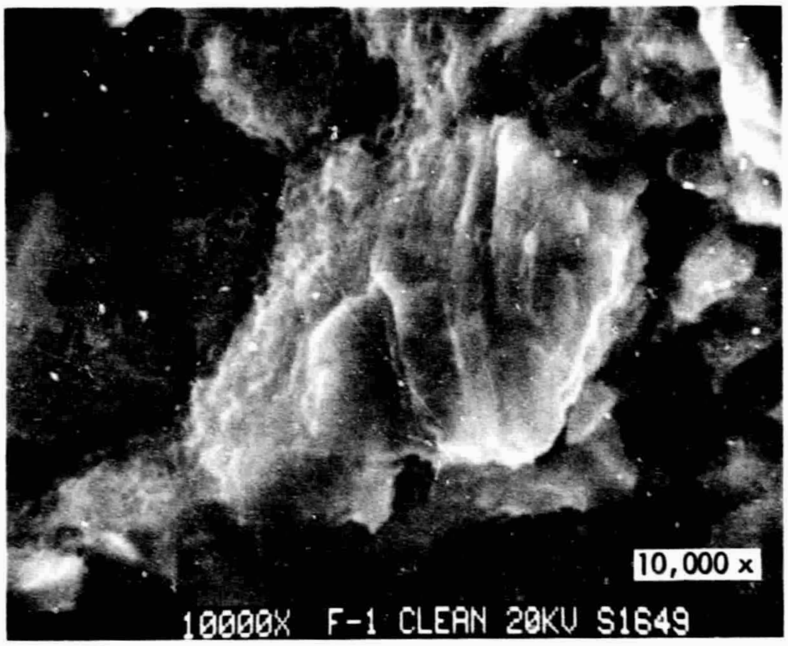

Figure 2. High Magnification Image of Fractured Blade Surface Showing Needle-Like Corrosion Products and Intergranular Nature of Cracking. Water-Base MBS Technique

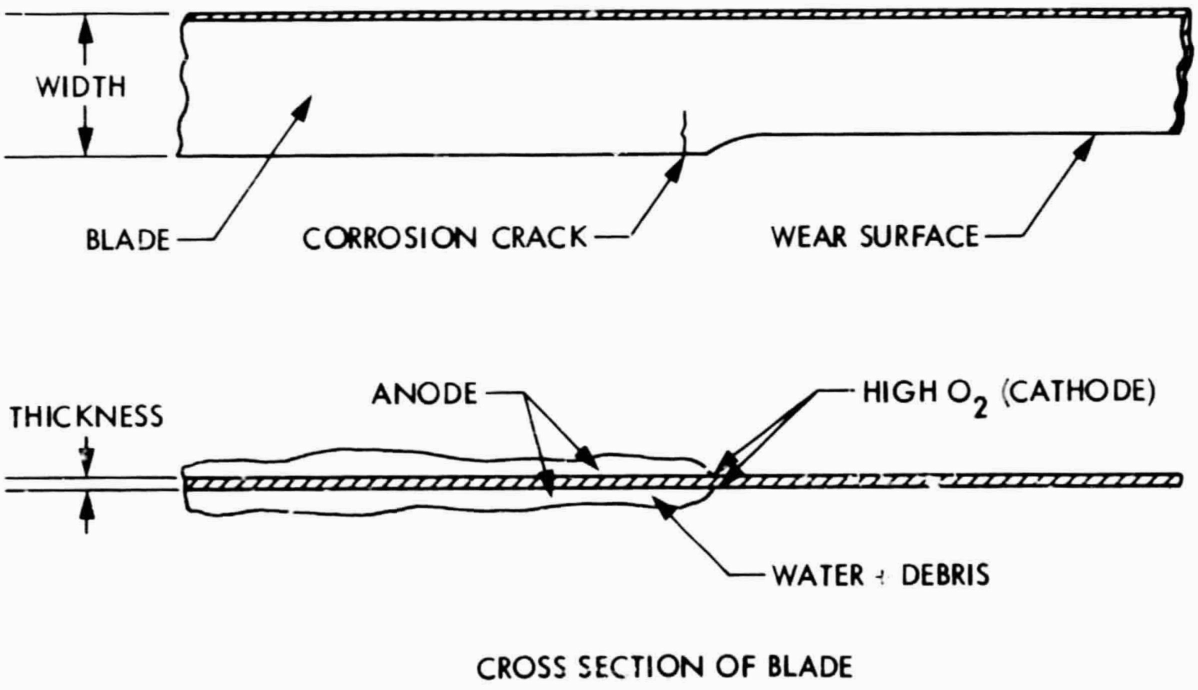

Figure 3. Blade Schematics Showing Location of In Service Failures and How the Oxygen Concentration Cell is Established

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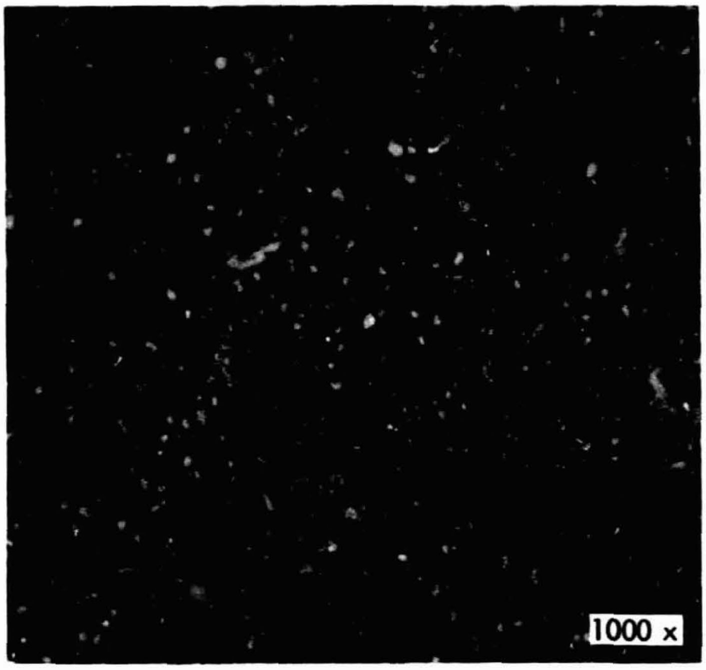

Figure 4. Micrograph of MBS Blade Material

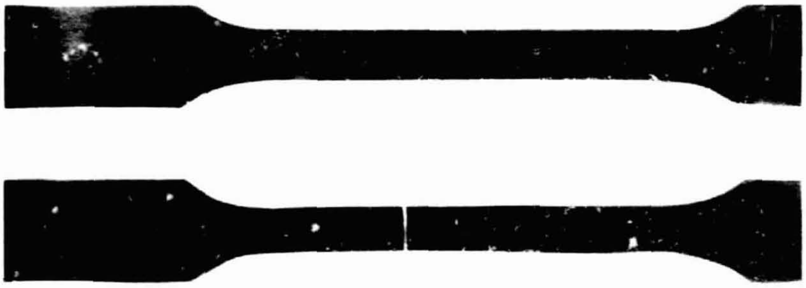

Figure 5. The Typical Configuration of Blade Sample Cross-Section Reduction and a Typical Fatigue Fracture of the Tested Blade Sample

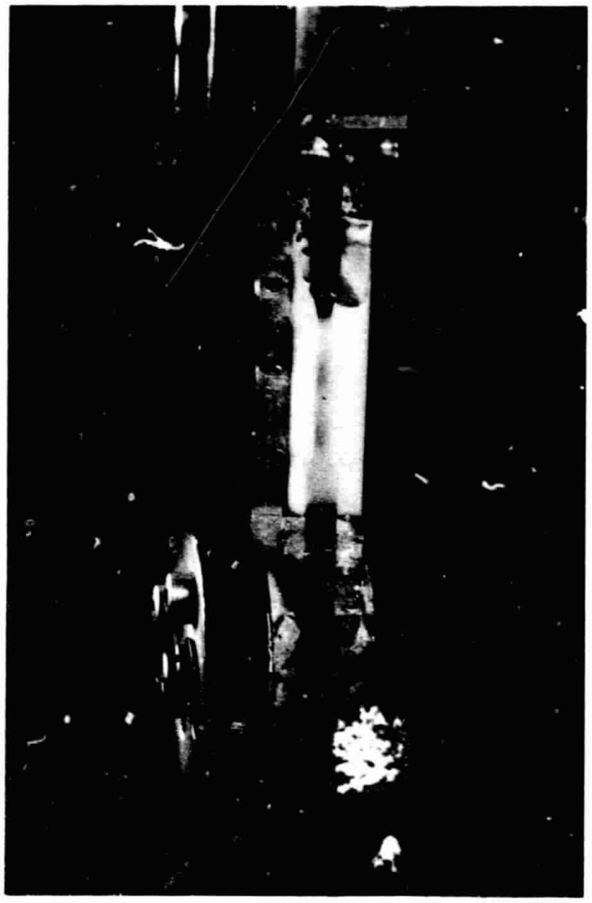

Figure 6. The Controlled Test Environment was Applied to the Test Section of Specimen by Using a Plastic Bag

Table 1. Quantitative Chemical Analysis of Varian Saw Blade by Peabody Testing Services P.O. No. GT 699592 CWO 19 2-5-80

Element	%
Mn	0.39
Si	0.21
P	0.015
S	0.011
Cr	0.15
Ni	0.07
Mo	<0.01
Cu	0.01
C	1.00
Fe	Base
Analysis Indicates Sample is 1095 Steel	

Table 2. Mechanical Properties of 1095 Steel Saw Blade

	As-Received Sample	Section-Reduced Sample
Yield strength (10^3 lb/in.^{2}):	254 (250-259)*	242 (225-269)
Ultimate strength (10^3 lb/in.^{2}):	276 (267-285)	260 (246-293)
Hardness: R_C56 (R_C53-58)		

( )* Showing minimum and maximum measured data of five samples

Table 3. Fatigue Test Conditions

$\sigma_{max} = 0.82\ \sigma_{yield}$

$\sigma_{min} = 0.70\ \sigma_{max}$ (for fatigue test) $\therefore R = 0.7$

Frequency = 10 Hz

Max test duration = 10^6 cycles ($\approx$28 h)

Table 4. Baseline Fatigue Test Results on 1095-Steel Blade Samples

Environment (or Slurry)	Number of Samples	Fatigue Life (Cycles)
PC oil*	3	242,500 203,700 357,200
Water	3	60,000 61,200 55,500
Air	5	All $>10^6$

*PC oil is a petroleum-based vehicle; it can be obtained from Process Research Corp.

Table 5. Fatigue Test Results of 1095-Steel Blade in Tap Water with Corrosion Inhibitors

Inhibitors	Fatigue Life (cycles)	Inhibitors	Fatigue Life (cycles)
PC oil	242,500 203,700 357,160	Wrico H-1015 (1% wt)	$>1 \times 10^6$ $>1 \times 10^6$ $>1 \times 10^6$
Soluble oil (2.5% Vol)	891,370 $>1 \times 10^6$ $>1 \times 10^6$	Penechrome 17 (0.3% wt)	$>1 \times 10^6$ $>1 \times 10^6$ $>1 \times 10^6$
LECO (0.67% Vol)	122,890 $>1 \times 10^6$ 37,500	Wrico H-7654 (0.4% wt)	$>1 \times 10^6$ $>1 \times 10^6$ $>1 \times 10^6$
CORTEC VCI-309 (5% wt)	49,945 $>1 \times 10^6$ $>1 \times 10^6$	Wrico H-7988 (18.1% wt)	210,600 52,700 $>1 \times 10^6$

Table 6. Cost Comparison: Selected Corrosion Inhibitors and PC Oil

Type of Inhibitor	Recommended Concentration	Cost of Slurry* $/gal
Tap water with:		
Soluble oil	2.5% volume	0.066
Penchrome #17	0.3% weight	0.023
WRICO H-7654	0.4% weight	0.046
WRICO H-1015	1.0% weight	0.156
PC oil	100%	5.00**

*Abrasive not included
**Additional wafer-cleaning solvent cost not included

Table 7. Fatigue Test Results of 1095-Steel Blade in Tap Water with Corrosion Inhibitors (Optimization Efforts)

Inhibitors	Fatigue Life (cycles)	Inhibitors	Fatigue Life (cycles)
Wrico H-1015 (1.0% wt)	$>1 \times 10^6$ (3 tests)	Wrico H-1015 (0.04% wt)	79,090
			81,700
			682,110
Penechrome 17 (0.3% wt)	$>1 \times 10^6$ (3 tests)	Penchrome 17 (0.03% wt)	62,470
			166,100
			410,120
Wrico H-7654 (0.4% wt)	$>1 \times 10^6$ (3 tests)	Wrico H-7654 (0.04% wt)	73,370
			72,550

DISCUSSION:

HEIT: Among the parameters for the evaluation of a suitable corrosion inhibitor, I notice the lack of any reference to concern over the effluent from those runs winding up in either a company-controlled or a municipally controlled sewage disposal plant. I would suspect some of the better performers are in the nitrite-chromate category, and they're rough as hell on the sludge.

O'DONNELL: I recognize your concern I guess several of those selected are considered non-heavy metal, non-polluting, as far as some of the requirements of EPA regulations are concerned.

DANYLUK: I'd like to make a comment about your fracture mode and the saw blades. Usually, the intergranular type of failure mechanism has almost always been related to some thermomechanical treatment of the steel. I was just wondering whether you had traced back the thermomechanical history of these individual saw blades.

O'DONNELL: We performed metallographic examination of these steel blades and essentially saw nothing abnormal. We saw the standard amount of martensitic formation, spheroidite-cementite particles. It looked like a fully hardened 1095 steel blade. Nothing abnormal appeared in the microstructure that we could ascertain. Many times some of these high-strength materials will show that type of fracture pattern when there is the evolution of hydrogen at the surface during the corrosion process. It's difficult to rule out the hydrogen embrittlement phenomenon that would also cause this fracture appearance.

DYER: The gist I got out of it was that it was very successful. You got some things that work and make it possible to use a water-base slurry.

O'DONNELL: In our fatigue test method--not real-world conditions, but as close to them as we felt we could get and be able to test a high number of blades and a high number of different corrosion inhibitors and concentrations--we did show significant results, in that four of them show very high promise and have very low cost.

ROSS: They have shown some success with regard to the problem of blade failure, but we're still a long way from water-based slurries in that we have lubricity concerns, we have grit suspension concerns, and we have a lot of drag forces in the system.

O'DONNELL: The one test that we've done in just this [illegible]t week is of suspension. We didn't know if we'd have a lot of settling out, so we ran the pump system with the 2.5% by percent of volume of the soluble oil in water with silicon-carbide abrasive. I believe it was a 2 lb/gal ratio for 20 hours. Essentially we saw no more settling out of silicon carbide than we've seen in the PC oil systems.

LANE: I have question about the motivation for this work. I gather there's a real difficulty in recycling the oil that is a high cost item. Is that correct?

O'DONNELL: It is a high up-front cost per gallon. Jack (Ross) will probably comment more on trying to recycle PC oil. We haven't done any of that, but it is identified as a very high-cost consumable, which we felt we could significantly reduce.

ROSS: That's right. The initial cost of the PC oil was the concern even during the period when Varian was still working on the project. If the PC can be replaced with water, obviously cost would be radically reduced. We have since suggested that reclamation may be the ultimate answer; we've very recently embarked on an investigation of that. I'd say that we've made some significant progress in the past two weeks. We certainly haven't solved the problem yet. The cost of consumables in the MBS system is a major factor in getting the cost down. Not only the oil but the abrasive and the bladepacks also.

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ECONOMICS

Chairman: M. Wolf, University of Pennsylvania

INTRODUCTION:

WOLF: Three years ago I talked with somebody about the labor content in multiblade slicing. I said it really should be about 10 or 20 saws per operator, if possible. The production manager with whom I talked answered, "Not really. With all these wafers I have on the saw there's such a tremendous economic value on each saw that if something starts to go wrong and a girl is close by, she can hear that something starts to go wrong, and she can turn off the machine and adjust it. And she saves all those wafers. But if she's 10 machines away, with all the noise these machines are making, she can't hear what is happening on this machine, and so I lose all the wafers on the machine. And I'd rather pay a few girls a little more and have a few more girls so that one girl is always between two machines and can hear what's going on and make adjustments." He says that's more economical than having more machines per operator. So there are many hidden aspects that can come to the surface with production experience.

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FIELD EXPERIENCE WITH VARIOUS SLICING METHODS

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ABSTRACT

Slicing methods used are internal diameter (ID) saw, multi-blade slurry (MBS) saw and multi-wire slurry (MWS) saw. Slicing parameters inlfuencing final wafer cost are reviewed based on field experience and interaction between the parameters are discussed.

1.0 INTRODUCTION

Substrate preparation in sheet form is a first step in solar cell fabrication. Sheets for silicon solar cells are often prepared from ingots sliced by mechanical means. This slicing step results in loss of silicon (called kerf loss), and this loss adds considerably to the overall cost because already much expense has accrued in forming the ingots. A number of different techniques for slicing silicon have beer tried and some have been limited to production use. Methods tried include:

- Internal or outer diameter (I.D. or O.D.) wheel saw.
- Multiblade saw, using slurry, or diamond particles plated to the blade.
- Spark discharge with wires or blades.
- Pulsed laser discharge.
- Electro-chemical removal with current (etch-cutting)
- Ultra-high pressure (100,000 PSI) water jet.

Among these techniques, the I.D. saw is the most extensively used in industry and is a well developed method for preparing large area sheets from silicon ingots for solar cells. Typical shortcomings of other techniques include excessive taper, unpredictable work damage, low mechanical yield, and lack of machine productivity (mainly because of slow cutting rate). The objective of this paper is to identify slicing parameters influencing wafering cost of silicon ingots for solar sheet materials. Slicing method used were I.D. saw, multi-blade slurry saw (MBS) and multi-wire slurry saw (MWS) with an emphasis on I.D. saw

2.0 SLICING TESTS

Slicing conditions used for both I.D. and MBS saw were chosen based on field experience at ASEC, in such a way that reasonably high wafer yield (~90%) can be obtained reproducibly. MWS slicing was carried out at Yusunaga Engineering Co., LTD. and slicing conditions were chosen to provide reliable operation.

Slicing Conditions

MBS slicing tests were conducted using a Norton 686 wafering machine (same as Varian 686). A pre-assembled blade package from Varian was loaded in the blade head and aligned and tensioned. NOTE; Difficulty in alignment and tensioning, especially in tensioning, forced ASEC to stop using pin type blade packages which are cheaper than pre-assembled blade packages. Detailed slicing conditions are given in Table 1.

A MWS slicing test was performed at Yasunaga Engineering Co., Ltd., useing their YQ-100 wafering machine. Detailed slicing information is given in Table 2.

I.D. slicing was carried out using wafering machines from Silicon Technology Corporation; Model STC-16 for 3" ingots. Table 3 shows slicing conditions used in the test.

Comparison of Wafer Parameters

The parameters obtained from the wafers of three different slicing types, MBS saw, MWS saw, and I.D. saw, were compared for the evaluation of the mechanical quality of the sliced wafers. After the wafers were demounted, degreased and cleaned, thickness, bow and roughness (RMS) were measured. Their average values, standard deviations, and ranges were obtained. Thickness was measured at seven points on each slice using a dial gauge (Mitutoyo, Model DGS-E), one at the center and six at points 120 degrees apart, and an average of these seven points data represented a thickness of a single wafer. Bow is measured by supporting a wafer on three points 120 degrees apart in the periphery. The center position of the slice relative to the three points is defined as bow. Bow was measured by a Brown & Sharp bow gauge. Taper was determined by taking the difference between the maximum and minimum slice thickness measured. Surface roughness (RMS) was measured in parallel to the cutting direction, using a Metro-surf (Model 181. Airtronics, Illinois).

Comparison of the measured parameters for different slicing types is given in Figure 1. Thickness variation, from wafer to wafer and within a single wafer, of the MBS wafer were higher than those of the I.D. saw and MWS saw. Bow and roughness (RMS) also indicated that the MBS saw wafers showed about a factor of two higher values than those with the I.D. saw wafers. In general, comparison of the parameters indicated that the wafers sliced with the I.D. saw and MWS saw had much smaller values and variations, than those with the MBS saw. Wafers sliced by the I.D. saw (cut at or below 2 IPM of cut rate) showed slightly better mechanical quality than those with MWS saw.

Add-On Slicing Cost

Input data for SAMICS were obtained from the slicing experiments performed and the costs were estimated based on SAMICS Workbook (September, 1977). Cost assessment on wire saw slicing was obtained from the information supplied by the manufacturer who did a slicing test.

Add-on slicing cost of three slicing types is shown in Table 4. MBS saw suffered from direct material cost, in which the blade package and slurry (P.C. oil and abrasive) form a major portion of the cost. Direct material cost forms a major portion of MWS slicing, which comes from expensive wire and slurry. Analysis of I.D. saw shows relatively uniform distribution in cost between equipment, direct labor and direct material. High equipment cost is mainly due to low wafer productivity per dollars invested for I.D. saw.

3.0 SENSITIVE SLICING PARAMETERS INFLUENCING WAFER COST

Slicing experience showed that the most important factors controlling final wafer cost are silicon cost (wafer thickness + kerf loss), add-on slicing cost, and finally mechanical yield. Wafer cost can be written in simple expression·

$$W = \frac{M + S}{Y}$$

Where, W: Wafer Cost
M: Material Cost (Silicon)
S: Add-on Slicing Cost
Y: Yield
and, $M = f\,(T + K)$
T: Wafer Thickness
K: Kerf Loss

Most importantly, there is a very strong interaction between these parameters, i.e., an effort to reduce silicon cost by decreasing either wafer thickness or kerf loss, results in increase of add-on slicing cost and reduction in wafer yield.

Slicing parameters for both MBS and I.D. saw influencing these three parameters are given in Table 5 for material (silicon) cost, Table 6 for add-on slicing cost, and Table 7 for yield. The tables show that there is a very strong interaction between the parameters; i.e., an effort to reduce silicon cost by reducing either wafer thickness or kerf loss, results in increase of add-on slicing cost and reduction in wafer yield, suggesting a necessity of optimization between these parameters. This procedure is illustrated in Figure 2, in which silicon cost (M) and add-on slicing cost (S) are shown as a function of wafer thickness and kerf loss. Final wafer cost is an addition of M and S, and cross mark (X) indicates minimum wafer cost. NOTE: Yield is considered in the figure.

4.0 CONCLUSION

Wafer parameters such as bow, taper, and roughness which may not be important factors for solar cell fabrication, were considerably better for I.D. saw than those of the MBS and MWS saw.

Analysis of add-on slicing cost indicated that machine productivity seems to be a major limiting factor for I.D. saw, while expendible material costs are a major factor for both MBS and MWS saw.

Slicing experience indicated that the most important factors controlling final wafer cost are 1) silicon cost (wafer thickness + kerf loss), 2) add-on slicing cost,and 3) mechanical yield. There is a very strong interaction between these parameters, suggesting a necessity of optimization of these parameters.

ACKNOWLEDGEMENT

The work described was supported by the Low Cost Solar Array Project of the Jet Propulsion Laboratory by agreement between NASA and DOE.

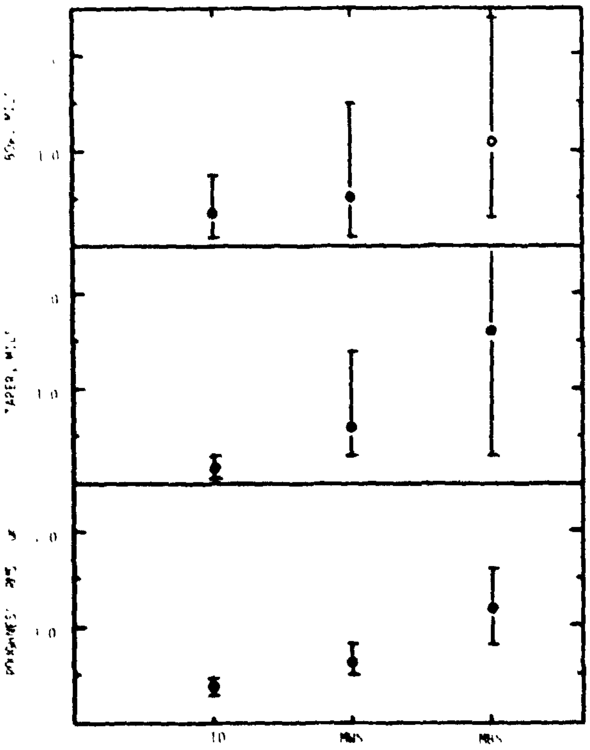

FIGURE 1

PARAMETERS OF WAFERS SLICED BY THREE DIFFERENT SLICING METHODS

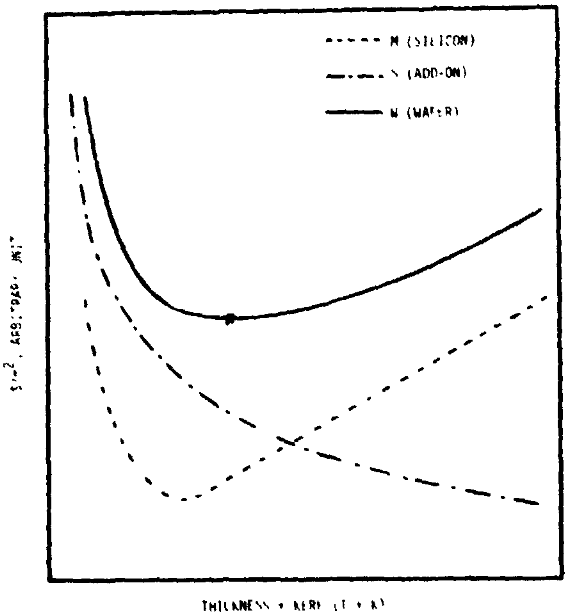

FIGURE 2

AN ILLUSTRATION OF FINDING AN OPTIMUM WAFER COST

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TABLE 1

MBS SAW SLICING CONDITIONS

BLADE PACKAGE	
Number of Blades	230
Spacer Thickness, mm (mils)	0 457 (18)
Blade Thickness, mm (mils)	0 203 (8)
Blade Width, mm (inch)	6.35 (¼)
SLURRY	
Abrasive (400,SiC), Kg (lb)	5 4 (12)
Suspension Oil (P.C Oil), liter (gallon)	6 2 (1.8)
Mix, kg/liter (lb/gallon)	0 79 (6.7)
Load on Blade, gram/blade	100
Blade Speed, cm/sec.	57
Wear Ratio	---
PRODUCTIVITY (WAFER)	
cm^2/Machine/Hour	1,005
cm^2/Blade/Hour	4,33

TABLE 2

MWS SAW SLICING CONDITIONS

WIRE	
Roller Pitch, mm (mils)	0 47(18.5)
Diameter of Wire, mm (mils)	0.16(6 3)
Number of Wires Under Cutting	163
Mean Unit Weight, g/cm/wire	13
Total Wire Tension, kg	1 7
Breaking Point of Wire, Kg	5 7
Wire Feed Rate, m/min	8
Reciprocation of Wire, Cycle/min.	65
Wears of Wire, um	12
SLURRY	
Abrasive, GC #1000 (16um) Kg	5
Lapping Oil, P C Oil, Kg	3
Wafer Thickness, mm (mils)	0 27(10 6)
Kerf Width, mm (mils)	0 20(7 9)
Slicing Time Hours	8 35
Mechanical Yield, %	97
Yielded Wafer Area, m^2	0 72
Productivity, cm^2/machine/hour	840

TABLE 3

I.D.SAW SLICING CONDITIONS

BLADE		
I.D., cm (inch)	15.24 (6)	
O D., cm (inch)	42.23(16-5/8)	
Core Thickness, mm (mils)	0.10 (4)	
Diamond Thickness, mm (mils)	0 28 0.30(11-12)	
Blade Rotation, R.P M	2,100	
Blade Return Speed, cm/min (inch/min)	38 1(15)	
Blade Stroke, cm (inch)	8 13(3 2)	
Blade Dressing, After Number of Slices	50	
COOLANT		
Flow Rate, l/min	120	
Mix Ratio, Water Rust-Lick	80 1	
Cut Rate, Inch/Minute	1	2
Slicing Cycle, Minute/Wafer	3 4	1 8
Productivity(wafer), cm^2/Machine/Hr	800	1,510

TABLE 4

ANALYSIS OF ADD-ON SLICING COST (SAMICS, 1977 DOLLARS) OF THREE INCH CZ INGOT. (PARENTHESIS NUMBERS IN UNIT OF $/m^2).

	MBS		MWS		I.D.	
	$/Wafer	%	$/Wafer	%	$/Wafer	%
EQUIPMENT	0.066	8.2	0.091	10.7	0.060	34.3
SPACE	0.029	3.6	0.028	3.3	0.030	17.1
DIRECT LABOR	0.158	19.6	0.197	23.2	0.044	25.1
DIRECT MATERIALS	0.552	68.6	0.531	62.6	0.039	22.3
UTILITIES	0.001		0.001	0.2	0.002	1.2
TOTAL	0.806 (177)	100	0.848 (186)	100	0.175 (38)	100

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TABLE 5

SLICING PARAMETERS INFLUENCING WAFER THICKNESS AND KERF LOSS

	MBS SAW	I.D. SAW
WAFER THICKNESS	INGOT DIAMETER CUT RATE BLADE PACKAGE - Spacer Thickness - Number of Blades - Alignment and Tensioning SLURRY - Abrasive Size - Density of Abrasive in Suspension Oil	INGOT DIAMETER CUT RATE BLADE - Tensioning
KERF LOSS	BLADE PACKAGE - Spacer Thickness - Number of Blades - Alignment and Tensioning SLURRY - Abrasive Size - Density of Abrasive in Suspension Oil	BLADE - Thickness of Diamond Plated Edge Tensioning MACHINE Accuracy of Travel Between Blade and Ingot

TABLE 6

SLICING PARAMETERS INFLUENCING ADD-ON SLICING COST

	MBS SAW	I.D. SAW
EQUIPMENT	CUT RATE BLADE PACKAGE - Number of Blades	CUT RATE
DIRECT LABOR	BLADE PACKAGE - Alignment and Tensioning INGOT - Mounting and Demounting DEGREASE - Sliced Wafers OPERATOR ATTENTION	BLADE Tensioning - Dressing INGOT - Mounting & Demonting CLEANING - Sliced Wafers OPERATOR ATTENTION
DIRECT MATERIALS	BLADE PACKAGE SLURRY - Abrasive - Suspension Oil DEGREASER - SOLVENT INGOT MOUNT	BLADE INGOT MOUNT COOLANT

TABLE 7

SLICING PARAMETERS INFLUENCING MECHANICAL WAFER YIELD

MBS SAW	ID SAW
INGOT DIAMETER WAFER THICKNESS - Spacer Thickness CUT RATE - Travel Speed - Load on Blade BLADE PACKAGE - Thickness of Blade - Number of Blades - Alignment and tensioning INGOT MOUNTING WAFER DEMOUNTING - Handling (slippery) OPERATOR'S SKILL - Blade Alignment and Tensioning - Special attention of last moment of cutting	INGOT DIAMETER WAFER THICKNESS CUT RATE BLADE AND HEAD - Core Material - Diamond Plating Condition - Dressing - Blade History - Tensioning - Accuracy of Travel between blade and ingot - Relative vibration between blade edge and ingot (centering) INGOT MOUNTING OPERATOR'S SKILL - Blade Mounting (Alignment and Tensioning) - Blade Dressing

DISCUSSION:

WOLF: I'll make one comment at this point, to keep the multiblade and multiwire people from walking out. I have found that the best performance of a machine is usually obtained in a real production environment. Often the manufacturers of the equipment themselves don't get the best performance out of their equipment because they don't get the experience in running it. There's always an exception to these generalizations, but this is frequently the experience.

This seems to be a general thing. People take time learning with a particular piece of equipment, and find out how to use it right. They make modifications on equipment frequently, to make it easier to use, to get better yield and so on. It's often very difficult, therefore, to make exact comparisons between methods because we often don't find out exactly what the experience is of the people who really have it down pat and are running it day in and day out under all optimized conditions. So I think we have to, in these comparisons, be a little bit careful with how we use these numbers.

N82 23666 D6

SOME TRADEOFFS IN INGOT SHAPING AND PRICE OF SOLAR PHOTOVOLTAIC MODULES

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ABSTRACT

Conventionally, silicon sheet is produced by growing single-crystal ingots from semiconductor-grade polysilicon and slicing them into wafers. Wafers are processed to make solar cells and, after interconnection in strings, are encapsulated to form a working module.

Growth of round ingots is cost-effective for sheets but leaves unused space when round cells are packed into a module. This reduces the packing efficiency, which approaches 95% for square cells, to about 78%. This reduces the conversion efficiency of the module by the same ratio. Shaping these ingots into squares with regrowth of cut silicon improves the packing factor, but increases growth cost.

By considering shaping ingots in stages from full round to complete square, a study of the cost impact on solar cell modules has been made. The sequence of module production with relevant price allocation guidelines is outlined. The effect of silicon utilization on sheet price is illustrated. Trade-offs due to shaping of ingot are discussed. Sheet and module prices are calculated for various slicing and material utilization scenarios. Effect of balance of system is outlined.

INTRODUCTION

The objective of the Low-Cost Solar Array (LSA) Project is to develop technologies for achieving a goal of \$0.70/peak watt (W_p)* for flat-plate photovoltaic modules by 1986. The working module evolves from silicon material formed into sheets. Conventionally, it is produced by growing cylindrical single-crystal ingots using Czochralski growers and slicing the ingot into circular wafers. These wafers are then processed to produce photovoltaic cells and are interconnected in close-packed flat strings with series-parallel combinations for electrical output. Encapsulation and module assembly is then done to provide rigidity, reliability and long life.

The price goal of \$0.70/W_p is broken down for each stage of module manufacture in Reference 1, based on performance criteria of material usage, process yields, efficiencies, etc., expected to be achieved during technology development.

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*All figures are in 1980 dollars.

Conversion efficiency of a module is important in determining its price. When packed, circular cells leave spaces that reduce module efficiency in direct ratio. Shaping ingots into square cross-sections, and recycling trimmed silicon, improves packing density but increases ingot growth cost. Other factors, such as cost of slicing circular vs square wafers, achievable thickness of wafers, and amount of kerf loss also affect the cost.

Sequence of Module Production

Multiple single-crystal Czochralski (Cz) ingots, of 15-cm. dia., can be grown from a single crucible with a growth yield of 92% to 94%. The resulting ingots are generally cropped at the seed and the tang end and are ground to uniform-diameter cylinders. Cropping and grinding yields of 85% to 90% are achievable.

Slicing of the ingot into wafers 10 to 15 mils thick (d), with kerf loss (k), of 6 to 12 mils gives a material utilization of about 15 to 25 wafers/cm of ingot length. Wafer breakage during this operation results in a slicing yield of 95%, which translates into 0.6 to 1.0 m^2/kg (corresponding to $d + \kappa$ of 27 to 16 mils). This results in a combined silicon-to-wafer yield (Y_{sh}) of about 81%. A similar loss of cells during processing with 95% cell yield (Y_c) and subsequent 99.5% module yield (Y_m) is expected.

These circular cells, when interconnected and arranged flat in a module, leave areas between cells. This results in a packing efficiency, (η_p) of only about 78%. Thus, the encapsulated cell efficiency (η_e) of 15% would give a module efficiency ($\eta_m = \eta_e \cdot \eta_p$) of 11.7%. Square cells on the other hand, can be closely packed, leaving very little unused sp The value of η_p then approaches 95% with the module efficiency η_m increasing to 14.25%.

Table 1 gives relevant projected price breakdowns and the criteria for Cz-type of photovoltaic (PV) modules.

Ingot Diameter, Growth, and Slicing

As seen from Table 1, the add-on price allocation for ingot growth and slicing is $\$27.4/m^2$. Growth cost in \$/kg can be reduced by increased throughput obtained by increasing ingot diameter.

Economic analysis for growth of different diameter ingots indicates the possibility of achieving add-on price as given in Table 2 (Reference 2). This analysis assumes multiple ingot growth from a single crucible. Estimates based on various slicing results (Reference 3) show that for a 10-cm-dia or a 10-x-10-cm cross-section ingot, material utilization of 25 slices/cm of ingot length is obtained (d + k = 16 mils). However, for a 15-cm-dia ingot, 17 slices/cm ingot length only has been achieved (d + k = 23 mils).

Table 1. Price Allocation Guidelines for Cz-Type PV Module

Price Allocations (add-on)	Silicon	\$/kg	14.0		
		\$/W$_p$		0.126	
	Sheet	\$/m^2	27.4		Ingot diameter 15 cm d + k 17.5 mils (slices/cm. 22.5)
		\$/W$_p$		0.193	Y_{sh} 0.810
	Cell	\$/m^2	21.0		
		\$/W$_p$		0.141	Y_c 0.950
	Encapsulation material	\$/m^2	14.0		η_p 0.780
		\$/W$_p$		0.120	η_e 0.150
	Module assembly	\$/m^2	14.0		Y_m 0.995
		\$/W$_p$		0.120	η_m 0.117
Goal	Module price	\$/W$_p$		0.700	

Table 2. Growth Prices for Ingots of Different Diameters

Ingot diameter (cm)	Add-on Growth Price (\$/kg)
10.0	28.00
11.0	25.14
12.0	22.28
13.0	19.42
14.0	16.56
15.0	13.70

Effect of d + k on Price Allocation

Because variation of d + k affects material use, it must influence the silicon material price and the growth price. The add-on price allocation for a sheet of \$27.4/m^2 can be divided equally between growth and slicing for the given d + k of 17.5 mils (Table 1). A 95% slicing yield then gives a sheet conversion of 0.92 m^2/kg of ingot, requiring a growth add-on of

$12.6/kg. With this price of growth, the effect of variation of d + k on allowable slicing price is shown in Figure 1. It shows a material price of $17.9/m^2 ($Y_{sh}$ = 81%) with an add-on sheet price of $27.4/m^2 split equally between growth and slicing, for 22.5 slices/cm of ingot length. Corresponding values of d + k (in mils) are also given for ease of conversion. For a total sheet price (including silicon material cost) of $45.3/m^2, the allowable slicing cost reduces drastically for increasing d + k. Thus, e.g., at 17 slices/cm (d + k = 23 mils), the price goal can be met only if the slicing cost is brought down to $3.30/m^2. If, however, one can achieve at least 20 slices/cm, a slicing cost of about $10/m^2 is able to meet the allocated price of the sheet.

Shaping

One way to avoid this high penalty for larger d + k would be to shape the larger diameter ingot into a square cross section of reduced dimensions. This would result in reduced d + k. However, the cut-away silicon will have to be regrown as ingot with additional expense. There will be a tradeoff between regrowth cost of shaved-off silicon and the savings due to reduced d + k and improved packing factor.

As shown in Figure 2, circular ingot of diameter D can be shaped anywhere from full circle (no shaping) to a complete square with parallel faces C a distance D/ 2 apart. The four hatched areas of cut-away ingot are recycled silicon, given by

$$X = D^2 \cos^{-1}\left(\frac{C}{D}\right) - C\sqrt{\left(D^2 - C^2\right)} \qquad (1)$$

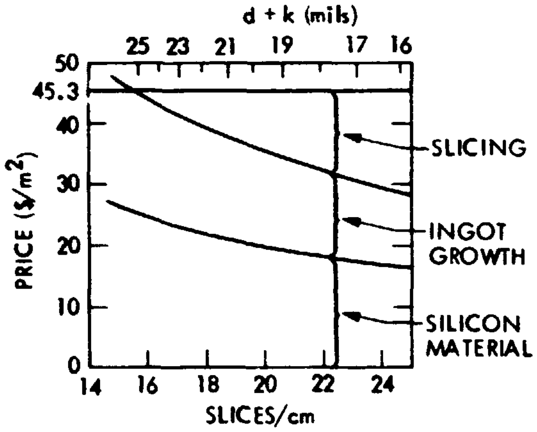
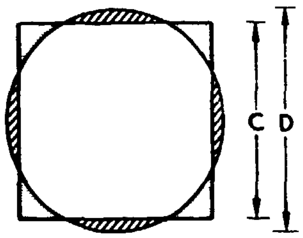


Fig. 1. Effect of Material Utilization on Ingot Growth and Slicing



▨ $X = D^2 \cos^{-1}\left(\frac{C}{D}\right) - C\left(\sqrt{D^2 - C^2}\right)$

☐ $Y = C^2 - C\left(\sqrt{D^2 - C^2}\right) - D^2\left(\frac{\pi}{4} - \cos^{-1}\frac{C}{D}\right)$

$\eta_p = 0.95 - \frac{Y}{C^2}$

Fig. 2. Calculation of Recycled Silicon and Packing Factor with Ingot Shaping

The cross-hatched areas contribute to the modification of the packing factor. This is given by

$$Y = C^2 - C\sqrt{\left(D^2 - C^2\right)} - D^2\left(\frac{\pi}{4} - \cos^{-1}\frac{C}{D}\right) \tag{2}$$

and the resulting packing factor as

$$\eta_p = 0.95 - \frac{Y}{C^2} \tag{3}$$

For a solar insolation I (1000 W/m^2), a general relationship between $\$/W_p$ and $\$/m^2$ is obtained as

$$(\$/m^2) = (\$/W_p)\cdot I\cdot\eta\cdot Y \tag{4}$$

where η and Y refer to the conversion efficiency and the process yield, respectively. Table 3 lists formulas used in this analysis.

Improved Packing and d + k versus Recycled Silicon

For a given parallel face distance C, the ingot diameter can be varied from D = C to D = 2.C. For a given C, the value of d + k is obtained by linear interpolation, with the end values fixed as 16 mils for C = 10 cm, 20 mil for C = 15 cm. By comparing the new allowable add-on sheet price to the new growth price, inclusive of recycled silicon, the advantage due to shaping is obtained as shown in Figure 3. For a given C, say 10 cm, the ingot growth add-on decreases with an increase in D (see Table 2). Further, the allowable sheet price increases due to better packing. Thus, a 12-cm-dia ingot gives a price advantage of about $\$6/m^2$ with η_p of 0.91. However, beyond a 12-cm-dia the growth cost reduction is compensated by increased recycling of silicon, and the advantage is lost. A maximum cost saving of nearly $\$8/m^2$ is obtained for a 15-cm-dia ingot with shaping, given C = 12 cm and η_p = 0.92.

Slicing Cost

The cost of slicing greatly depends upon cross-sectional dimensions of the ingot being cut. Three different cost scenarios are considered in the present analysis:

Case (i): For an ingot with larger cross-sectional dimensions, the slicing speed may be lower and the blade life may be inferior. The cost of the machine may also be higher than that for an ingot with smaller dimensions. Based on these assumptions the add-on slicing cost will increase with increasing C [Figure 4, Case (i)].

Case (ii): The parameter may be adjusted so a constant add-on cost may be attainable regardless of ingot dimensions [Figure 4, Case (ii)].

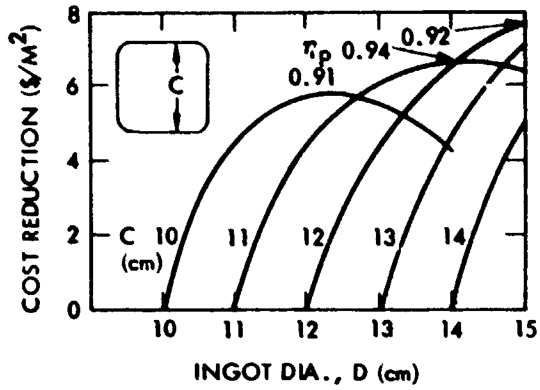


Fig. 3. Cost Saving Due to Shaping as a Function of Ingot Diameter

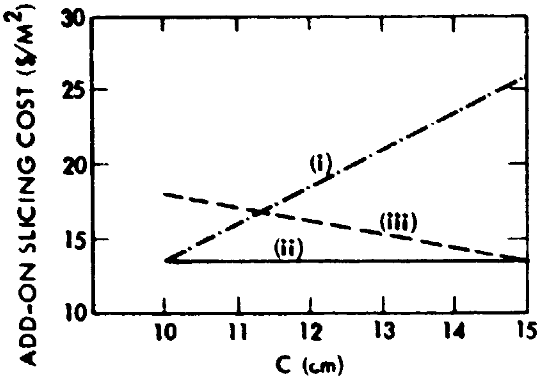


Fig. 4 Three Scenarios of Slicing Cost as a Function of Depth of Cut, C

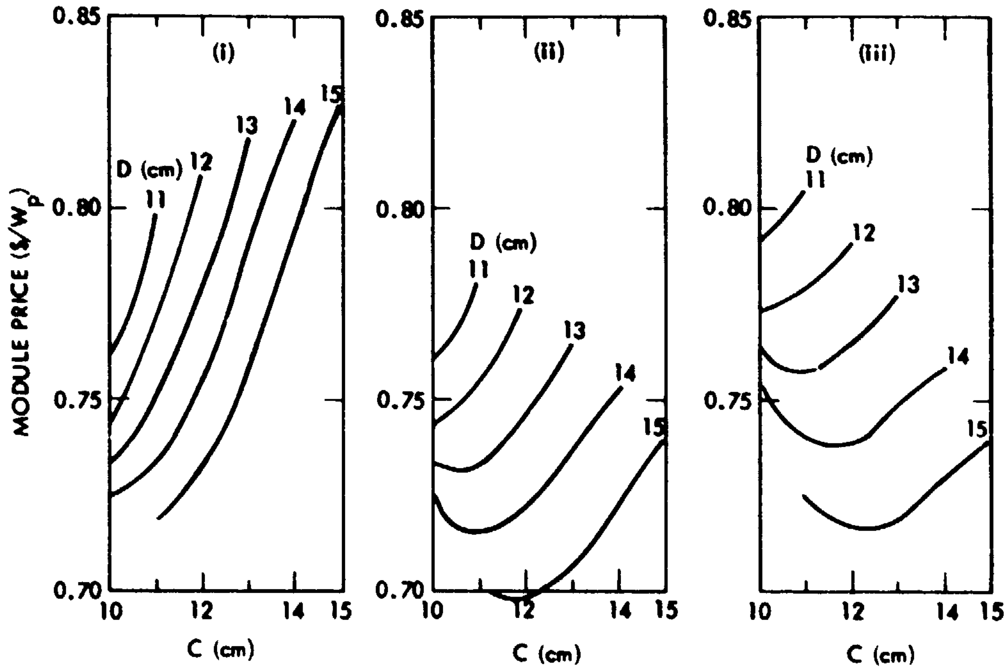


Fig. 5. Module Price as a Function of C for the Slicing Scenarios, Cases (i), (ii), and (iii), of Figure 4

Case (iii): With proper development efforts, increased blade life and slicing rate can be achieved. Automation will result in reduced labor cost. Thus, increased throughput due to larger diameter will result in reduced add-on slicing cost [Figure 4, Case (iii)].

In addition, a rough estimate of shaping cost, based on IPEG analysis (Reference 4) using an outer diameter (OD) saw, gives an add-on cost of \$1.80/m of ingot length. This can be done by one blade, or two parallel blades, with the ingot rotated 90° after completion of each cut.

Figure 5 shows the module price in $\$/W_p$ for the three slicing scenarios. The price of the module is least for the largest-diameter ingots. As expected, Case (i) shows maximum advantage due to shaping of a 15-cm-dia ingot to a

Table 3. List of Formulas

Module Price	$\$/W_p$ (module)	p_m
	$\$/m^2$ (module)	$P_m = p_m \cdot I \cdot \eta_m$
Encapsulation Materials Add-on	$\$/m^2$ (module)	C_{m1}
	$\$/W_p$ (module)	$c_{m1} = C_{m1}/I \cdot \eta_m$
Module Assembly Add-on	$\$/m^2$ (module)	C_{m2}
	$\$/W_p$ (module)	$c_{m2} = C_{m2}/I \cdot \eta_m$
Cell Price	$\$/m^2$ (cell)	$P_c = \left[P_m - \left(C_{m1} + C_{m2}\right)\right] Y_m/\eta_p$
	$\$/W_p$ (module)	$p_c = p_m - \left(c_{m1} + c_{m2}\right)$
Cell Fabrication Add-on	$\$/m^2$ (cell)	C_c
	$\$/W_p$ (module)	$c_c = C_c \cdot \eta_p/I \cdot \eta_m \cdot Y_m$
Sheet Price	$\$/m^2$ (sheet)	$P_{sh} = \left(P_c - C_c\right) Y_c$
	$\$/W_p$ (module)	$p_{sh} = p_c - c_c$
Silicon Price	$\$/m^2$ (sheet)	$C_{si} = [0.0591 \cdot (d + k) \cdot Si]/Y_{sh}$ Si is silicon price, \$/kg
	$\$/W_p$ (module)	$c_{si} = C_{si} \cdot \eta_p/I \cdot \eta_m \cdot Y_m \cdot Y_c$
Sheet Add-on	$\$/m^2$ (sheet)	$C_{sh} = P_{sh} - C_{si}$
	$\$/W_p$ (module)	$c_{sh} = p_{sh} - c_{si}$

complete square of $C \approx 11$ cm. Cases (ii) and (iii) show that in general there will be a value of C between full circle and full square, resulting in minimum module price. A saving of about 2 to 10 ¢/W_p is obtainable by shaping, depending upon the slicing scenario used.

A similar calculation is done for a 15-cm-dia ingot with two different d + k values at C = 15 cm of 24 mils and 20 mils. However, the d + k value is kept constant at 16 mils for C = 10 cm. Linear interpolations have been done for intermediate C values for both cases. The resulting module prices are shown by the two curves in Figure 6. This shows that the module price will be higher for larger d + k as expected, but the advantage of shaping will be even greater.

Array Installation

Increased packing factor and the consequent improved module efficiency has an added advantage when array installation costs are considered (Reference 5). Thus, a 10% efficient, \$0.70/W_p module will need \$0.60/W_p add-on for a \$60.0/m^2 array installation, resulting in a total installed price of \$1.30/W_p. With the same total array installed price of \$1.30/W_p, one could afford to pay more than \$0.70/W_p for the module if its efficiency is greater than 10%. The module price, p_m, in \$/W_p would then be shown as:

$$p_m = 1.30 - 60/I \cdot \eta_m \tag{5}$$

Based on this premise, Figure 7 shows the savings (p_m - module price per watt with shaping) as a function of C with D as a parameter. Considerable saving is obtained with ingot shaping for all values of D from 10 cm to 15 cm. A maximum advantage of about 15¢/W_p is achievable by squaring a 15-cm dia ingot.

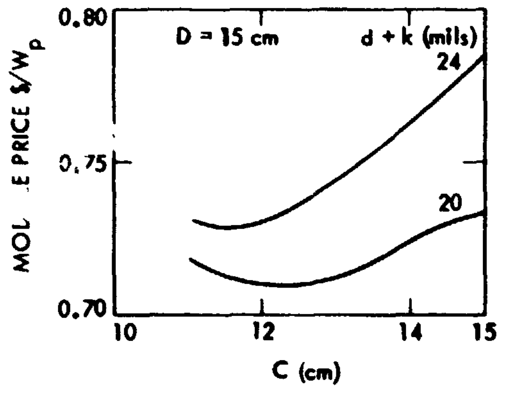


Fig. 6. Effect of d + k and Shaping on Module Price

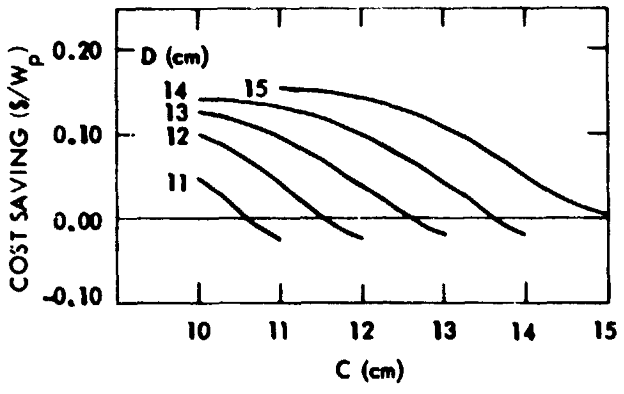


Fig. 7. Effect of Array Installation and Shaping on Module Price

DISCUSSION

Shaping ingots for solar photovoltaic modules affect module price in various ways. Slicing thinner pieces and reducing kerf saves polysilicon material and reduces the ingot growth cost. Similarly, improvement in packing factor reduces encapsulation cost. These cost benefits are, however, offset to a certain extent by regrowth cost of cut silicon and the shaping costs involved. Additional cost benefits occur in the balance of the system because of a more efficient module.

There may be other advantages of shaping, such as ease in slicing of multiple ingots and processing of square cells, etc. Incomplete squares with rounded corners may have the advantages of less chipping of corners during slicing and available spaces for interconnects.

Cost reduction in slicing of large-diameter ingots may make shaping less attractive. High shaping costs and poor ingot growth yields will also have a similar effect.

CONCLUSION

The severe penalties in add-on price due to increasing slice thickness and kerf are presented. Trade-offs between advantages of improved packing efficiencies and material use and disadvantages of recycling silicon and shaping costs are developed for different slicing scenarios. It is shown that shaping results in cost saving of up to 21% for a 15-cm dia ingot.

ACKNOWLEDGMENT

The author wishes to thank K. M. Koliwad, M. H. Leipold, and J. K. Liu for helpful discussions. Discussions with A. H. Kachare and A. D. Morrison are also acknowledged. T. McConnell's help in some of the computations is also appreciated.

REFERENCES

1. Aster, R.W., Price Allocation Guidelines January 1980, DOE/JPL-1012-47, January 15, 1980.

2. Leipold, M.H., Radics, C., and Kachare, A., Cost of Czochralski Wafers as a Function of Diameter, DOE/JPL-1012-37, February 15, 1980; LSA Project Progress Report 17, DOE/JPL-1012-54, September 1980 to February 1981, pp. 180-185.

3. LSA Project Progress Report 17, DOE/JPL-1012-54, September 1980 to February 1981, pp. 211-221.

4. LSA Project Progress Report 14, DOE/JPL-1012-42, August to December 1979, pp. 355-357.

5. Wolf, M., private communication.

DISCUSSION:

SCHMID: What kind of cost did you assume for the actual shaping itself, which would probably be a band-sawing operation?

DAUD: I did a rough IPEG, and compared it with the grinding. I came out with about $1.80 per meter length of the shaping. That's what I have assumed here.

ROBERTS: What effect do you think that shaping of the ingot is going to have on edge-chip and surface damage and so forth?

DAUD: Depending upon what kind of mask you are using, you may be able to accommodate slight variation in the edge chipping. Another thing I have not included is the etching of the silicon that is cut and which is to be regrown. If you include that cost, the picture may be a little different.

WOLF: I would like to mention that this is really not new technology. In the fabrication of space cells in the early 60s, this was done. At the time, about 2-1/2-inch-diameter ingots were grown that did not have regular diameter, and the cells fabricated were usually 2-x-2-centimeter and 1-x-2-centimeter. What existed at the time were templates that production girls could hold over the ingots, and see how many 2-x-2s and 1-x-2s they could cut out of it. Then the ingot was sectioned length-wise into 2-x-2 and 1-x-2 sections, and the outside parts of the ingots were etched and remelted in the next load in the crystal pulling furnace. The square and rectangular sections were then sliced, at that time on OD slicing machines, later on multi-blade slicing machines. So this is a practical technology.

ILES: I think the conclusions are good; I think you should include the practical case for modules where normally we use textured glass and reflecting back surface to somewhat offset that low packing density. It goes from 78%, to something like 85% or 88% effective packing density because of back reflection from bottom of the textured glass back onto the cells. I think at least for the next year or two that looks like it's sort of standard technology.

SENSITIVITY ANALYSIS OF ADD-ON PRICE ESTIMATE FOR SELECT SILICON WAFERING TECHNOLOGIES

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ABSTRACT

Silicon sheet technology is being developed for the Low-Cost Solar Array (LSA) Project, sponsored by the U.S. Department of Energy. One way of producing silicon sheet is to grow ingots from polysilicon, either by the Czochralski (Cz) process or by casting, and slicing the ingots into wafers.

In order to achieve the LSA price goal of \$0.70/W_p, the price allocation for Cz ingot growth plus slicing is \$27.4/m^2 for circular wafers. The price allocation for cast ingot plus slicing is \$36.3/m^2 for square or rectangular wafers. The cost of producing wafers from silicon ingots is a major component of the add-on price of silicon sheet. Wafering technology therefore needs considerable improvement in order to meet the price goals.

Presently, internal-diameter (ID) sawing, multiblade slurry (MBS) sawing and fixed-abrasive slicing technique (FAST) are the three wafering methods being developed by the LSA Project.

Economic analyses of the add-on price estimates and their sensitivity for the ID, MBS, and FAST processes are presented. Interim Price Estimation Guidelines (IPEG) are used for estimating a process add-on price. Sensitivity analysis of price is performed with respect to cost parameters such as equipment, space, direct labor, materials (blade life) and utilities, and the production parameters such as slicing rate, slices per centimeter and process yield, using a computer program specifically developed to do sensitivity analysis with IPEG. The results aid in identifying the important cost parameters and assist in deciding the direction of technology development efforts.

INTRODUCTION

The Low-Cost Solar Array (LSA) Project, sponsored by the U.S. Department of Energy, is developing the technology for manufacturing photovoltaic modules. Project goals are to achieve technical readiness by 1982 and commercial readiness by 1986, by producing modules at the price of \$0.70/W_p (1980\$).

Developing the technology for producing large-area silicon sheets (LASS) is one of the project tasks. One approach is to grow molten polysilicon as ingots, using the Czochralski (Cz) method or casting processes such as the heat-exchanger method (HEM) with directional solidification, and to slice the ingots into wafers. The three wafering techniques that are being developed by the LASS Task are: (1) internal-diameter slicing by ID saw,

(2) the multiblade slurry (MBS) technique and (3) multiple-wire fixed-abrasive slicing technique (FAST). The economic analysis of the add-on price estimates for these wafering techniques, in the light of the LSA Project goals, is of particular interest in this study.

In order to achieve the module price goal, the price allocation for Cz ingot growth plus the slicing process is $\$27.4/m^2$ for circular wafers, and the price allocation for cast-ingot growth plus slicing is $\$36.3/m^2$ for square or rectangular wafers (Reference 1). Distributing the allocation equally between the two processes, the growth cost will be $\$14.m^2$ for Cz and $\$18/m^2$ for cast ingot. Assuming wafering at the rate of 25 slices/cm, the allocation for growth is \$14/kg for Cz ingot and \$18/kg for cast ingot, as the conversion factor for $\$/m^2$ to \$/kg is 1 for 25 slices/cm. However, it appears that for 15-cm-dia ingots the wafering rate may be as low as 17 slices/cm. The growth cost of \$14/kg would amount to $\$20.2/m^2$ for wafering of 17 slices/cm, leaving only $\$27.4 - \$20.2 = \$7.2/m^2$ for wafering. Taking into account the increased silicon utilization of thicker wafers, the allocation for wafering would be less than $\$7.2/m^2$ for 15-cm-dia ingots. For smaller-diameter ingots the growth cost will be more than that for 15-cm-dia ingots (Reference 2); however, the slices per centimeter can be increased. For square ingots, the allocation for wafering at 25 slices/cm would be $\$36.3 - \$18.0 = \$18.3/m^2$.

The price estimation method used is described below. The add-on price for each of the three wafering processes is computed and the important cost parameters are identified. Based on the sensitivity analyses of the key parameters, conclusions are drawn suggesting the direction of technology development.

SENSITIVITY ANALYSIS USING IPEG (SAIPEG)

The add-on price for a process is estimated using the Interim Price Estimation guidelines (IPEG) (Reference 3). The price is estimated by using the following equations from IPEG 2 (the improved version of IPEG) (Reference 4).

$$\text{AMC} = 0.52 \times \text{EQPT} + 109.0 \times \text{AREA} + 2.8 \times \text{DLAB} + 1.2 \times (\text{MATS} + \text{UTIL}) \qquad (1)$$

$$\text{PRICE } (\$/\text{m}^2) = \text{AMC } (\$/\text{yr})/\text{QTYPYR } (\text{m}^2/\text{yr}) \qquad (2)$$

where

AMC = Annual manufacturing cost (\$/yr).

EQPT = Total installed cost of equipment (\$). Coefficient 0.52 corresponds to equipment life of 10 years.

AREA = Area required by the process equipment and its operators (ft^2).

DLAB = Annual cost of direct labor (\$/yr). Coefficient 2.8 is used if the fringe benefits are not included in DLAB.

MATS = Annual cost of materials and supplies (\$/yr).

UTIL = Annual cost of utilities (\$/yr).

QTYPYR = Quantity of wafers produced (m^2/yr).

The input data for the base case of a process for the production parameters and the cost parameters are obtained by projections based on experience and judgment.

SAIPEG is a computer program for doing sensitivity analysis using IPEG. The sensitivity analysis of a process add-on price is performed by SAIPEG with respect either to the production rate or to any cost parameters varied one at a time with the remaining data held constant. The production rate and the cost parameters in turn are varied by changing some of the base-case input parameters.

SAIPEG RESULTS OF WAFERING PROCESSES

The sensitivity analysis of the add-on price is performed for each of the three wafering techniques. The sensitivity of the key parameters and their impact on the price are discussed in detail below.

Multiple Ingot Wafering With ID Saw

An earlier study of wafering 15-cm ingots individually by ID saw has shown that it is hard to meet the price goals of \$7.20/m^2; it requires a plunge rate of 12 to 15 cm/min, which is not practicable (Reference 5). One of the ways of improving the throughput of ID wafering is to build a machine capable of handling multiple ingots simultaneously. The ID saw considered in this analysis is suitable for slicing three 15-cm-dia ingots simultaneously. The input data for the base case is given in Table 1. QTYPYR, AMC, the price and the price breakdown in terms of cost parameters are presented in Table 2. Each machine will produce 6139 m^2 of wafers annually at a cost of \$93,673, giving a price of \$15.26/m^2. The price breakdown reveals that utilities and area-related costs are negligible. Cost of EQPT, DLAB and MATS are distributed fairly equally, amounting to 25%, 32%, and 37%, respectively.

Effect of production variation in terms of the plunge rate and the blade life is shown in Figure 1. The base-case data assume a blade life of 1530 slices (3 ingots x 30 cm long x 17 slices/cm), requiring a new blade for each run. The price is reduced to \$10/m^2 by increasing the blade life to 4000 slices and the plunge rate to 5 cm/min. This requires improvements in the quality of the blade. It may be noticed in Figure 1 that for a given plunge rate the decrease in price with blade life beyond 2500-3000 slices or more is not significant. To achieve the price goal, a plunge rate of 5 cm/min or more and a blade life of 4000 slices may be required.

The effect of varying DLAB in terms of machines per operator (MPO) and labor pay rate is shown in Figure 2. By increasing MPO from 6 to 12, the price is reduced from \$15.26/m^2 to \$12.85/m^2. Due to the asymptotic nature of the curves, there is no significant saving in increasing MPO beyond 12.

Table 1. Base-Case Data For ID Wafering Process

INGOTS CUT PER RUN	3.00
INGOT LENGTH (CM)	30.00
INGOT DIAMETER (CM)	15.00
SLICES PER (CM)	17.00
PLUNGE RATE (CM/MIN)	3.80
INGOT SET UP TIME (HRS)	0.50
SAW SET UP TIME (HOURS)	0.50
BLADE LIFE (SLICES)	1530.00
NON PRODUCTIVE TIME/YR (DAYS)	20.00
PROCESS YIELD	0.95
MACHINE COST ($/EACH)	45000.00
MACHINE LIFE TIME (YEARS)	10.00
AREA PER MACHINE (FT^2)	50.00
LABOR PAY RATE ($/HR)	6.50
MACHINES PER OPERATOR	6.00
BLADE PRICE ($/EACH)	100.00
OTHER CONSUMABLES ($/RUN)	20.00
POWER CONSUMPTION (KW/EACH)	1.50
ENERGY RATE ($/KWH)	0.05

Table 2. Price Estimation Results of the ID Wafering Process Using Base-Case Data

PRODUCTION PER YEAR (M^2) = 6,138.83

ANNUAL COSTS ($) = 93,672.52

ADD-ON PRICE ($\$/M^2$) = 15.26

PRICE BREAKDOWN	PERCENT
EQUIPMENT	24.98
AREA	5.82
DIRECT LABOR	31.69
MATERIALS	36.74
UTILITIES	0.77
TOTAL	100.00

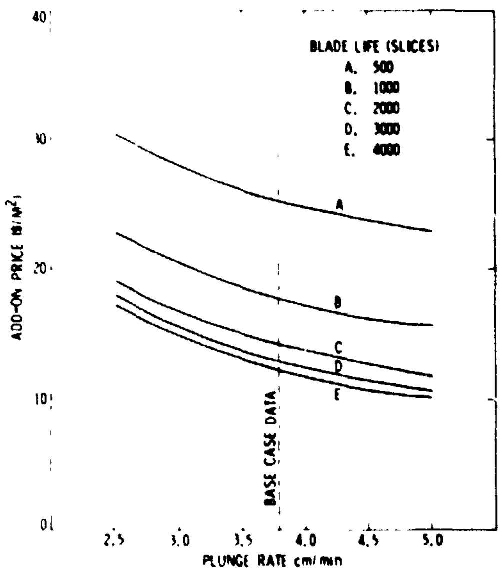

Fig. 1. Add-on Price vs Production Rate for Wafering 15-cm-Dia Silicon Ingots (17 slices/cm) With ID Saw

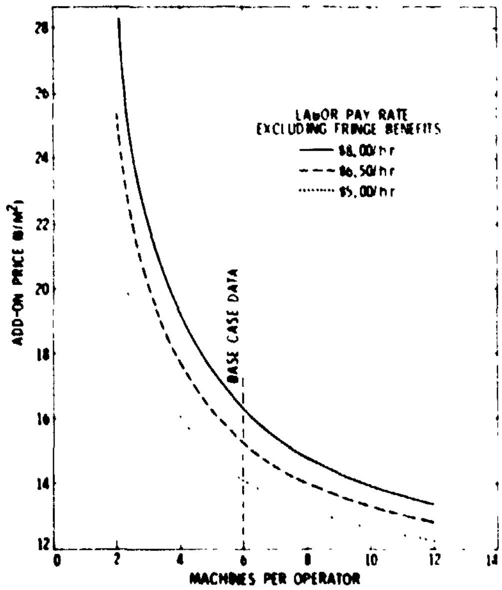

Fig. 2. Add-on Price vs Direct Labor Cost for Wafering 15-cm-Dia Silicon Ingots (17 slices/cm) With ID Saw

By increasing the blade cost from \$100 to \$140, the price is increased from \$15.26/m^2 to \$17.23/m^2. By reducing the blade cost to \$60, the price would be reduced to \$13.63/m^2. MATS cost contributes nearly one third of the price. It must be reduced, and blade life must be increased. By increasing EQPT cost from \$45,000 each to \$60,000 each, the corresponding increase in price amounts to only 8%.

In addition to the above analysis, a price estimate is made for wafering 10-cm-square ingots at 25 slices/cm and at a plunge rate of 5 cm/min. The blade is assumed to last for one run (2250 slices). The price for this case is \$15.13/m^2, which is very close to that for wafering 15-cm-dia ingots (Table 3); its sensitivity is very similar to that for the 15-cm-dia ingots.

Table 3. Price Estimation Results of the Wafering Technologies

	ID		MBS				FAST	
INGOT SIZE	15 cm DIA	10 cm SQ	15 cm DIA	12.5 cm DIA	10 cm DIA	10 cm SQ	15 cm DIA	10 cm SQ
QUANTITY/YEAR (M^2)	6138.83	6797.25	3198.29	2657.31	2115.27	2693.25	5109.90	6483.75
AMC (\$)	93,672.52	102,862.78	59,660.54	65,173.48	73,358.89	73,358.89	59,646.21	59,984.99
PRICE (\$/M^2)	15.26	15.13	18.65	24.53	34.68	27.24	11.67	9.25
PRICE BREAKDOWN (PERCENT)								
EQUIPMENT	24.98	22.27	36.61	33.51	29.77	29.77	26.15	26.01
AREA	5.82	5.19	6.58	6.02	5.35	5.35	14.62	14.54
DIRECT LABOR	31.69	28.28	8.31	7.61	6.76	6.76	31.06	30.88
MATERIALS	36.74	43.58	47.06	51.55	56.96	56.96	25.07	25.48
UTILITIES	0.77	0.68	1.44	1.31	1.16	1.16	3.10	3.08
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
RELEVANT DATA FOR COMPARISON								
SLICES/CM	17.00	25.00	21.00	21.00	21.00	21.00	19.00	25.00
SLICING RATE (MM/MIN)	38.00	50.00	0.10	0.10	0.10	0.10	0.085	0.10
BLADE LIFE (RUNS)	1530†	2250†	1.00	1.00	1.00	1.00	3.00	5.00
MACHINE COST (\$)	45,000.00	45,000.00	42,000.00	42,000.00	42,000.00	42,000.00	30,000.00	30,000.00
DUTY CYCLE	0.97	0.96	0.98	0.98	0.97	0.97	0.95	0.92
NON PROD (DAYS)	20.91	20.50	8.00	7.67	7.36	7.36	21.11	20.59
INGOTS/RUN	3.00	3.00	1.00	1.00	1.00	1.00	2.00	2.00

†BLADE LIFE IS SLICES INSTEAD OF RUNS.

Wafering With MBS Saw

The blades required to slice an ingot of a certain length are arranged with spacers according to the number of slices/cm required and are held in a blade head. The whole ingot is sliced into wafers simultaneously. Silicon carbide, used in a slurry, acts as an abrasive.

A circular ingot of 10-cm dia is considered for the analysis. The input data for the MBS wafering process, QTYPR, AMC and the price breakdown in terms of cost parameters, are given in Tables 4 and 5. Each machine produces 2115 m^2 of wafers annually at a cost of $73,359, resulting in an add-on price of $34.68/$m^2$. This price breakdown in terms of cost parameters indicates that materials cost is the primary contributor, amounting to nearly 57% of the price. The second important cost parameter is EQPT, amounting to nearly 30% of the price. Contributions of DLAB, AREA and UTIL are not significant.

Table 4. Base-Case Data For MBS Wafering Process

INGOTS CUT PER RUN	1.00
INGOT LENGTH (CM)	27.00
INGOT DIAMETER (CM)	10.00
SLICES PER CM	21.00
SLICING RATE (MM/MIN)	0.10
SET UP TIME (HOURS)	0.50
NON PRODUCTIVE TIME/YR (DAYS)	7.00
PROCESS YIELD	0.95
MACHINE COST ($/EACH)	42000.00
MACHINE LIFE TIME (YEARS)	10.00
AREA (SQ. FT.)	36.00
LABOR PAY RATE	4.88
MACHINES PER OPERATOR	27.00
BLADE PACK PRICE ($/PACK)	60.00
BLADE PACK LIFE TIME (RUNS)	1.00
ABRASIVE USED (POUNDS/RUN)	2.00
ABRASIVE COST ($/POUND)	3.30
VEHICLE USED (GALLONS/RUN)	4.00
VEHICLE COST ($/GALLON)	0.51
BEAM ($/RUN)	1.00
POWER CONSUMPTION (KW/EACH)	1.70
ENERGY RATE ($/KWH)	0.05

Table 5. Price Estimation Results of the MBS Wafering Process Using Base-Case Data

PRODUCTION PER YEAR (M^2) = 2,115.27

ANNUAL COSTS ($) = 73,358.89

ADD-ON PRICE ($/$M^2$) = 34.68

PRICE BREAKDOWN	PERCENT
EQUIPMENT	29.77
AREA	5.35
DIRECT LABOR	6.76
MATERIALS	56.96
UTILITIES	1.16
TOTAL	100.00

If it is possible to accommodate two ingots instead of one per run with a slight increase in slurry consumption, the production will be doubled, reducing the price to nearly $18.00/m^2, which is in a reasonable range. Effect of production variation in terms of slices/cm and slicing rate is shown in Figure 3. By increasing the slicing rate from 0.1 mm/min to 0.2 mm/min, the price is reduced from $34.68/m^2 to $17.84/m^2. In addition, if two ingots are sliced simultaneously, the corresponding price would be $8.92/m^2, which is close to the desired value. The decrease in the price achieved by increasing the slices/cm for slicing rates more than 0.15 mm/min is not significant. Efforts in increasing the throughput rate must be directed toward achieving multiple-ingot slicing simultaneously and increasing the slicing rate.

By reducing the EQPT cost from $42,000 each to $30,000 each, the price is reduced from $34.68/m^2 to $31.73 m^2, which is not significant.

Material cost being the primary cost driver, every effort should be directed to reducing the materials cost. Effects of variation in blade-pack price and blade-pack lifetime (runs) on price are shown in Figure 4. By increasing blade-pack life to two runs and reducing the blade pack price to $30, the price is reduced from $34.68/m^2 to $21.92/m^2. In addition, if two ingots are sliced simultaneously, instead of individually, the corresponding price would be $10.96/m^2.

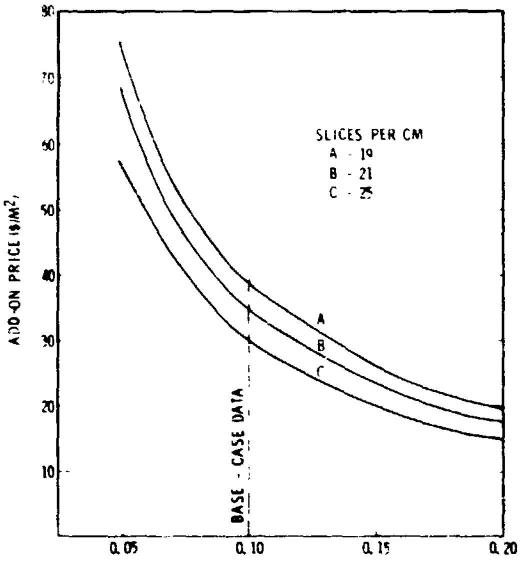

Fig. 3. Add-on Price vs Production Rate for Wafering 10-cm-Dia Silicon Ingots (21 slices/cm) with MBS Saw

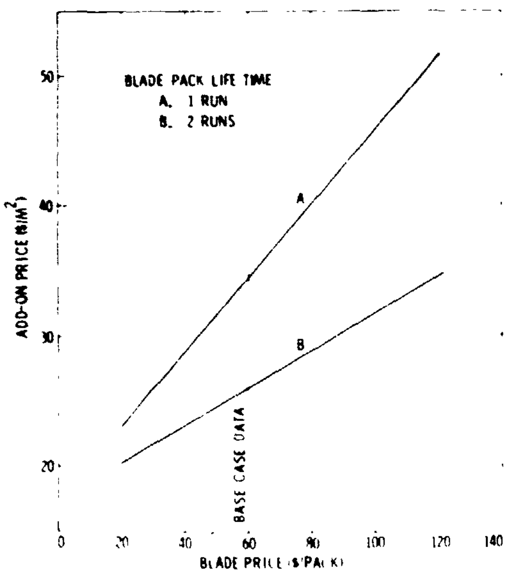

Fig. 4. Add-on Price vs Material Cost for Wafering 10-cm-Dia Silicon Ingots (21 slices/cm) with MBS Saw

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The effects of varying production in terms of slicing rate and process yield are presented in Figure 5. By increasing the slicing rate from the base case of 0.085 mm/min to 0.1 mm/min, the price is reduced from $11.67/m^2 to $9.99/m^2. In order to obtain a price less than $10/m^2, it may be necessary to achieve a process yield of not less than 0.95, averaged over the wire-pack lifetime, and a slicing rate of at least 0.10 mm/min, which is the contract goal.

Direct labor cost is a major factor in the price. Sensitivity analysis with respect to MPO and the labor pay rate is presented in Figure 6. By increasing the MPO from 10 to 14, the price is reduced from $11.67/m^2 to $10.64/m^2. As the curves become asymptotic to the MPO axis, the impact of increasing MPO to more than 14 will not have a significant effect.

By varying the materials cost in terms of wire-pack life from three runs to five runs, the price is reduced from $11.67/m^2 to $10.50/m^2 (Figure 7). By further reducing the wire-pack cost to $100, the price will be reduced to $10.00/m^2. However, for a blade-pack life of one run, the price will be $17.52/m^2.

By reducing the machine cost from $30,000 each to $20,000 each, the price is reduced to $10.65/m^2. The advantage of increasing machine lifetime from 10 years to 15 years is of the order of 23 cents/m^2, which is not significant. Reduction of space requirement from 80 ft^2 to 60 ft^2 reduces price from $11.67/m^2 to $11.25/m^2. Increasing the space requirement to 100 ft^2 would raise the price $12.10/m^2. Slight gain is achieved by reducing the space requirement.

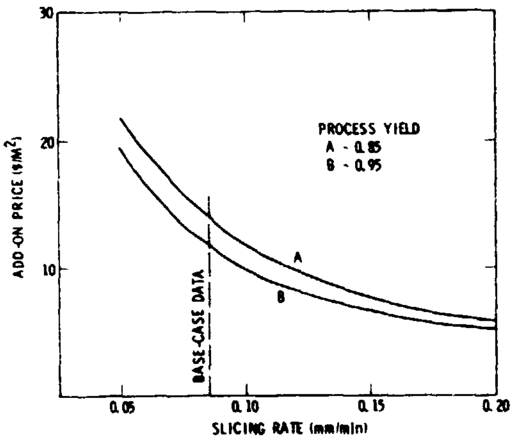

Fig. 5. Add-on Price vs Production Rate for Wafering 15-cm-Dia Silicon Ingots (19 slices/cm) by FAST

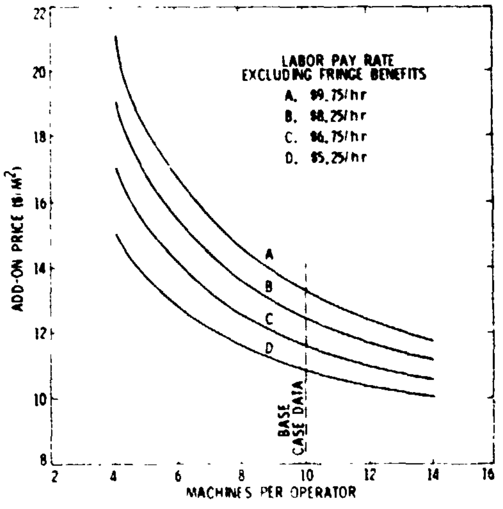

Fig. 6. Add-on Price vs Direct Labor Cost of Wafering 15-cm-Dia Silicon Ingots (19 slices/cm) by FAST

The production rate can be increased if the parameters such as slicing rate and slices per cm, given in Table 3, are valid for ingots of larger cross section. A considerable amount of technology development is needed to meet this requirement. Using the data of Table 3, the price estimates for 10-cm-sq, 12.5-cm-dia and 15-cm-dia ingots are \$27.24/m^2, \$24.53/m^2 and \$18.65/m^2, respectively (Table 3).

Wafering With FAST

Multiple wires plated with diamonds are used as cutting edges. The wires are spaced according to the slices/cm required. The whole ingot is sliced simultaneously.

Two-15-cm-dia ingots sliced simultaneously are considered for analysis. The input data for the base case are given in Table 6. The QTYPYR, AMC and the price breakdown in terms of cost parameters are give in Table 7. Each machine produced 5110 m^2 annually at a cost of 59,646, resulting in an add-on price of \$11.67/m^2. The direct labor cost contributes 31% of the price. Equipment and material cost influence are nearly equal, contributing 26% and 25% respectively. The area cost is 15% and utilities cost is 3%.

Table 6. Base-Case Data For FAST Wafering Process

INGOTS CUT PER RUN	2.00
INGOT LENGTH (CM)	30.00
INGOT DIAMETER (CM)	15.00
SLICES PER CM	19.00
SLICING RATE (MM/MIN)	0.085
SET UP TIME (HOURS)	1.50
NON PRODUCTIVE TIME/YR (DAYS)	20.00
PROCESS YIELD	0.95
MACHINE COST ($/EACH)	30,000.00
MACHINE LIFE TIME (YEARS)	10.00
AREA (FT^2)	80.00
LABOR PAY RATE ($/HR)	6.75
MACHINE PER OPERATOR	10.00
BLADE PRICE ($/TWIN PACK)	140.00
BLADE PACK LIFE TIME (RUNS)	3.00
POWER CONSUMPTION (KW/EACH)	3.73
ENERGY RATE ($/KWH)	0.05

Table 7. Price-Estimation Results for the FAST Wafering Process Using Base-Case Data

PRODUCTION PER YEAR (M^2) = 5,109.90

ANNUAL COSTS ($) = 59,946.21

ADD-ON PRICE ($/M^2) = 11.67

PRICE BREAKDOWN	PERCENT
EQUIPMENT	26.15
AREA	14.62
DIRECT LABOR	31.06
MATERIALS	25.07
UTILITIES	3.10
TOTAL	100.00

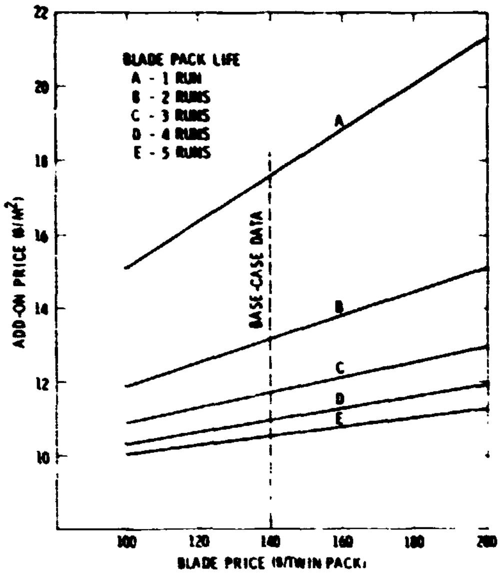

Fig. 7. Add-on Price vs Material Cost for Wafering 15-cm-Dia Silicon Ingots (19 slices/cm) by FAST

In addition to the above analysis, a price estimate is done for wafering 10-cm-square ingots at a rate of 25 slices/cm and a slicing rate of 0.10 mm/min. The wire pack is assumed to last for five runs. The price for this case is \$9.25/m^2 (Table 3).

CONCLUSIONS

The add-on prices are estimated for the ID, MBS and FAST wafering processes. The important parameters are identified by the price breakdown in terms of cost parameters. Based on the sensitivity analysis of the key parameters, these conclusions are drawn:

1. The projected price estimates for the three wafering technologies are higher than the allocation for wafering circular ingots. Sensitivity analyses idicate that these technologies have the potential of achieving the price goal with appropriate development efforts. However, wafering multiple ingots 10 cm square at 25 slices/cm, using ID or FAST processes, does meet the goals.

2. For the ID wafering technique, it is highly desirable to investigate the possibility of slicing three 15-cm-dia ingots simultaneously. The efforts may be directed to achieve a plunge rate of 5 cm/min and a blade life of 4000 slices. The MPO may be increased to 12.

3. For the MBS wafering technique, the major cost driver is materials. The possibility of slicing ingots of large size, up to 15-cm dia, with the same projected data for those of 10-cm dia, may be investigated. The efforts may be directed toward slicing two ingots simultaneously. The production rate may be enhanced by achieving a slicing rate of 0.2 mm/min.

4. For the FAST process, the production rate may be increased by improving the slicing rate to 0.1 mm/min. It may be attempted to wafer 15-cm-dia ingots at a rate of more than 19 slices/cm. The labor cost may be reduced by increasing MPO to 14. Efforts may be made to increase the blade life to five runs and reduce the blade-pack price.

5. If the projections made in base-case input data could be achieved, the price estimate for FAST, being the lowest of the three, has a better potential of achieving the price goal. However, the ID sawing technique, being the most mature technology of the three, has a greater chance of success. For the MBS technique, achievement of multiple-ingot slicing and slicing of larger-sized, ingots would be necessary to meet the price goal.

ACKNOWLEDGMENTS

The author sincerely thanks T. Daud, A. Morrison and K. Dumas of Jet Propulsion Laboratory for supplying the base-case data for the ID sawing, MBS, and FAST processes, respectively, and for discussions.

REFERENCES

1. Aster, R. W., Price Allocation Guidelines, January 1980, JPL Publication No. 80-51, DOE Report DOE/JPL 1012-47, Jet Propulsion Laboratory, Pasadena, California, January 15, 1980.

2. Leipold, M. H., Radics, C., and Kachare, A., Cost of Czochralski Wafers as a Function of Diameter, JPL Publication No. 80-25, DOE Report DOE/JPL 1012-37, Jet Propulsion Laboratory, Pasadena, California, February 15, 1980.

3. Aster, R. W., and Chamberlain, R. G., Interim Price Estimation Guidelines: A Precursor and an Adjunct to SAMIS III, Version One, JPL Internal Document No. 5101-33, Jet Propulsion Laboratory, Pasadena, California, September 10, 1977.

4. Aster, R. W., "IPEG 2: Improved Price Estimation Guidelines," Proceedings of the 14th Project Integration Meeting, JPL Publication No. 80-21, DOE Report DOE/JPL 1012-42, pp. 355-357, Jet Propulsion Laboratory, Pasadena, California, December 1979.

5. Daud, T., Liu, J. K., and Fiegl, G., "Economics of Ingot Slicing with an Internal Diameter Saw for Low-Cost Solar Cells," Presented at 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12 through 15, 1981.

DISCUSSION:

DYER: Why was the down time only seven days on the multiblade saw and it was 20 days on the other saws?

MOKASHI: That was the data given in consultations with persons at JPL and the MBS contractor. They say that the machine shouldn't receive much maintenance and for annual maintenance seven days per year is more than enough. For general analysis (SAMICS) 20 days per year is considered for maintenance and repair. In the case of the MBS they feel the machines are more versatile and they don't need so much time for annual maintenance.

DYER: Are things like coffee breaks, employee meetings, and training and all that comprehended in that?

MOKASHI: In the equation used, it is assumed that eight hours per day includes coffee break and the person is assumed to work 220 days per year, allowing for vacation and all that. Allowing for shift operation, labor is assumed to be 4.7 times the eight-hour shift. That is how the labor cost is calculated.

OSWALD: You assumed there that you were cutting, with an ID saw, three-6-inch-diameter ingots simultaneously. Is there any such technology existing or anybody working on such a thing? I'd like to know how you get it.

MOKASHI: Although the attempt has not been made so far to slice more than one ingot of large diameter in ID saw, analysis indicates that one way of reducing the price is to increase the throughput. This is only an idea. These are the projections and it may be at the preliminary stage to think about how we can reduce the price. One way to increase the throughput is to slice more than one ingot simultaneously. That may require a larger internal diameter of the saw and some other developmental efforts.

MORRISON: I just wanted to add that, in the Project, we were seriously considering funding a proposal to do just that--three ingots simultaneously. With the cutback of FY81 funds, we were forced to drop that.

UNO: If Taher's (Daud) paper was good as far as the economics of using the squared-off ingot are concerned, what kind of price projection would you have if you mounted three of those, rather than rounded?

MOKASHI: It is given in my slide for three 10-cm-square ingots. And the price was close to that for the three 15-cm-diameter ingots.

LIU: Maybe I can clarify that a little bit. The numbers that Anant (Mokashi) is projecting down here are only for the slicing cost, so they do not take into account the packing factor. So if you do take that into account, you do get a benefit also.

SUREK: This thought always occurs to me whenever I see sensitivity analyses of things that don't yet exist...future technologies. If you were going to look at the base case as today's technologies, since these technologies are used today by existing industry, would you come up with somewhat different conclusions as to exactly how you would proceed to reduce the cost?

MOKASHI: That is how we started. In the first case we consider the existing technology and estimate the price and identify what are the major cost drivers. Based on that, thinking is initiated and even though today's technology may not show it is possible to do things at least from the analysis point of view we find out "if we can do this" how much effect it is and that may be the way to go ahead.

DAUD: There have been analyses done for the one-ingot cutting of 4, 5, 6-inch by various people and this is sort of an extension based on the work that JPL was proposing to fund.

WOLF: In looking at the big table that you just had on here a moment ago, it wasn't quite clear to me why in some cases going from the 15-cm-diameter to the 10-cm-square case, the cost per square meter stayed about constant, and in other cases it went up considerably, and some cases it went down considerably. What were the differences in the assumptions that made these prices behave this way?

LIU: The conventional thought is that changing the number of slices per centimeter doesn't affect the cost of wafering, but in the case of the multiblade saws and the multiwire saws, they do change it, because they potentially have higher throughput per unit saw and because you can pack more wires and cut more slices per same size ingot. So that's what the effect would be.

FUERST: Was your table the one that mentioned the price of $140 for the wirepacks used in the FAST method? (to F. Schmid) Two packs for $140? How many wires per pack? Less than 10¢ per wire? It's very ambitious. Right now you can buy steel strips direct from the mill for approximately the same cost, but you're going to take tungsten wire, diamond plating and diamonds, and get approximately the same cost?

SCHMID: Wire is very cheap. We are using plated steel wire, and the plated steel wire comes in at far below a cent per wire itself. And the process is a very low-cost process. I really do not think that $70 is ambitious.

FUERST: Do you have any estimates now of what you're paying for diamonds per wire, including the plating process?

SCHMID: Yes. All of that has been calculated, and I think that if you look at a concentration of 100--the cost works out to less than 5¢ a wire. Everything included.

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WAFERING ECONOMIES FOR INDUSTRIALIZATION FROM A WAFER MANUFACTURER'S VIEWPOINT

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Introduction

In assessing the potential of slicing techniques for the photovoltaic sheet industry, a basic issue arises concerning the ability of the wafering equipment industry to meet future needs:

> Given the current state-of-the-art in wafering technology, can the technology be further developed to meet and surpass the national goal of $0.70/Wp?

This paper addresses the key technical limitations which inhibit the lowering of value-added costs for these state-of-the-art wafering techniques. From the best experimental results to date a projection has been made to identify those parts of each system which need to be developed in order to meet or improve upon the value-added cost reduction necessary for $0.70/Wp photovoltaics modules.

The major portion of the silicon wafer material used for solar cells today is sliced on the Internal Diameter (ID) and Multi-Blade Slurry (MBS) saws. Although a Multi-Wire Slurry (MWS) saw capable of slicing 10 cm x 10 cm square materials is not commercially available, this saw has been added for comparison and is considered as slicing 10 cm round material. A brief description of the three saw types follow:

1. MBS - The machine under study represents a standard multi-blade slurry system such as the Varian model 7176. The ingot is forced up into the multiple blade assembly, which is reciprocating at a low frequency (80-120 cycles/min.). The material is abraded away from beneath each blade by abrasive particles in a continuously recirculating slurry. The total cutting time for an ingot is long (>15 hours), but the large number of simultaneous cuts provide a wafer area throughput roughly equal to the other two techniques. Expendable materials costs for blades, oil, and abrasive are much greater than with the ID saw, but less than with the MWS. Wafer thickness and taper are also much more difficult to control than with the ID saw. The initial capital investment, however, is two to three times lower than either the ID or MWS saws.

2. ID - The ID saw slices one wafer at a time, but does so at a high output. The rigidity of the annular diamond plated blade edge, combined with high blade speed and diamond abrasive, allows high feed rates to be used. The wafered area throughput is usually higher than for the MBS or MWS saws. The blade is the only consumable used and its cost per wafer is low. In addition, the ID saw has good potential for automation, and cleaning costs after wafering can be reduced significantly. The initial capital investment, however, is higher than for the MBS saw.

3. MWS - A wire saw of the type made by the Yasunaga Engineering Company of Japan is considered here. This saw uses an abrasive lapping process like the MBS saw. Instead of strip steel blades though, a single strand of wire is wound in multiple loops on grooved rollers. Fine wires and abrasive particles allow wafers to be cut at the lowest center to center spacing of any of the techniques. But wire cost is high; consumables costs are higher for this process than for either of the others. Machine wear, especially on the grooved rollers, is a problem. Thus, maintenance is high and reliability low. Capital cost is comparable to the ID saw.

Another type of wire saw which uses a fixed abrasive, such as the FAST saw now under development, has the potential for competing with these other techniques. This saw has not been included here because: (1) it is not commercially available and it is not clear when a production tool will be available; (2) major technical problems are yet to be resolved; and (3), we lack sufficient data on it to make a good comparison.

ECONOMIC MODEL

The flow chart in Figure 1 illustrates how the various cost factors combine to contribute to the final wafer price. Because this cost analysis is concerned only with the wafering aspect of this problem it begins with an assumed ingot cost after sizing. Then, using various wafering assumptions (which are explained in the next section), a final wafer cost is computed for each ingot cost and wafering technique. An explanation of this computational method follows.[1]

We start with the silicon material cost.

A - Ingot Cost ($/kilogram)

In this analysis A is given

B - Material Yield (meters^2/kilogram)

(E1)

$$B = \frac{a}{2.33b}$$

Where a = yield including breakage in decimal fraction
b = center to center spacing of wafers in mm.

C - Silicon Material Cost ($/meter^2)

(E2)

$$C = \frac{A}{B}$$

The next four factors are all machine running costs in $/hour.

(E3)

D - Machine Capital Cost ($/hour)

$$D = \frac{c}{d}\left(\frac{1}{e} + \frac{f}{2}\right)$$

Where:
c = capital investment per machine ($)
d = running hours per year
e = period of depreciation (years)
f = interest rate per year in decimal fraction

E - Labor Cost Per Machine ($/hour)

(E4)

$$E = \frac{g}{h}$$

Where:
g = operator cost including overhead ($/hour)
h = number of machines per operator

F - Power Cost ($/hour)

(E5)

$$F = i \cdot j$$

Where: i = power per machine (kilowatt)
j = energy cost ($/kilowatt-hour)

G - Floor Space ($/hour)

(E6)

$$G = \frac{k \cdot l \cdot m}{d}$$

Where: k = $/foot^2/year
l = area required per saw (ft^2)
m = excess space required (ft^2)

An output figure per machine in meters^2/hour is needed to convert D, E, F and G into wafering add-on costs in $/meter^2.

H - Output (meter^2/hour)

(E7)

For MBS and MWS saws

$$H = \frac{60 \cdot n \cdot a \cdot s}{(1+p) \cdot (q+r)}$$

For ID saws

$$H = \frac{60 \cdot n \cdot a \cdot s}{(n \cdot (1+p) \cdot q)+r}$$

Where: n = number of wafers cut per blade, bladepack, or wire length
p = machine downtime for maintenance over total running time
q = cycle or run time (min.)
r = total time spent on blade installation, work piece change, and dressing for blade or bladepack (min.)
s = area per wafer (meters^2)

Other wafering add-on costs are blades and consumables.

I - Blades ($/meter^2)

(E8)

$$I = \frac{t}{u \cdot a}$$

Where: t = tool cost ($/blade, bladepack, wire length)
u = tool life (meters^2)

For the ID saw, the cost of consumables is negligible. For slurry saws:

J - Consumables ($/meter^2)

(E9)

$$J = \frac{(v \cdot w)+(y \cdot z)}{a}$$

Where: v = oil cost ($/gallon)
w = oil use (gal/meter^2)
y = abrasive cost ($/lb)
z = abrasive use (lb/meter^2)

Wafer cleaning costs are not directly included. Analysis shows that direct materials add less than 1% to the wafer cost, and labor is included in the labor costs per saw.

The total wafering add-on price can now be calculated.

K - Wafering Add-On ($/meter^2)

(E10)

$$K = \frac{D+E+F+G}{H} + I + J$$

And the final wafer cost is the sum of the silicon material cost and the wafering add-on.

(E11)

$$\text{Total Wafer Cost } (\$/\text{meter}^2) = C + K$$

TECHNOLOGY DISCUSSION

This analysis attempts to answer two questions. First, how do state-of-the-art results for each of the three wafering techniques compare over a range of ingot prices from 100 to 300 $/kg? Secondly, a 1986 scenario is shown. The ingot price is assumed to drop to 25 $/kg, which corresponds to 14 $/kg feedstock and 11 $/kg ingot value added.[2] At this cost, what developments in each saw type would allow production at less than 37 $/Wp for wafers or 56 $/m^2 at 15% cell efficiency. All costs are in 1980 dollars and correspond to the national goals, as allocated by the Jet Propulsion Laboratory.[3]

State of the Art Comparison

The set of assumptions for the state-of-the-art comparison are listed in Table 1 under heading I for each saw type. The numbers for the ID and MBS saws are based on the best experimental results to date in work done at Semix. The numbers used for the MWS are based on a JPL report, and some limited work done at Solarex.[4] A further explanation of some of the assumptions is also given below.

The ID saw uses a standard 22 inch blade. The wafers are 10 cm square and are cut at .023 in (0.58 mm) center-to-center spacing with .012 in (0.30 mm) of kerf loss. This results in .011 in (0.28 mm) thick wafers. The variable r at 120 minutes is the sum of 45 minutes for blade change, 60 minutes for dressing during the life of the blade, and 15 minutes for workpiece changes.

The MBS saw has two cases, a and b. In case a, 10 cm square wafers are cut at .024 in (0.61 mm) center to center spacing. The blades are .006 in (0.15 mm) thick with .018 in (0.46 mm) spacers. A #400 grit is used in a concentration of 4 lbs to a gallon of oil, resulting in a 24 hour run time. In case b, 10 cm by 15 cm rectangular wafers are cut at .026 in (0.66 mm) spacing. The blades are .008 in (0.20 mm) thick with .018 in (0.46 mm) spacers. With the .008 in blades, a higher abrasive concentration (6 lbs/gallon) and a higher feed pressure can be used, resulting in a 14 hour run time.

The MWS saw studied here can cut a maximum of 79 cm^2 in the form of 10 cm round wafers. The .018 in (0.46 mm) spacing produces .012 in (0.30 mm) thick wafers with .005 in (0.13 mm) wire and 10 micron SiC abrasive. Wire use is approximately 100 meters per wafer. The abrasive concentration is 12 lbs to a gallon.

Table 2 lists the results of the cost analysis. Looking at the Best To Date portion the following conclusions can be drawn.

- At all ingot prices the ID sawing technique demonstrates a lower wafer cost. This results from the high material yield and low consumable and blade costs.

- The MWS is competitive only at the highest ingot cost, and then only marginally. This is because this technique has very high blade and consumable costs and only at high ingot prices does the MWS's superior material yield make up for the high wafering add-on costs. The large wire and consumable costs for the MWS saw are illustrated in Figure 2.

- Development of automated wafer retrieval, loading and transport through cleaning to reduce labor costs
- Lower capital costs
- Machine development to allow slicing of .008 to .010 inch thick wafers with a cycle time of less than three minutes.

For MBS sawing the following improvements must be made:

- Reduce cutting time through high reciprocating speed
- Lower center-to-center spacing
- Decrease blade pack costs
- Better human engineering or automation for easier blade pack tensioning, loading, and unloading
- Reduced vibration, closer machine tolerances and better blade alignment accuracy in order to cut thin wafers.

These technologies can be developed to the point necessary to improve the national photovoltaic cost goal only through commitments by the wafering equipment manufacturers and continued support by DOE and JPL to pursue these areas of critical technology development.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Z. C. Putney for his guidance and Ms. J. Harley for her assistance.

REFERENCES

1 Several of the equations used were derived from equations presented in the pamphlet "Cost Comparisons for the Slicing of Semiconductor Materials with ID and Slurry Saws," Meyer & Burger AG, 3613 Steffisburg-Station, Switzerland, June, 1980.

2 Based on a JPL SAMICS projection for the Semix process of .09 $/WP ingot value added with .021 inch spacing.

3 Aster, R.W., Price Allocation Guidelines January 1980, JPL Publication 80-51, January 15, 1980.

4 Chen, C.P., Multi-Wire Slurry Wafering Demonstrations, LSSA Project Task Report 5101, February 22, 1978.

5 Development of A High Efficiency Thin Silicon Solar Cell, JPL Contract 954883, Final Report, December 1980, Solarex Corporation.

6 Storti G., etal High Efficiency Ultrathin Coplauer Back Contact Cells, Fourteenth IEEE Photovoltaic Specialists Conference - 1980.

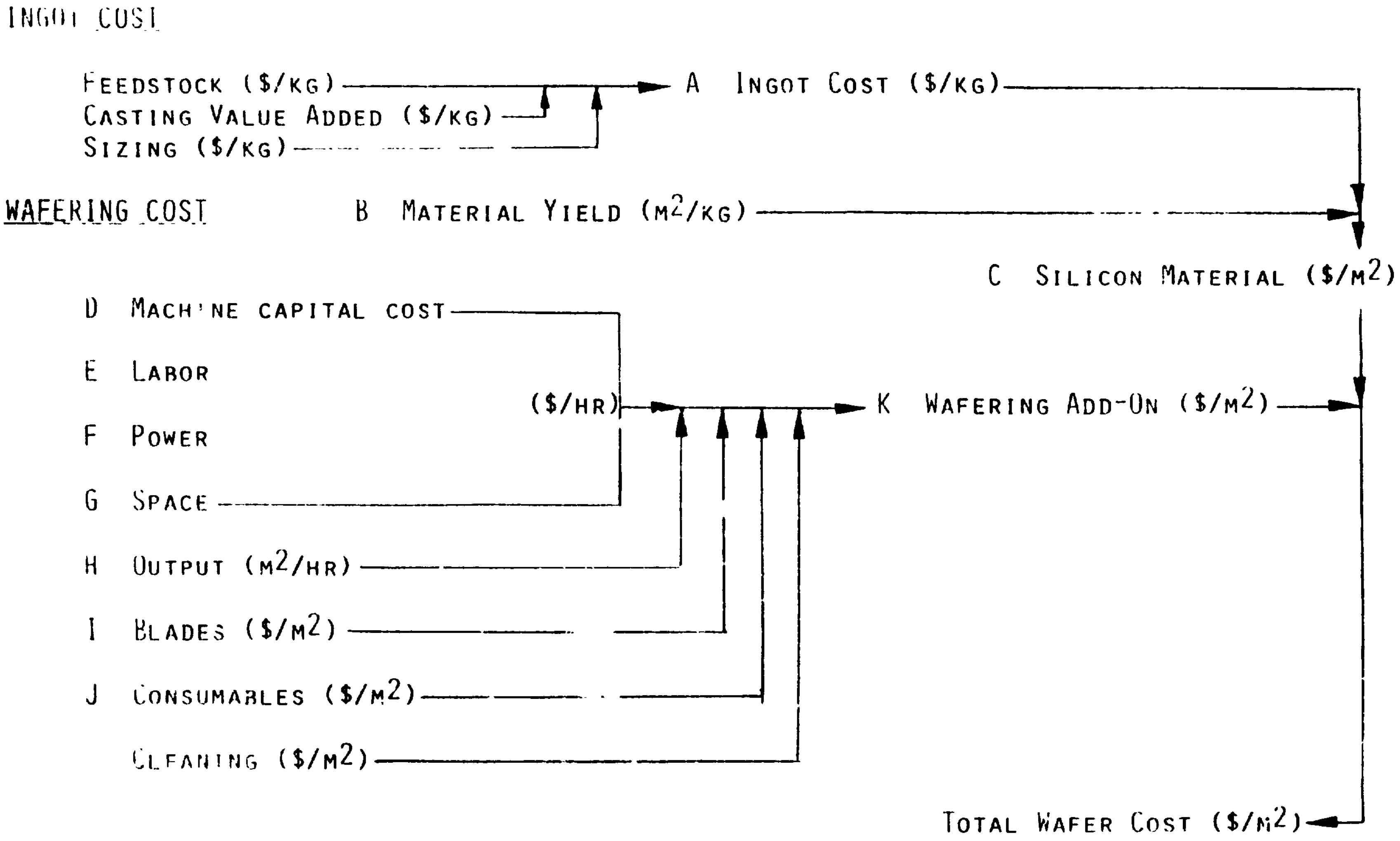

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FIGURE 1 WAFERING COST ANALYSIS FLOW CHART

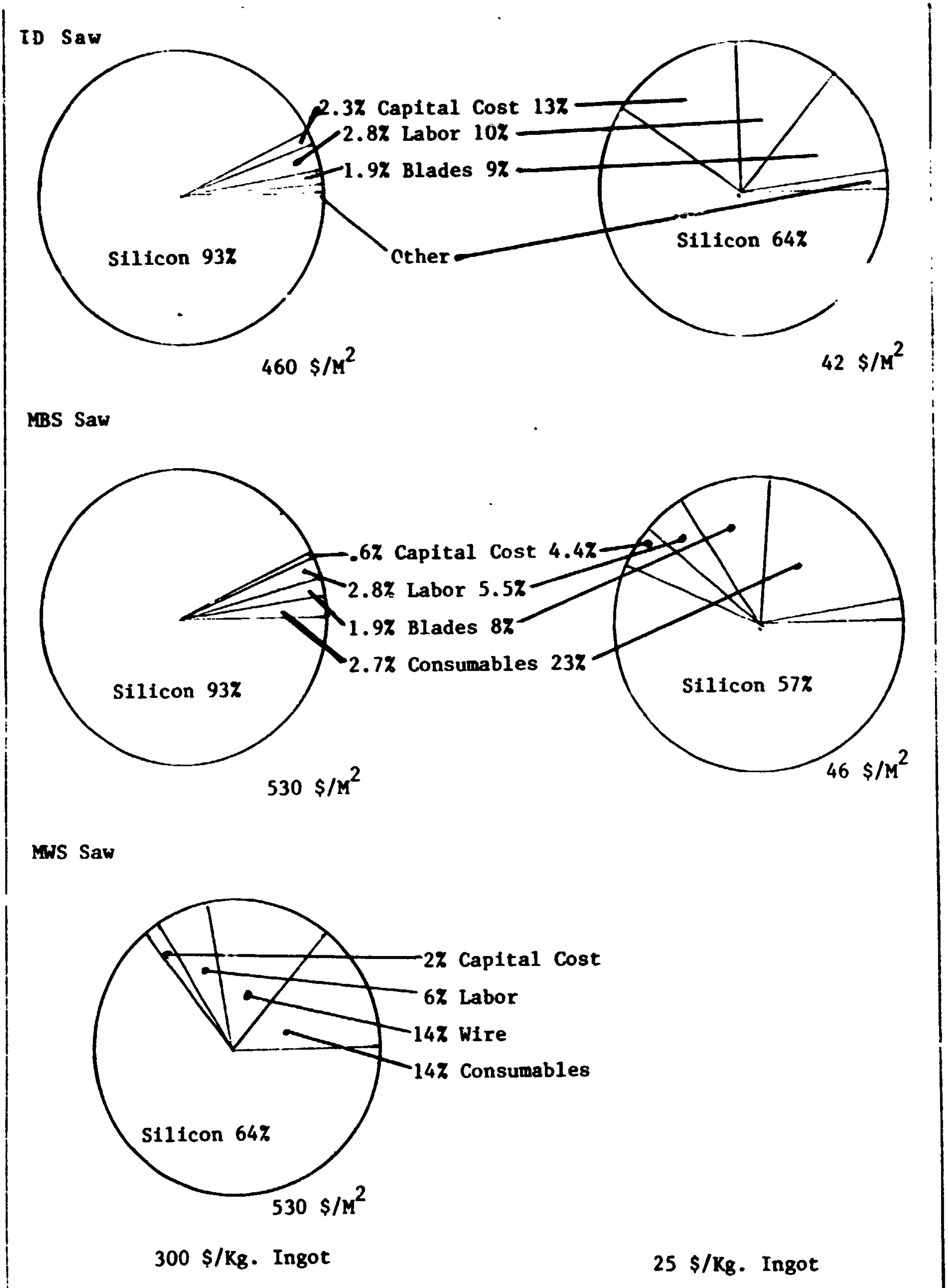

Figure 2. Wafer Cost Contributions at 300 and 25 $/Kg. Ingot Cost.

TABLE 1
SSUMPTIONS

	ID		MBS			MWS
	I	II		I	II	I
a yield	.95	.98		.95	.98	.95
b center to center spacing, mm (in)	.584 (.023)	.457(.018)	a	.610 (.024)	.457 (.018)	.457 (.018)
			b	.660 (.026)		
c capital cost, $	60,000	50,000		22,000	60,000	50,000
d running hours per year	6,000			6,000		6,000
e depreciation, yrs	7			7		7
f interest rate	.12			.12		.12
g operator cost, $	15			15		15
h machines per operator	6	12	a	6	6	3
			b	4		
i power use, kW	2	3		1.5	5	1
j energy cost $/kWhr	.07			.07		.07
k space, $/ft^2/yr	4.5			4.5		4.5
l space required, ft^2	75			45	90	50
m excess space	1.2			1.2		1.2
n # of wafers per blade, bladepack, or wire length	1,500	1,800	a	312	458	222
			b	288		
p machine stand still	.05			.05		.05
q cycle or run time, min	2.75	2.75	a	1,380	360	480
			b	840		
r other non slicing time, min	120	120		90	30	120
s wafer area, m^2	.01	.015	a	.01	.015	.0079
			b	.015		
t tool cost, $	125	100		40	25	.0057
u tool life, m^2	15	27	a	3.12	6.89	8.1×10^{-5}
			b	4.32		
v oil, $/gal	--			5.00		5.00
w oil use, gal/m^2	--			.727	.242	.727
y abrasive, $/lb	--			2.25	3.5	7.5
z abrasive use, lbs/m^2	--		a	2.9	2.5	8.7
			b	4.4		

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TABLE 2

RESULTS

	BEST TO DATE				1986 SCENARIO	
	ID	MBS a	b	MWS	ID	MBS
Material Yield, m^2/kg	.698	.668	.617	.892	.920	.920
Silicon Material Cost, \$/m^2	143	150	162	112	27.1	27.1
	286	299	324	224		
	430	449	486	336		
Output, m^2/hr	.192	.115	.252	.158	.299	.987
Machine Running Cost, \$/m^2	10.6	6.43	2.94	10.7	5.65	2.06
Labor, \$/m^2	13.0	21.7	14.9	31.6	4.18	2.53
Power, \$/m^2	.73	.96	.44	.44	.70	.35
Floor Space, \$/m^2	.36	.35	.16	.32	.23	.08
Blades, \$/m^2	8.77	13.5	9.75	74.0	3.78	3.70
Consumables, \$/m^2	---	10.7	14.2	72.5	---	10.5
Wafering Add-On, \$/m^2	33.5	53.6	42.4	190	14.5	19.2
Total Wafer Cost, \$/m^2	180	200	200	300	42	46
	320	350	370	410		
	460	500	530	530		
Total Wafer Cost, \$/Wp	1.50	1.70	1.70	2.50	.28	.31
	2.70	2.90	3.10	3.40		
	3.80	4.20	4.40	4.40		

Cell efficiencies used for total \$/Wp are:
12% in Best to Date Section
15% in 1986 Scenario

Silicon Ingot Cost : in Best to Date section are 100, 200, and 300 \$/kg
: in 1986 Scenario is 25 \$/kg

DISCUSSION:

SCHMID: Frank, you've acknowledged that the FAST technique has many advantages, but have made an assumption that it would not be available to you. Why have you made that assumption?

FUERST: I made the assumption because it is not available to us now. We still are not convinced of its technical readiness. I did not want to project into '86 with a machine that is not working to our satisfaction now, whereas both the other techniques are. I feel more confident with our projections with a machine that is proven at the present time.

SCHMID: I think one of the major projections that you're making and one of the greatest difficulties that you have in projecting is on the kerf plus thickness to achieve--and nowhere have you assumed getting--25 wafers per cm, or 64 wafers per inch, which is something that has been achieved on the FAST machine, so I think one of the major hurdles has already been demonstrated with the FAST machine.

FUERST: We are eagerly awaiting further developments on that machine and as soon as one is available, we'll be happy to buy one or many of them.

WOLF: Also, 25 wafers per cm has been demonstrated on the ID machines, it seems to me.

FUERST: Yes, the numbers I used correspond approximately to 22 wafers per cm. 25 wafers per cm have been demonstrated on the ID saw, but not in the wafer size that we've assumed here.

GLYMAN: Your second last chart showed 28¢ for the ID and 31¢ for the MBS. Now are these cost, or price? You said you didn't use IPEG. I don't think you plugged in any overhead costs into your numbers.

FUERST: They are included in terms of machine costs, investment over life of machine, interest paid on the investment cost of the machine, overhead on labor. We assume $6 per hour labor cost, which is high in 1980 dollars at 150% overhead.

SUREK: Frank, I missed something. Were these best-to-date results demonstrated for the semicrystalline material?

FUERST: For both the MBS and the ID saw, yes. The wire saw, no. As I said, those are all taken from a report.

SUREK: What sort of yields were obtained?

FUERST: Typically, over 95%. We've had some that were much better than that. That was the main criterion in picking those assumptions: yield. It had to be above 95%. We have in fact achieved closer spacings, but not at good yields.

DYER: The question of the surface of the multiblade and the wire saw slices I haven't heard addressed much in this conference. I'd like to hear from a multiblade champion and a multiwire champion, and then somebody who makes solar cells. I'd like to find out what sort of a wavy surface that thing gives, and then I'd like to hear if the solar-cell manufacturer can stand it. We've done wafering of cells before at TI, and sometimes the surface just didn't come out so well, and you wondered whether they could accept any sort of metallization. On the ID saw you can generally produce a slice that's smooth enough to make a solar cell, but is that true for the multiblade and the multiwire? I think that's a challenge.

FUERST: First of all, the solar-cell specifications are much looser than those you would use in the semiconductor industry. Taper specs on the MBS can be as high as 2 to 4 mils over a 4-inch length, and that is not a problem in processing. Waviness can be a problem. It has not been a problem in production with the MBS saws, but it can be if you don't use them properly. It's always been said that the ID saw produces greater surface damage on the wafer. We're only beginning to work with that problem, and I couldn't really speculate on it.

KOLIWAD: In general, the waviness has not been a problem, unless the whole wafer ends up like a potato chip. But, if there are undulations on the surface itself, that's really not much of a problem. Secondly, the question about the damage depth effect on the solar cell. We presented a very extensive paper in 1978, in the Photovoltaic Specialists Conference. We did extensive studies of the damage depth on ID and multiblade and we also looked at the effects of those things on solar cell efficiencies. And we came to conclusions for ID wafering that were exactly what Dr. Schwuttke observed, as far as the depth of damage was concerned. In the case of multiblade, the damage depth was 10 microns compared to 25 to 50 microns for ID wafering, which is consistent with what the semiconductor industry people have seen. In the case of multiblade, the damage of 10 microns was considered to be not extensive--as a matter of fact, so much so, that you don't even have to remove it, if you're going to texturize the surface. The paper contains all this data about efficiencies, and we measured the efficiency by incrementally moving the damage also just to check to see if a certain amount of damage is acceptable or not.

I would like to solicit some comments from the wafer manufacturers and from the machine manufacturers, particularly on the number of machines per operator. In the analysis you have to assume something. You start with one machine per operator, whatever is accepted level for today's machines and so on. As you know, it is extremely hard to get data directly from the manufacturers. By the way, Martin Wolf has done extremely good effort in the last four or five years continuously updating the practiced technology, which includes a lot of things like coffee breaks, people sleeping on the machines, etc., and Martin has done several reports, which are available. But when you do the sensitivity analysis, the sensitivity analysis basically tells you the relative variations with respect to any given parameter. It does not give you any absolute number. So you can take those curves, and look at them, and secretly put your data point wherever you think you are. My question to the wafer manufacturers is: how many machines per operator do they realistically think are practically possible, not just today but four or five years from now?

KACHAJIAN: In response to Kris's question regarding the number of machines that can be run by an operator, we have currently one customer running 10 machines with one operator, and I think we'll learn later this evening that four or five years from now, we may have 50 to 100 machines run by one operator.

WOLF: I had opened this session with a comment with respect to the multiblade saw which was that we had a tremendous value on the machine, and it's important to want to keep the yield up, to have more people watching. I think the answer to the problem is that we have to learn to develop better sensing systems that will indicate readily if something starts to go wrong on the machine so that we don't need an operator there listening as some of the sound is changing, and so that one learns how to detect these oncoming changes early enough before too many wafers are ruined, and either the machine shuts itself off or sets off an alarm, and so on.

KACHAJIAN: We have that now, Martin. If there's a coolant fault, the machine will finish the cut, come back up, no alarms or bells, but a red light will go on distinguishing that machine from any other. So in the din of the noise, it's not as bad as you paint it. They can look down the line and see a machine with a fault of some sort, which we detect at this point.

WOLF: I was told on the MBS that there are things you don't see that start to go wrong and then very suddenly lead to catastrophic faults. Wafer breakage and so on, so that something seems to indicate something going wrong just as sounds, and they even told me that they tried to put on sound detectors, and at that time, they couldn't tell whether the operator's ear was more sensitive then the mechanical detectors they could put on. Now, I think that is again a state-of-the-art question with time, when they learn what frequencies to listen to, or what type of changes to listen to, and it will be just as good as or better than what an operator can do. So I think that these are technology questions where proper development can be done and should be successful.

DYER: We don't make solar-cell slices, but we slice, and I want to bring up some production problems. Now maybe half the people in this room don't really know what the problem is with regard to production of slices. Let me just take that example he made: The red light goes off. Now remember, we've made this so that there's just one man per 15 saws; that means there's no maintenance man back there. This man would have to not pay attention to the 14 other saws and go fix that thing. Now let me tell you what actually happens. If it's a bell, the bell bothers him, he'll go disconnect the bell. If it's a light, turn off the light. Let the yield go down, let anything happen, but fix the machine. Because that guy is just running back and forth between 15 machines. It's bad enough when we run back and forth in our smaller number of machines, now. I can give you horror stories as to what we've done to your saws in our place because this problem hasn't been addressed.

KACHAJIAN: I recognize the problem, and I guess the only answer is one of education. We've set up a seminar in our plant where we set aside a room for training people on a show-and-tell basis. Right next door, we have three machines allocated for test, for education, for operating by these customers of ours.

WOLF: I suspect the answer, to some degree, is not just that bells go off or lights flash, but that the machine shuts itself down in the proper manner, and doesn't keep running in a faulty way. And so then just your machine down time gets longer, if the man doesn't go there early enough, but at least your yield is reasonably maintained, and nothing really major can go wrong in the meantime. Now, I think Larry (Dyer) referred to the question of the maintenance people, and this is something I also had on my mind when I looked through these economic analyses, I see a machine availability of 90% listed, then I say I have to put in a maintenance man for something like one to two times this amount of time that the machine is down. At least there will be one man working most of the time that the machine is down, and in addition, he may have to repair a part after the machine is running again, or he spends time making sure parts get reordered, and so on. So I think it's more than a 1:1 ratio, normally. And so in economic analyses I think we ought to put something in for the upkeep of the machines and it is a higher priced labor than the operator labor.

KACHAJIAN: In the semiconductor business, you've got to look at that business as a competitive marketplace, and down time is critical. We've developed our equipment with that parameter in mind. As an illustration, I can say that one of our customers with over 100 machines, during a period of time extending about 15 months when demand exceeded supply, had 99% up time running seven days a week, 24 hours per day. What is also critical is that it's still a batch-wise process, and we have to get away from that.

WOLF: Yes. Whatever the down time of the individual machine is, that's what has to be accounted for, and this is one of the major considerations in the economic analysis. What is the reliability of the machine, how much is its availability, what are the costs of repairs?

ILES: Listening to all these fabulous projections, I think again that the problem of ganging ID wheels, even two of them, seems to be much simpler than perhaps 99% uptime, and complete automation for 50 machines. Perhaps we need the push that somebody mentioned, e.g., that the multiwire saw has to come on before the ID people are going to try and at least give us a conclusive experiment that proves that it's very difficult and maybe impossible to gang ID.

The work damage in general depends on the particle size and the rate of cutting. I think you have to be very cautious. At the moment, the ID saw certainly has around 25 microns work damage, because they run very quickly. Most multiwire saws are running 10 to 15 and thereabouts. But if the multiwire saws start running 6-hour cycles and 9-mil slices, you may find that you have to remove 1 or 2 mils of that 9-mil slice to get rid of the work damage, and then have to process a 7-mil slice down the line which might have some impact on the yield. I think you may find not always running the saw as fast as you can is necessarily the way to go.

SCHMID: As you increase the throughput through the machine, number of machines per operator will naturally go down. That's something that you really have to take into serious consideration. You would not be able to handle 10 machines per operator at speeds that would be greater than 4 mils per minute.

WOLF: In analyzing the labor content, it's always good to separate into machine loading and unloading time, into bladepack preparation time, and just machine watching time. For the machine watching time, you can easily keep a large number of machines per operator, but the unload-load time is constant per machine, per run. You can improve on this and learn how to speed this up with proper tooling and so on, but there's always a limit. There's always more or less a constant in the whole calculation.

Now, to this other question. How good are our assumptions? Regarding MBS, what can we do to oscillate at much higher rates, or with longer strokes? Can we get the tangential tool speed considerably up above what it is now?

LYNAH: The stroke rate that we presently are limited to is 250 strokes per minute. We have a capability to go above that, but the machine's hopping around too much. We have sawed at 150 strokes per min, and it's quite smooth. Unfortunately, we haven't noticed the straight-line relationship between the stroke speed and the sawing rate. And I have to again get back to what I feel is our basic problem, the feed. And I feel that possibly we're not getting a true picture of the stroke rate and sawing rate. But 150 means that we should get the cutting rate of our saw up about 50% over the present sawing.

FUERST: I was hoping Fred Schmid would talk a little bit about his solution to increasing cutting speed. There is an obvious solution and I have in fact worked with a machine designed for 1000 cycles per minute. We've cut at 800 cycles per minute. I wouldn't try to oscillate the workpiece at that speed. I think that would be asking for a lot of trouble. The stroke is shorter than that which you would find on the Varian MBS. The total tangential velocity increases about an order of magnitude.

SCHMID: The problem in going to high speeds is the acceleration forces at the end of the stroke. Obviously you'd want to reduce the mass of the bladehead as much as possible. With wire, you can do that because the tension on the wire is about 5 pounds, and so you can use a much lighter frame. The other thing that we're looking at is balancing off those forces so it's 180° out of phase, and making sure that the forces are all center-lined, so everything is balanced out. Using isolation and vibration mounts, you prevent the transmission of vibration from the drive unit to the bladehead itself. Those things can considerably increase the speeds. We've run speeds up to 500 feet per minute. Typically, we run around 400 feet per minute. I think 250 strokes is around 370 feet per minute. That 400 that we run routinely is with a single-head machine.

WOLF: With respect to the question of speeding up oscillatory motions, I think Mr. Lynah's approach that he discussed this morning about storing the energy in springs sounds to me like a very good approach. Just get a resonant system and don't try to dissipate all that energy in the outside machine frame, but rather store it and reuse it. But the oscillatory motion has its own problems with the particular type of blade wear and the question of having to abrade your workpiece at the end of the stroke with zero velocity. It seems that nobody has been able to work out a system where with rotary motion we can have multiple blades, and multiple cutting action at the same time.

ILES: Perhaps the multi-blade people could consider the analog of a rotating ingot and have an out-of-phase moving workpiece and tool. I wonder if perhaps you could take some of this problem at the end of the stroke out of it by having the two moving out of phase. Have the workpiece and the work tool working in opposition, so that the relative speed is increased by something like a factor of 50%.

LIU: I'd like to point out something else that's been overlooked in the discussion with the multiblade and multiwires. We heard a lot yesterday from the lubricant people with regard to the ID technology. I don't really think we've really examined that to the detail that we've done with the ID saws. So maybe that's another area to look at to increase the cutting speed.

WOLF: This is certainly an area which needs more exploration. It seems, from what we have been hearing, that it might be a factor-of-2 affair, rather than an order of magnitude affair, but even a factor of 2 at this point is very worthwhile exploring. Maybe if some miracles happen, it will turn out to be more than a factor of 2. The whole question of cutting action that is taking place as we have been seeing at this meeting is very unclear still. And so some considerable progress might be made once one really understands what is happening.

LIU: I think one advantage that we have with the multiblades and multiwire saws is that you can actually increase the throughput of the machines by just multiplying the number of wires or blades that the machine uses. You really don't have to increase the actual cutting speed of the physical wire or blade through the ingots, all this as opposed to a single-slice cutting technique like the ID saw.

FUERST: One comment that was significant that was made earlier was the one made by Fred Schmid in the discussion with Professor Werner: you don't maintain the point contact if you have a diamond-coated blade such as on the MBS saw. He didn't think you can maintain the pressure per particle that is necessary or that is achieved in slurry slicing where you actually have a point or a very short line contact. Is there anybody here from TI, who worked on the project that they had, slicing with diamond-coated blades?

DYER: I observed that project from a distance. I remember that it cut very fast at one time, and then it ran into some problem or something. It was dropped. It looked like at least an idea that could go on, i.e., combining the idea of the rotating crystal with the multi-blade saw, and it looked like it was worthy of at least somebody grabbing hold of it. Of course, when you get to the end of it, you're left with this little neck in the middle, and you have to cut that, and you have to do something to the thing so that it doesn't fall apart. So I think they just put some epoxy on the top. That may not be the best thing, maybe you'd want to put a series of spacers in or something. I really believe that it still a viable concept.

Has anybody considered or used or tried the idea of using a really cheap material for these blades, like some say as rigid as possible and as cheap as possible and as high-temperature as possible, e.g., a plastic?

FUERST: In the work done at TI, the blades were coated on the MBS saw, and they attempted to make slices using the normal mode of reciprocating motion with an ingot mounted beneath. The results were very poor, slicing times weren't good, slicing ability of the blade dropped off after the first cut. Then they went to the rotating crystal. They rotated the crystal at the same time they were reciprocating the bladehead. The results were very good, then they got very high cutting rates. Of course, they had the problem of 200 wafers all bound together by the tiny nipple running down the center of them. It was very difficult to demount.

WOLF: I was thinking of a blade by GE, diamond-coated uniformly along the cutting edge, make a very hard smooth cutting edge, and still have a free abrasive rolling underneath. This is not the fixed-abrasive-type system, but just a very hard tool, a counterpart of where the movable abrasive pushes against, but does not wear off the tool. The tool is harder than the workpiece, and the tool does not get abraded this way. We have to somehow look for ways of decreasing tool wear--that's one of our big costs--labor costs in mounting the tool of the bladepack, and cost of the blades, so if you could get to 100 runs per bladepack, we may have an economical system there.

SCHMID: By using a loose abrasive in combination with a fixed abrasive you tend to break down the bond, in fact you destroy the tool very quickly, because the loose abrasive is working on the nickel to release the diamond and you lose it.

WOLF: I'm not talking about embedded diamond. I'm talking about a uniformly coated grown crystal, a single crystal of diamond all along the cutting edge.

SUREK: Would you necessarily want to use any of these cutting techniques and approaches if you were to cut cheap silicon, maybe metallurgical-grade silicon, or would you want to maybe use that plastic blade which you can throw away after five cuts, or use a completely different approach where you're not worried about kerf and wafer thickness any more?

KOLIWAD: What happens in case we are to cut, not semiconductor-grade silicon, but metallurgical-grade silicon where we have silicon-carbide particles? What will be the blade life? Can we assume our projections to hold true there? Eventually, I think, we may go in that direction to further reduce the cost. So now we are at a point where we have those kinds of things to consider also.

Still, we have to have some estimation of the cost. So how cheap is the cheap plastic? Is there any state of the art we can establish?

WOLF: Also, I think that we ought to recognize that steel is one of the cheapest materials we have around, and practically all plastics cost a lot more than steel.

KOUNDAKJIAN: We manufacture ID blades. In the history of the ID blades you can see, 1960 to 1965, they were single-layer diamond. Because of the friction of certain points, it was getting real hot, and taking all the diamonds. We should start thinking about multilayer plating and some kind of cooling channels on the diamond section. When you have a multilayered diamond, you shouldn't have any difficulty when you're slicing. I think you should look into that point, 10 to 12 mils diamond depth on the wire.

MORRISON: To respond to Martin's suggestion of a hard blade for free-abrasive wafering: right now, what we have is a soft blade and a hard workpiece. The process works because the hard workpiece fractures. A hard-blade material would have to be so hard it would not fracture as easily as the silicon. In that case, the one thing to worry about, I'm afraid, is the shadowing effect that Werner talked about this morning. One hard free-abrasive particle that's larger than the others will lift that blade away from all the other abrasive particles and only one will cut at a time.

WOLF: On the other hand, if you have a long cutting length, there will be a number that are cutting. Certainly, I agree there will be probably an order of magnitude fewer grains cutting at a time, but still it may be worth while if we can extend the tool life significantly.

AHARONYAN: Re ID cutting with low kerf loss: we've seen some small reductions in kerf over the past two or three years. One of the biggest stumbling blocks is the core of that blade, the stainless sheet metal that has to be used to support the cutting edge. The blade saws that we're looking at for 10- to 15-cm ingots are generally 22 inches in diameter or 27 inches in diameter. Normally, they would need a 6-mil core as a minimum to get a good stiffness. We have found that we can make blades with a 4.8-mil core which is going to reduce our kerf by 1.2 mils and still maintain a good stiffness, get good slicing action. So I think one of the biggest things we can do in terms of blade development is find material that's going to give us the stiffness of a 6-mil stainless steel sheet yet have thickness of 3 or 4 mils. That will bring us down into the 9-mil kerf-loss range for these blades. That's one of the biggest steps we can do. We have to have some clearance between the diamonds. If we plate 9 mils of diamonds, we have to have a little bit of space between the diamond particles and the surface of the blade. You can make a very thin blade, but it's not going to cut well, unless you have this clearance. The core material seems to be a big area for improvement. Right now, the material is just plain old stainless steel sheets that are work-hardened to a very high tensile strength.

DAUD: Question to Peter (Aharonyan): if he could comment on etching the core and then making the blade--will it work or not?

AHARONYAN: We've done some etching, and we've seen some small differences. We've also done some heat treating and also seen some differences. But they're not dramatic. I think what has to be done is just a plain old percentage increase in the tensile strength of the material. Right now, we're working with material on the order of 250,00 to 300,000 psi. If we can increase tensile strength by 30% or 40%, we can reduce the thickness by 30% to 40%, in the core. The stainless steels we're using now are about as strong as they can be made.

DYER: I'd like to make a comment on the ID saw, I'm not necessarily in favor of it for the solar cells. But, it is the thing to be used, I think that the machine has to be developed more than the blade. I think that the manufacturers may be up against a material-strength limit in the material they use for the blade core. I think we have to pay more attention to what the blade is doing and design some things into the machine to make it help the blade do that without fracturing the slice. The things that come to mind include: in order to decrease the contact stresses, as you're plunging through this material, you need to have the blade so that it's in contact all the time, rather than just part of the cycle. This means you have to have a concentric head which at the present time, means that you have to use a slightly more time-consuming setup of the mechanically tensioned head. If someone could develop one that could be done quickly with a hydraulic ring, but tensioning equally all around, then that's fine.

Other things include taking care of the out-of-plane vibrations spoken of by Dr. Kuan. Lubricants with a damping quality could help that. The idea in the Siltec contract of using air-bearing slippers on either side of the crystal to squeeze it down to where it's running as close to the center of a theoretical plane as possible, that's another that ought to be included.

The in-plane vibrations are made worse by any imbalances in the system. And they're also made worse by having this big heavy head come down on the thing. So maybe if you could lighten up the head as much as possible, and have some automatic way to wash the sludge and perhaps broken slices out of the machine, make this all built into the design of the thing. And then one that I don't even know whether it's possible: if you could make a force-sensitive cutting, so that if the contact stresses get beyond a certain level, then the saw no longer puts that full force on, but waits until the stress falls below the level, then comes down. All of these things have to be done, and maybe could accomplish the goal of reducing the kerf. I think if we could do all those things, then the blade manufacturers could make the thin-core blades.

AHARONYAN: A lot of things you mentioned are the things that either we have now, or we're working on in our development. But getting back to the point of centering the ID of the blade, we think that that's a very important factor in cutting efficiency and getting good results. We have a blade mount now, and we're also looking to improve it, which we think can do that job relatively quickly and perhaps as easily as the hydraulic blade mounts that people are using now. But even if it's a little more difficult it may be worthwhile to spend the extra 15 or 20 minutes every two or three days to get the machine to its full capability of using the 100% of the diamonds on the ID.

WOLF: I think we got away from the economic analysis and looked at the technical questions of what can make the results of these analyses come true, which I guess is really the core of the whole thing. The analysis is only as good as the technical improvements that can be realized.

NEW TECHNOLOGY

Chairman: G.S. Kachajian, Silicon Technology Corp.

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OVERVIEW OF A NEW SLICING METHOD-- FIXED ABRASIVE SLICING TECHNIQUE (FAST)*

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ABSTRACT

FAST is a new slicing technique that has been developed to slice silicon ingots more effectively. It has been demonstrated that 25 wafers/cm can be sliced from 10 cm diameter and 19 wafers/cm from 15 cm diameter ingots. This has been achieved with a combination of machine development and wire-blade development programs. Correlation has been established between cutting effectiveness and high surface speeds. A high speed slicer has been designed and fabricated for FAST slicing. Wirepack life of slicing three 10 cm diameter ingots has been established. Electroforming techniques have been developed to control widths and prolong life of wire-blades. Economic analysis indicates that the projected add-on price of FAST slicing is compatible with the DOE price allocation to meet the 1986 cost goals.

INTRODUCTION

Silicon crystals have been sliced into wafers for the semiconductor industry by the Internal Diameter (ID) and Multiple Blade Slurry (MBS) techniques. While these processes were developed for semiconductor applications, they cannot be utilized, as they exist today, for photovoltaic applications. Unlike semiconductor devices where silicon material constitutes sometimes less than one per cent of the cost, the cost of silicon wafers comprises about half the cost of a solar panel. The wafering technique to produce silicon wafers from ingot is one of the important steps towards reducing costs for terrestrial photovoltaic applications. The slicing process must be low cost and must combine minimum kerf plus slice thickness to achieve high material utilization. With improved material utilization alone, the contribution of the cost of polysilicon and crystal growth for photovoltaic power generation, dollars per peak watt, is significantly reduced. Therefore, material utilization is critical for reducing costs to make photovoltaics a reality for terrestrial applications.

Besides being most developed and commercially available, the advantages of an ingot process towards making sheet are high throughput, purification of meltstock during growth, consistent quality, simple instrumentation and control; however, material utilization and kerf in slicing limits the low-cost potential. In fact, the justification for silicon ribbon processes is based on the premise that slicing cannot be cost effective. As the cost of polysilicon meltstock is reduced to the goal of $14/kg kerf losses in slicing become less significant but material utilization is still critical. The combination of an effective slicing process with an ingot process, such as the Heat Exchanger Method (HEM), allows the economical production of square shaped high conversion efficiency material to produce high power density modules at low cost.

SLICING TECHNIQUES

The essential parameters for a slicing technique for photovoltaic applications are (i) low-cost process, (ii) low expendable costs, (iii) high material utilization and (iv) produce high quality product. There are three commercially used wafering processes, *viz.*, ID, MBS and Multiple Wire Slurry (MWS) techniques. A comparison of the parameters for these wafering methods is shown in Table I. It can be seen that the advantages are low expendable material costs in ID, low equipment and labor costs in MBS, and high material utilization in MWS; however, the ID is limited by material utilization, and MBS and MWS by their high expendable materials costs. A new slicing technique under development, the Fixed Abrasive Slicing Technique (FAST), combines the low expendable material advantage of ID, low equipment and labor costs of MBS and high material utilization of MWS.

TABLE I. A Comparison of the Essential Parameters of Wafering for Different Slicing Techniques

Parameter	ID	MBS	MWS	FAST
Equipment costs	High	Low	High	Low
Labor supervision	Medium	Low	High	Low
Throughput	Medium	Medium	Low	High
Expendable costs	Low	High	Very high	Low
Material utilization	Low	Medium	High	High
Surface damage	High	Medium	Medium	Low

In the FAST process (1) a multiple-wire bladepack is stretched in a frame and reciprocated on rails. Diamond is fixed onto the wires and used as an abrasive for slicing silicon. Diamond has been demonstrated to be an effective abrasive for silicon via the ID process and, therefore, the expendable materials costs are kept low. The simplified equipment concept of reciprocating bladehead keeps the FAST slicer costs low and this has been proven by the MBS. The best material utilization of wire slicing (2) is also incorporated in FAST. This feature is possible with wire because once the wire cuts through it no longer contacts the workpiece, hence less clearance is necessary. This reduces kerf and also make it possible to slice thinner wafers. In the MWS the silicon being sliced is completely lost when a wire breaks. For the FAST approach, a broken wire results in loss of two wafers it is contacting. In addition to the above advantages to FAST the surface damage of the sliced wafers is lower (3) than that reported for other slicing technologies (4).

FAST is a new slicing technique that has been developed to slice ingots more effectively. Work has been carried out in three areas, *viz.*, machine development, blade development and testing.

FIXED ABRASIVE SLICING TECHNIQUE (FAST)

Machine Development

Initially a MBS slicer was used for evaluation of FAST slicing. Prior work reported in literature showed very limited success with slicing using diamond plated flat blades and wires. In the development of FAST it was found that the slicing is heavily dependent on pressure at the diamond tips during slicing. Effective slicing was not achieved with diamond plated wires used in a conventional MBS setup because of insufficient pressure at the cutting edge. Significant improvement was achieved when the crystal was rocked. Under this condition the kerf length or contact between the wire and the workpiece was minimized thereby maximizing the pressure at the diamond tips used in slicing. The MBS slicer was further modified by changing the feed system; the feed forces required for wire slicing were considerably lower than used in MBS slicing, hence a more sensitive and reproducible feed mechanism was incorporated. Grooved guide rollers were also installed on either side of the workpiece so that the feed force could be increased as well as to improve the slicing accuracy. With all the modifications to MBS equipment the workpiece size was limited to 4 cm x 4 cm cross-section. The concept of FAST was proven by demonstrating (i) slicing 25 wafers/cm at high yields, (ii) slicing wafers to a thickness as low as 100 μm, (iii) reducing kerf width to as low as 160 μm, (iv) absence of any edge chipping in sliced wafers and (v) surface damage depth of 3-5 μm (3).

Experience with the modified MBS slicer showed some essential parameters which could not be incorporated. A new high speed slicer was designed and fabricated. The essential features of this machine were lightweight bladehead, longer stroke, sensitive feed mechanism, crystal rocking assembly, variable guide roller position and vibration isolation of the drive unit. A schematic of the bladehead is shown in Figure 1. This unit is designed to accommodate up to 30 cm long and 15 cm diameter workpiece. The lighter bladehead and longer stroke allowed faster reciprocation and, consequently higher surface speeds; 130 meter/min has been achieved with this unit as compared to 30 meters/min with the modified MBS unit. A more rigid support system minimized vibrations at these high speeds.

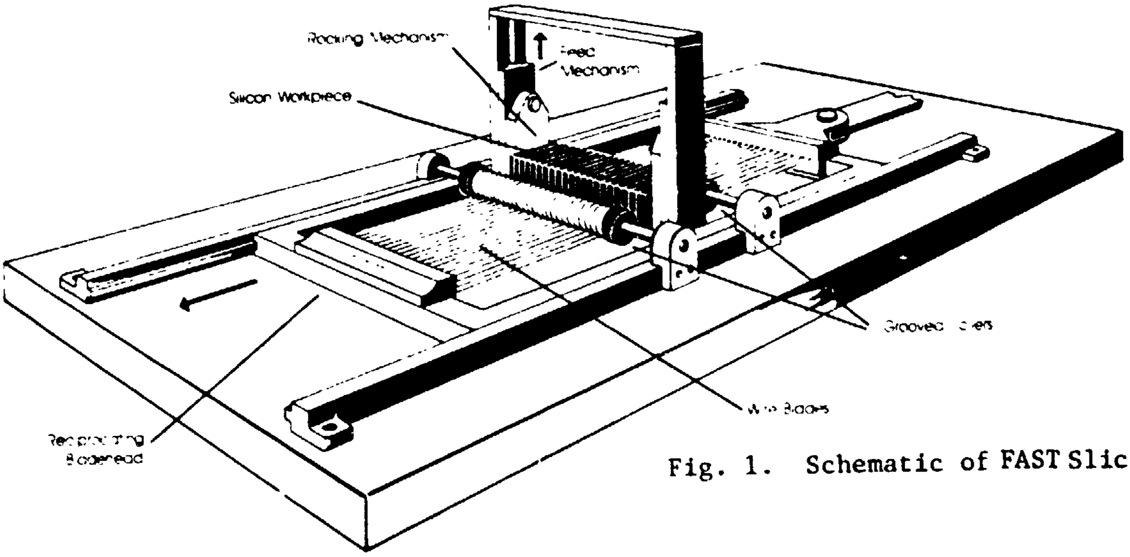

Fig. 1. Schematic of FAST Slicer

The prototype slicer designed is a two-bladehead unit linked to a single drive unit. The two bladeheads will be reciprocated 180° out of phase so that the acceleration forces will be counterbalanced equal and opposite, thereby cancelling each other. This will allow even higher speeds, less vibration and more effective slicing.

Blade Development

In order to slice effectively it is imperative to have a good blade; for FAST slicing it is important to develop effective wire blades. More detailed information on this aspect is discussed in another paper of this conference (5). In the initial stages of FAST development the only fixed abrasive wires available were diamond impregnated wires (6). Testing with these wires showed that they suffered diamond pull-out. Nickel plating of commercially available wires prolonged their life.

A wire-blade development program was, therefore, initiated to produce fixed-abrasive wires for FAST slicing. Two types of approaches were pursued, viz., impregnated blades and electroplated blades. In the former case diamonds were pushed into a soft copper sheath on a high strength core; this wire was then nickel-plated to prevent diamond pull-out. Techniques were developed to impregnate diamonds in the cutting edge only--the bottom half-circumference of the wire. Significant advances were made but this approach needs much more development.

Prior to this program there was no source of electroplated wires. Even though plating of ID blades is carried out in the industry the large surface area-to-volume ratio in the case of wires presented problems. Electroplated wire-blade development has involved optimization of type and size of wire core; coatings on the wire substrate; nature, type and size of diamonds; plating baths, etc. (5). Techniques have also been developed to electroform the diamond plating to reduce kerf and achieve long life of the wirepacks (5).

Testing

The present work is a report on slicing of 10 cm diameter, 10 cm x 10 cm cross-section and 15 cm diameter silicon workpieces at 19 wafers/cm. With 10 cm diameter even 25 wafers/cm have been demonstrated.

One of the first variables studied by FAST was the surface speed. Figure 2 shows slicing tests of 10 cm diameter as a function of surface speed. A comparison of data from Tests A and C shows that by doubling the surface speed the average slicing rate increased from 59 μm/min to 145 μm/min, a factor of 2.45. Test B was carried out using the same wirepack as Test A for a second slicing life test. The average slicing rate for Test B was 122 μm/min, a slight decrease showing deterioration of cutting effectiveness. The data in Figure 3 is for slicing tests using a mixture of 15, 30 and 45 μm diamond size electroplated wirepack spaced at 19 wires/cm and shows a life of three 10 cm diameter ingots at an average cutting rate of 127, 82 and 75 μm/min. The surface speed during this experiment was 120 meters per minute.

Figure 4 shows the slicing test carried out using the same electr[illegible]ed wirepack. The diamond size used was 30 μm and the surface speed of t[illegible] . Si

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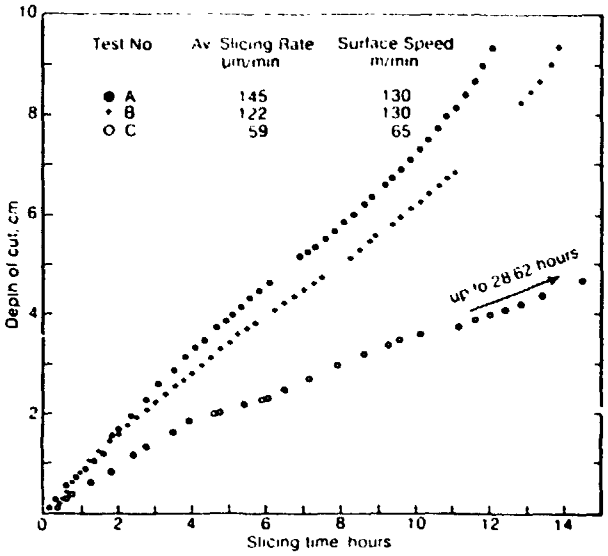

Fig. 2. Slicing performance showing the effect of surface speed

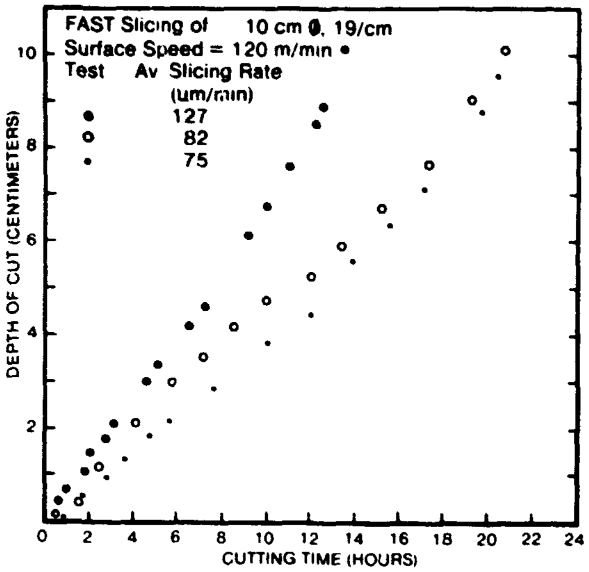

Fig. 3. Slicing of three 10 cm Ø ingots using same electroplated wirepack

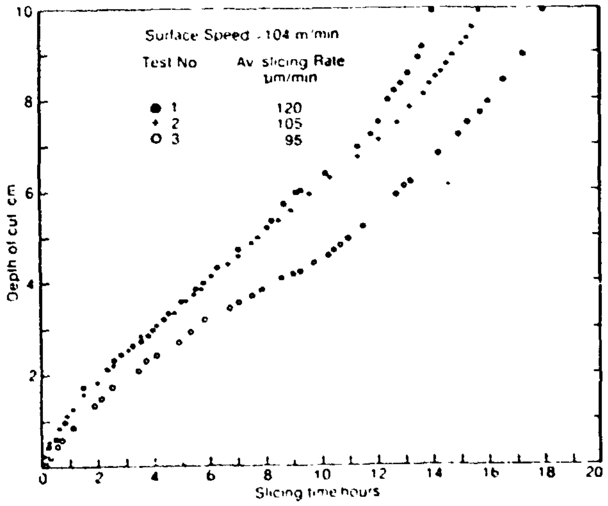

Fig. 4. Slicing performance from the same wirepack using 30 µm diamonds

slicer was 104 meters per minute. The average slicing rate for tests 1, 2 and 3 were 120, 105 and 95 µm/min respectively.

A similar test with wires impregnated with 45 µm diamonds showed an average slicing rate of 72 µm/min on a 10 cm diameter workpiece. These wires could not be used for a second slicing test; in fact toward the end of the first test wafer breakage was observed which was attributed to loss of cutting effectiveness.

In order to reduce the kerf width for slicing 25 wafers/cm a 30 µm diamond electroplated wirepack was used. During the first test a 99.1% yield (222 out of 224, 10 cm diameter wafers) was achieved with an average slicing rate of 77 µm/min. In this test low feed forces of only 24.4 gms/wire were used. Very good surface quality of wafers was achieved and the average wafer thickness of 0.195 mm with a kerf of 0.205 mm. During the second slicing test the average slicing rate dropped to 45 µm/min and the yield was only 36.2%. The average wafer thickness increased to 0.249 mm with kerf of 0.151 mm. The data shows that during the first slicing test considerable diamonds from the sides of the wires were pulled out, thereby reducing kerf, increasing wafer thickness and decreasing the average slicing rate. The plot of the depth of cut with time is shown in Figure 5.

Slicing tests with 15 cm diameter silicon workpiece were also carried out. For the larger kerf length 60 µm natural diamonds were electroformed into a

V-shape so that the diamonds were fixed only in the cutting edge of the wires. The average slicing rate was 74 μm/min. This is considerably higher wafering rate especially in view of the larger kerf length. During the test some wire wander was observed because the diamonds on the top surface of the wires could not be completely eliminated. The non-uniform nature of the top surface caused perturbation and, therefore, the wires did not seat well in the guide rollers. The data for this run is shown in Figure 6.

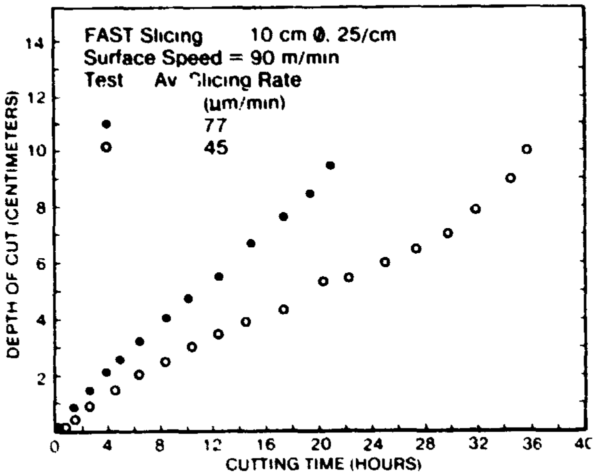

Fig. 5. Slicing results of
10 cm Ø ingots at 25 wafers/cm

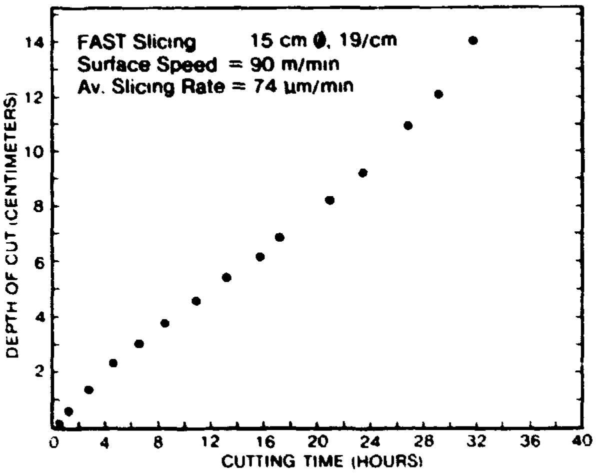

Fig. 6. Slicing performance
of 15 cm Ø ingot

ECONOMIC ANALYSIS

The economic analysis has been carried out to estimate the projected add-on price of FAST slicing using IPEG methodology (7). It is intended to use a FAST slicer with two bladeheads reciprocating 180° out of phase. Each bladehead will slice a 10 cm x 10 cm x 30 cm bar to produce wafers of 10 cm x 10 cm cross-section. Two types of scenarios were developed, a conservative and an optimistic case, to estimate the projected price. The assumptions and the final add-on price are shown in Table II. Even in the conservative case the final value is less than half of the price allocation (8) for ingot technologies to meet DOE price goal of $0.70/peak watt in 1986.

CONCLUSION

The Fixed Abrasive Slicing Technique (FAST) combines the low expendable materials advantage of ID, low equipment and labor costs of MBS and high material utilization of MWS. Besides FAST produces a wafer which shows no edge chipping and with a surface damage of only 3-5 μm. This new slicing technique was initially developed by modifying a MBS slicer. After establishing the proof of concept a high speed slicer was designed and fabricated.

Techniques were developed to produce wirepack with equal spacing and tension. The wire-blade development program has involved impregnation and electroplating techniques. It has been shown that diamonds can be fixed only in cutting edges of wires. With electroforming it has been possible to control the shape and size of the plating.

Slicing effectiveness has been demonstrated on 10 cm and 15 cm diameter ingots. It has been possible to slice 25 wafers/cm on 10 cm diameter ingots and 19 wafers/cm on 15 cm diameter ingots. A blade life of slicing three 10 cm diameter ingots has been demonstrated.

Projected economic analysis has shown that the FAST technique will be able to slice silicon ingots effectively to meet the DOE price allocation for 1986 goal of $0.70 per peak watt.

TABLE II. IPEG ANALYSIS FOR VALUE ADDED COSTS OF FAST SLICING USING CONSERVATIVE AND OPTIMISTIC PROJECTIONS OF TECHNOLOGY

	Estimate	
	Conservative	Optimistic
Equipment cost, $	30,000	30,000
Floor space, sq.ft.	80	80
Labor, units/operator	5	10
Duty cycle, %	90	95
Set-up time, hrs	1.5	1.0
Slicing rate, mm/min	0.1	0.14
Slices/cm	22	25
Yield	90	95
Expendables/run, $	28	14
Motor power, h.p.	5	3
Conversion ratio, m^2/kg	0.85	1.0
Add-on Price, $/$m^2$	13.13	5.9

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*Supported in part by the LSA Project, JPL, sponsored by DOE through agreement with NASA.

REFERENCES

1. F. Schmid and C. P. Khattak, ERDA/JPL 954373, Final Report (Phase I), December 1977.

2. M. H. Leipold, C. Radics, and A. Kachare, "Cost of Czochralski Wafers as a Function of Diameter," JPL Publication 80-25, February 15, 1980.

3. C. P. Khattak and F. Schmid, Proc. 2nd. Photovoltaic Solar Energy International Conf., Berlin (West), (1979).

4. T. Daud, J. K. Liu, G. A. Pollock and K. M. Koliwad, Proc. 13th IEEE Photovoltaic Specialists Conf., Washington (1978).

5. C. P. Khattak, F. Schmid and M. B. Smith, Proc. JPL/LSA Project Wafering Workshop, Phoenix, AZ, June 1981, to be published.

6. Laser Technology, Inc., No. Hollywood, CA.

7. Interim Price Estimation Guidelines, JPL Document 5101-33, September 10, 1977.

8. Aster, R. W., "Price Allocation Guidelines, January 1980," JPL Publication 80-51, January 15, 1980.

DISCUSSION:

JACKSEN: Could you give us some taper and wafer-to-wafer dimensional variations, especially when you were cutting 4-mil wafers?

SCHMID: In the initial work with the 686, to cut 25 per centimeter you have to be slicing with reasonably good accuracy. Those tests were performed with much larger kerf. Basically we were looking at 10 mils. So we actually were slicing wafers around 5 mils thick and were seeing taper of maybe a thousandth of an inch. On the new machine we are seeing less than that at the higher speed. As your cutting rates go up your accuracy tends to get better.

JACKSEN: You mentioned this reciprocating machine. Has that machine been built or do you anticipate it being built?

SCHMID: The machine that we have is an R&D prototype and we feel that that machine is very similar to the prototype machine that would be used as the production prototype. There isn't that much change.

JACKSEN: The main reason I am asking is to understand what increase you can expect from your productivity figures from that reciprocating machine. Obviously you are running at a higher rate of meters per minute and I was wondering what you projected your meters per minute of slicing rate would be with a reciprocating machine.

SCHMID: We now are running between 350 and 400 feet per minute for most of these tests. We have gone through all of the calculations and we think by balancing it out you save horsepower, you take out vibration and you can go to higher speeds which does help you in your slicing performance. That is why we would expect to be able to exceed the actual cutting rate that we have set here as a goal.

DYER: You were mentioning that you had facilities for accurate alignment. If you are going to put something into production for an industry that has to produce slices cheaply then it has to be something that an operator can do easily and without a great deal of training. What I envision in that is perhaps something where you have the alignment fixture on a cart and push it up against the machine and clamp, pull something towards them and lock it in. You shouldn't have to expect them to read a dial indicator or anything like that.

SCHMID: This is the R&D machine in which we had to make sure that we did have the accuracy. Once the machine is set up there is no reason to have to realign it. It is nice to be able to have a serviceman come in and check to be sure that it is lined up properly, and that really is the goal. As for the tensioning, the way we tension these wires is by elongation and that is where you do have to read a micrometer.

DYER: Doesn't the saw blade have to be lined up every time you put a new pack on?

SCHMID: With this technique it is possible to circumvent that. We now are checking it optically to see that the wires are running true.

SYSTEM FOR SLICING SILICON WAFERS

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The newly patented process described here is a system for slicing silicon wafers that has distinct advantages over methods now widely used. The primary advantage of the new system is that it allows the efficient slicing of a number of ingots simultaneously at high speed.

In one of the methods now used, an inside-diameter saw cuts at constant surface speeds, with rapid slicing of one ingot at a time. In a second method, a reciprocating gang saw provides multiple cuts, but in a relatively long time. A third method, a wire technique, marries some of the advantages of the other two methods but has a severely limited service life. Any method that would provide simultaneous fast multiple cuts on several ingots with fewer system breakdowns would be worth considering.

The new cutting concept presented here presents an alternative to the old methods in which the cutting action is performed mechanically, most often with diamond particles that are transported to the cutting zone by a fluid vehicle or have been made an integral part of the blade by plating or impregnation.

The new system uses a multiple or "ganged" band saw, arranged and spaced so that each side, or length, segment of a blade element, or loop, provides a cutting function. Figure 1 illustrates the key functions associated with a single-blade element, operating with a single work station. One end is the driving pulley and the opposite is an idler that is instrumented to maintain tension and detect blade failure. In the event of blade failure, the instrument senses the problem and stops the blade to prevent catastrophic ingot damage. The design would provide for withdrawal of the failed blade while continuing the cutting cycle with a minimum of damage.

Each blade is maintained precisely in position by guides as it enters and leaves each ingot. These expendable guides can be translating ribbons or slowly rotating disks. In the case of rotating disks, as illustrated, the guides rotate one-half revolution during a cutting cycle. This provides fresh, unworn guide material to prevent blade wobble. The guides are designed to be inexpensive and easily replaceable. They are replaced as a unit rather than individually to reduce down time.

The cutting action is performed with a conventional abrasive slurry composed of diamond grit suspended in an oil- or water-based vehicle. The distribution system draws the slurry from the supply reservoir and pumps it to the injection tubes to supply it to each side of each ingot. A flush system is provided at the outer end of the work-station zone. In order to reduce potential damage, a pneumatically driven flushing fluid is provided for removing cutting fluid and cutting debris. This is collected by a drain, filtered, and returned to the reservoir for reuse. This technique would minimize blade wear and damage to the drive system.

The blade is made of a ductile material and is relatively wide and thin in cross-section. It is fabricated without teeth, but during operation the cutting edge passes over a knurling wheel that deforms or refigures the cutting edge sufficiently to serrate it. The formation of these serrations would increase blade-edge thickness due to lateral deformation of the blade; to correct this, the blade is passed between a pair of cylindrical surface rollers. The blade is thus refigured before each cutting pass (see Figure 2).

The primary purpose of the serrations is to transport the slurry from the distribution system to the cutting surface and to provide egress for chips and debris.

The work station contains the mechanism for holding and advancing the ingot. The figures depict the ingot held in the work station and advanced from below; however, due to the nature of the serrated blades, it may be more effective to utilize an overhead feed with the serrated blade edge on top. The feed system should be instrumented to provide a constant unit load throughout the cutting cycle.

Figure 3 illustrates a plan view of the multiple assembly. The fan pattern provides sufficient space for the drive and tension mechanisms.

The rollers and idlers would be sized to maintain the internal stresses of the blade at a sufficiently low level, resulting in long service life. The fan configuration at each end of the machine would allow a standard blade length. The long blades would reduce wear and permit many cutting cycles before the blade would need replacement.

The number of work stations representing the number of ingots to be sliced will depend upon the installation. The probable practical limits would be a minimum of two or three, which would make the investment uneconomical, to a maximum of 20, beyond which it would be mechanically unwieldy.

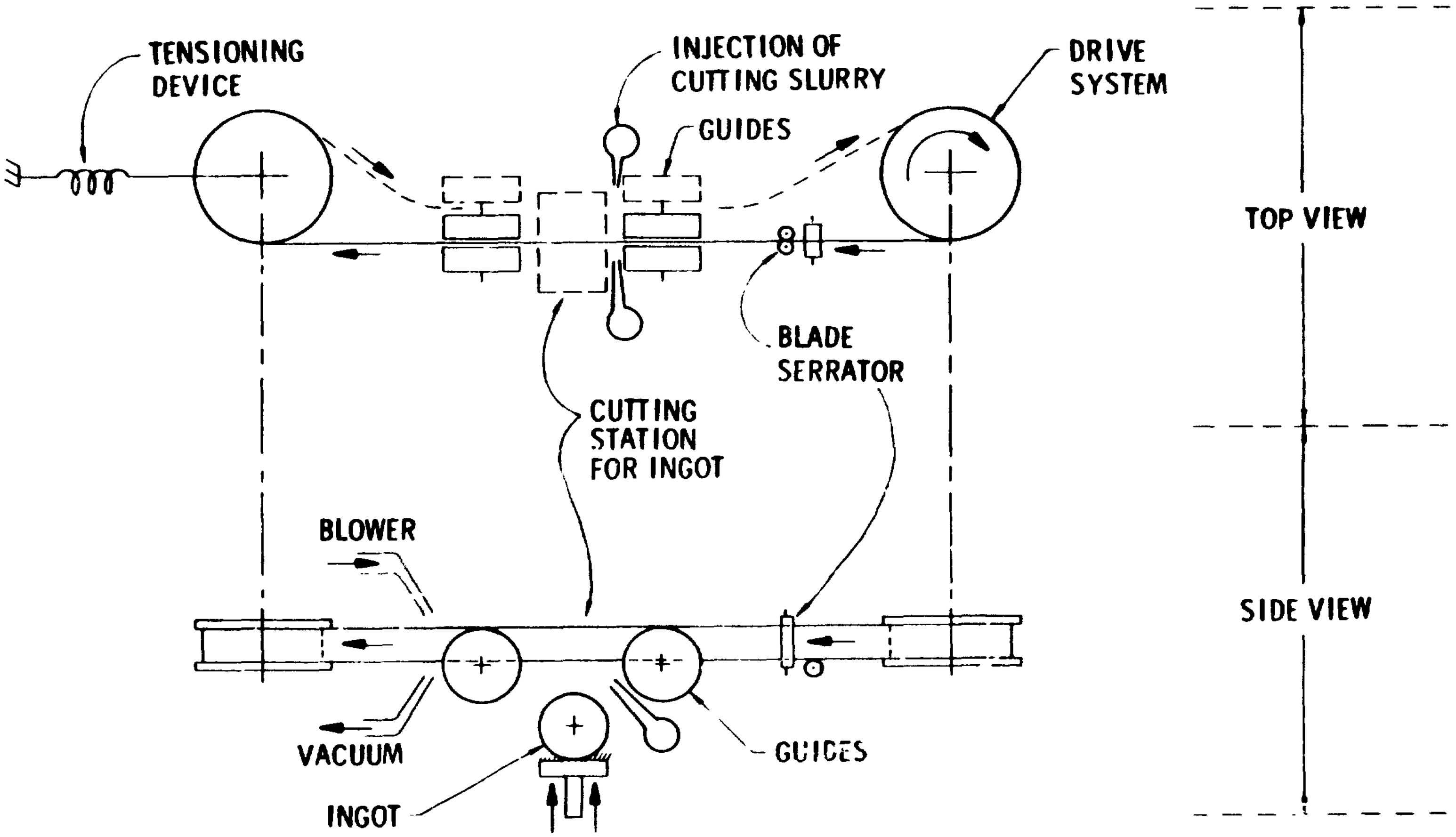

Fig. 1. Representative Single Element (One Direction Only)

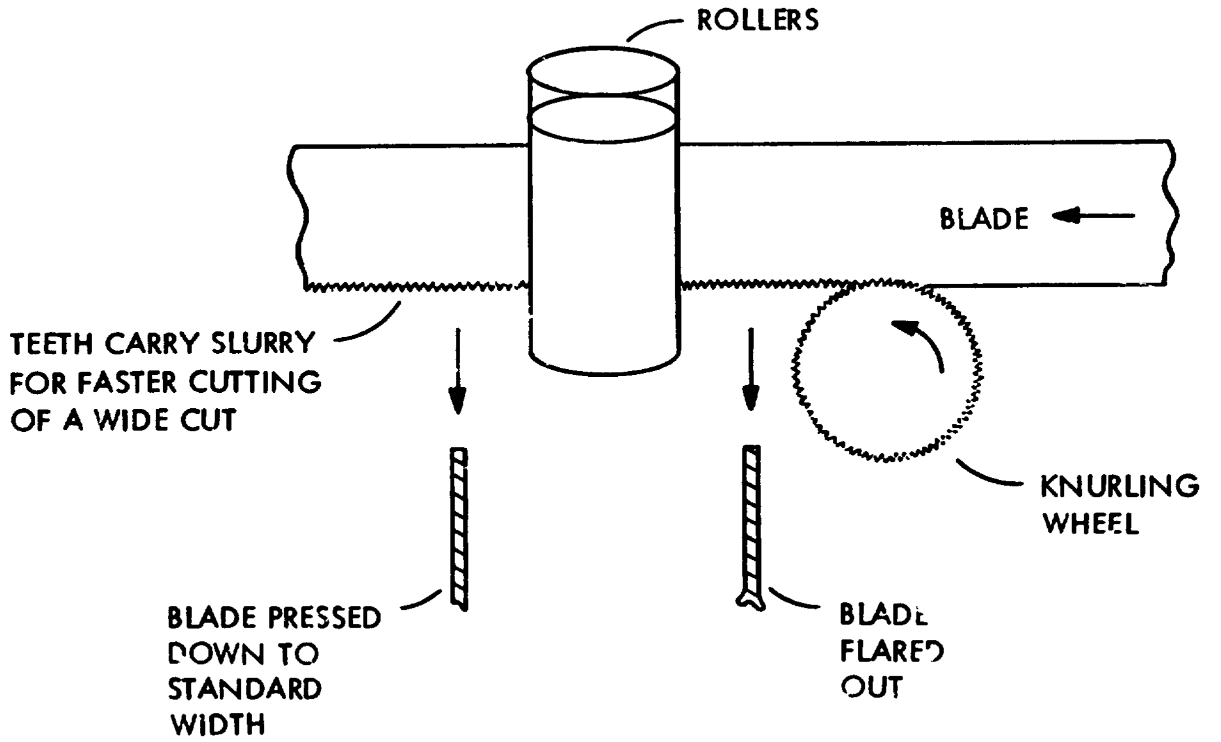

Fig. 2. Blade Serrator

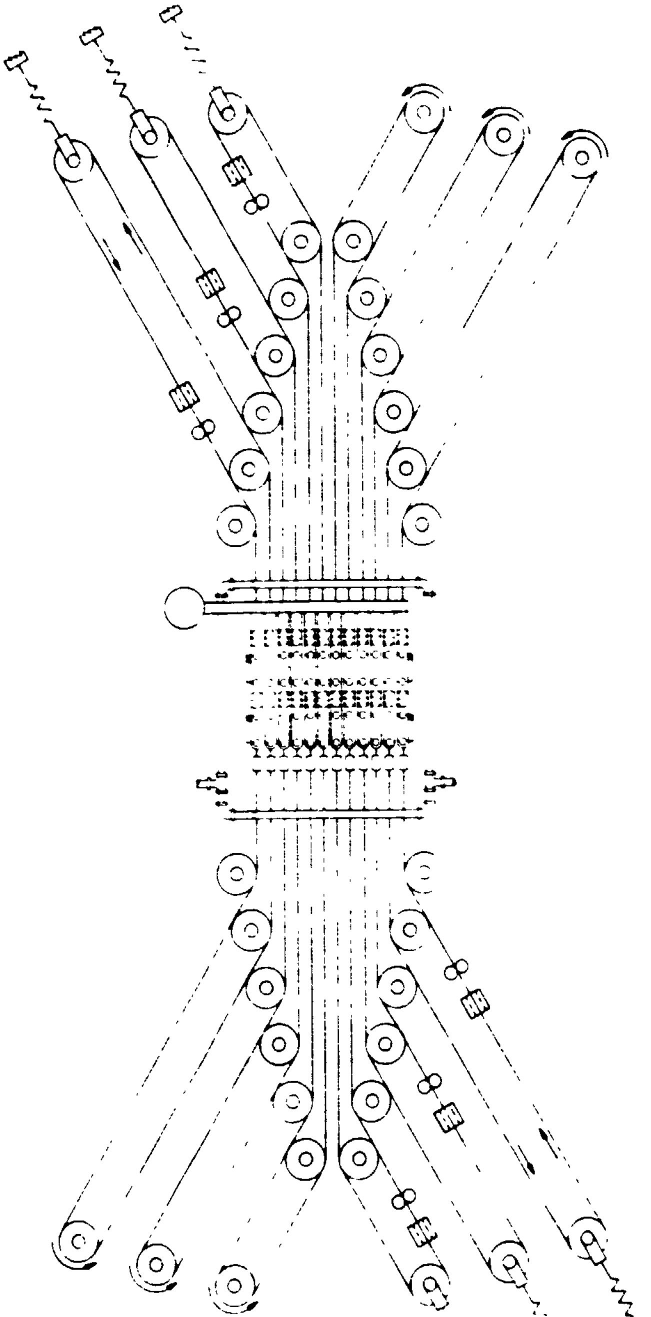

Fig. 3. System for Slicing Silicon Wafers

DISCUSSION

DYER: I see one difficulty. If you have alternating directions you will have a torque in the slice, particularly as it gets toward the bottom, and this may be a difficulty because the friction operating in both directions is going to have a tendency to break the slices off in a torsional fashion.

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DIAMOND SHEET - A NEW DIAMOND TOOL MATERIAL

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DIAMOND SHEET - A NEW DIAMOND TOOL MATERIAL

DIAMOND SHEET is termed a diamond tool material because it is not a cutting tool, but rather a new material from which a variety of different tools may be fabricated. In appearance and properties, it resembles a sheet of copper alloy with diamond abrasive dispersed throughout it. It is capable of being cut, formed, and joined by conventional methods, and subsequently used for cutting as a metal bonded diamond tool.

ABRASIVE

DIAMOND SHEET is normally made with industrial diamond as the abrasive material. If materials or cutting conditions require, other types of abrasive may be used. Diamond sizes range from 100/120 screen size (149 - 125 microns) for coarse cutting operations, to single didget micron sizes for fine polishing. Work is being done on extending the range of coarse sizes, and some 60/80 screen size (250 - 177 microns) has been made experimentally. Diamond contents up to as nigh as 100 concentration (approximately 25 volume percent) can be manufactured.

SIZES

The current available size range of DIAMOND SHEET is .005 to .030 inch (.127 - .762 mm) for thickness, 3 inch (76.2 mm) maximum width, and 10 inch (254 mm) maximum length. The width and length maximums will probably be expanded in the future. Widths up to 4.5 inches (114.3 mm) and lengths up to 24 inches (609.6 mm) have been made experimentally.

MATRIX

The metal matrix in DIAMOND SHEET is a medium hard copper alloy which has performed well in most applications. This alloy has the capability of being made harder or softer if specific cutting conditions require it. Other alloys have also been used including a precipitation hardened aluminum alloy with very free cutting characteristics.

The standard copper alloy matrix provides cutting characteristics very similar to that of a conventional molded copper alloy diamond tool. Because of the complete densification and homogeneous microstructure in DIAMOND SHEET, it's cutting life is normally significantly improved. On a direct comparison basis, some tools made with DIAMOND SHEET have removed almost four times as much material as conventional molded tools of similar composition.

FABRICATION

The flexibility of DIAMOND SHEET allows it to be fabricated into a variety of products. Sections may be easily cut from pieces up to .020 in. (.508 mm) thick with paper cutting tools such as scissors and paper punches. Thicker sections may be cut and formed with hand metal working tools. Die cutting may be done on all thicknesses. Brazing, soldering, and organic abrasives may be used for joining.

SAWING

One of the most outstanding uses for DIAMOND SHEET, and the reason it was originally developed, is for thin cutting and slicing tools. Very close dimensional control can be maintained on the thickness, and tools are easily cut or blanked to shape.

For wafering applications, DIAMOND SHEET is a possible saw material for multiple blade saw cutting. Some limited tests made using solid strips of sheet showed it to be very free cutting with a good surface finish as compared to electroplated diamond and loose abrasive techniques. Tests have been limited because the sheet does not have sufficient strength to withstand the normal tensioning operation. Work is being done to join DIAMOND SHEET to a high strength alloy backing to overcome this problem. With I.D. and band saw blades, the possibility exists of replacing the present electroplated coating with DIAMOND SHEET segments.

The preceeding applications could be accomplished by wrapping or folding DIAMOND SHEET strips over the blade cutting edge. A greater advantage can be obtained by butting or insetting the sheet on the edge. By this method, the cutting edge relief could be controlled and could be made less than the one particle width required for electroplated or loose abrasive tools. This would allow smaller kerf losses with existing blade backings, or thicker backings with less possibility of distortion using existing abrasive widths.

Circular saw blades blanked from DIAMOND SHEET have proven to be very effective in dicing and slotting operations. An economical method of using such saws is to have a saw mechanism capable of using a range of blade diameters, and utilize a set of increment flanges. A blade may then be set up with a large flange, used until rim exposure is too small, then set up with the next smaller set of flanges for further use.

SURFACING TOOLS

Surfacing tools such as laps, bevelers, hones, etc. can be made by cutting full sections, segments, strips, or pellets of DIAMOND SHEET and attaching them to a backing. Such tools are ideally suited to prototype and short run production items. Because of their long cutting life, such tools can also be expected to compete favorably in normal production situations.

For wafering applications, laps virtually any diameter can be constructed for dimensioning and removing surface defects in wafers. The cutting characteristics of DIAMOND SHEET can provide rapid material removal and good uniform finishes while eliminating costly and machine damaging loose abrasives.

Surfacing tools with simple or compound curves can be formed by using male/female forms to mold and hold the DIAMOND SHEET as it is attached to a backing.

RING TYPE TOOLS

Tools such as core drills, ring cutters, and blanchard type wheels can be made by forming DIAMOND SHEET around a mandrel of the proper size, and attaching it to an appropriate backing.

Core drills as small as 3/16.in have been formed from sheet .020 in. thick. Small diameter core drills have been used successfully with only a single layer of sheet and an open butt joint. Larger single layer drills require a soldered or brazed joint to prevent flaring. In use, formed core drill sections are soldered to a mandrel or held directly in a collet.

Tools for surfacing operations such as ring cutters and blanchard wheels are formed using two or more layers of DIAMOND SHEET which are soldered or brazed together while being formed. The ring thus formed is mounted in a reusable backing plate.

Tools of this type are inexpensive and due to their thin walls, well suited to high speed, high unit pressure operations. On some very hard materials, DIAMOND SHEET tools have been the only econimical method of material removal.

The examples of tools which can be made with DIAMOND SHEET represent only the most obvious examples of what can be done with it. The listing does not include items which are so mundane as to be overlooked such as files, or simply used loose as sandpaper for the hand finishing operations. On the other extreme are applications which are not normally associated with abrasive tools such as bearing surfaces (diamond to diamond) and wear resistant surfaces.

I.D. SLICING AND THE AUTOMATED FACTORY

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Silicon wafering in the semiconductor industry today is done almost exclusively on I.D. saws operating semiautomatically. One machine operator is required for support of every four to ten saws. The exacting cost goal of the Low-Cost Solar Array Project demands a much higher level of automation. The I.D. saw of today must be enhanced to operate with less human intervention. This improved saw must be integrated into a slicing system which makes maximum use of each individual saw. The slicing system, in turn, must be controlled by some central intelligence so it can meet the demands of the overall manufacturing process.

The objective of automation is, of course, increased productivity. The ratio of process output to resource input must be increased while the desired production rates are maintained. The output of a solar array factory is measured as peak output power of the finished product. The measure of resources used is the cost of materials, capital equipment, labor, and consumables.

The saw productivity can be increased by reducing silicon waste, decreasing usage of consumables, keeping the saw slicing, and increasing the cutting speed. These variables are strongly interrelated. An improvement in one may adversely affect others. Since the saw improvements which follow are evaluated qualitatively only, a net productivity gain is possible only if no negative effects are likely.

The I.D. saw as it exists today is capable of cutting a number of wafers automatically. The desired number is entered manually from the machine control panel, and operation is initiated. When the correct number of wafers is completed, operation stops. The machine now sits idle until the operator removes the wafers and restarts the slicing operation. An automatic wafer removal system would eliminate the need for manual intervention. The unpredictable human response is eliminated enabling the saw to spend more time slicing and thereby reducing idle time.

Another area which requires action by the operator is blade dressing. Blade deflection monitors are widely used to determine when a blade needs service. If axial blade deflection exceeds a preset limit during a slice, the slice is completed and the saw is stopped before a new slice is started. An alarm light alerts the operator who must manually dress the blade. A strip chart recorder maintains a record of deflection versus time which can be used to determine what part of the blade needs dressing.

Blade dressing affects blade life, wafer quality, kerf loss, and slicing speed. Proper blade dressing is a necessity for high productivity. An automatic system which can interpret blade deflection data and can respond with the correct dressing action is an important machine enhancement. Excess blade deflection can also be caused by loss of blade tension. When dressing does not restore correct cutting action, retensioning is usually necessary. Early detection of tension loss would permit corrective action before blade damage occurs and would eliminate unnecessary blade dressing.

Occasionally, a wafer will stick to the back of the blade and, if not removed, will break subsequent wafers. Corrective action is to shut down the saw and to flush out the wafer or the pieces with a water stream. Detection of this condition is important because saw operation will be largely unattended and loss of a considerable number of wafers could result.

A portion of potential productivity is lost because of the compromise necessary in cutting speed. High cutting speed will cause edge chipping on entry and exit. A fixed speed system must be operated at a speed slow enough to limit edge chipping. This speed is lower than is possible in the bulk of the material; therefore, total cycle time is increased. Programmed feed enters the ingot slowly to prevent edge chipping and then increases speed in the center to the highest value consistent with acceptable wafer quality. The cutting speed is decreased again at the end of the cut. The net result is a higher average cutting speed. Programmed feed rate increases saw productivity by increasing average slicing speed.

After a slice has been completed, the blade must be withdrawn before another slice can be started. Withdrawal time can be reduced considerably with simple saw modifications. Decreasing the blade withdrawal time reduces the time the saw is not cutting.

The goal of most of the aforementioned machine enhancements has been to reduce the necessity for human intervention with machine operation. A large slicing operation may involve dozens or possibly hundreds of saws. Because human presence on the production floor is limited, alarm conditions indicated on the individual machines can be overlooked, thus reducing productivity.

There is also a need for record keeping to anticipate reloading of silicon, blade changes, and other maintenance operations. Since the controls on newly designed saws are microprocessor based, a digital serial communication interface can easily be added with the necessary firmware to send needed information to a central point.

This central monitoring point would have to receive data from a large number of saws, store the data, and display the information to the operator. The basic data received from the machines would be their state (i.e. cutting, idle, or alarmed) and an indication of a wafer being completed. The central monitoring system must have enough intelligence to act as a controller on a communication link with many stations and to operate on the data provided so that it can be presented in a usable manner to the operator.

The most likely configuration for interface with an operator is a CRT and a keyboard. Alarm data would be displayed automatically. Display of other data could be requested using the keyboard.

Distributed control is a concept that has been used for several years now and is becoming more popular in the process control industry. The system intelligence is distributed as is the system hardware. Intelligence is placed close to the source of data or point of control. Various intelligent components communicate over a "data highway." They can pass data among themselves and pool their computational power to control the system.

The data highway is the key element of the system. It permits high speed communication among system elements. In situations where there are many system components which do not need to send or to receive large volumes of data, the components are connected via a low speed bus to a data concentrator. This concentrator assembles and disassembles the message to be sent or to be received on the data highway.

Careful examination of the slicing system with central monitoring reveals many of the features of distributed control. Each saw is a data source and control point which communicates with a central monitoring point over a low speed serial data bus. If the central monitoring point is used as a data concentrator and connected to a data highway, a distributed control system is created.

The primary function of this control system is to coordinate the activities of the entire system and to insure that each element is operating near its maximum capacity. Many elements in solar array processing are similar to the slicing element in that they are made up of many components (saws) operating in parallel. If the control system can keep each component operating near capacity, the total number of components can be reduced from the number required for an uncontrolled system. Efficient control should reduce capital equipment requirements.

A secondary function of the control system is exchange of information among system elements. This can be used by the destination element to improve its operation; for example, the results of product inspection can be fed back to the slicing element for possible corrective action.

Data fed back to the slicing process would be useless unless the identity of the saw which produced the off-specification product is known. This could be accomplished by adding a wafer marking operation after slicing. A less expensive alternative would be to add intelligence to the wafer transport element and to use the data highway to pass the desired source and destination information. This is another area where equipment cost may be reduced.

Another important feature of a distributed control system is its ability to log data on its own operation. This data base can be used for off-line analyses to test schemes for improving process performance.

Distributed control simplifies interfacing equipment built by different manufacturers because standardization is required only at the data highway level. Equipment can be built with hardware and software designed to interface with the data highway. System design would then require system software only.

Application of distributed control will improve productivity by reducing material waste and lowering capital expenditures. Successful integration of an I.D. saw into an automated factory requires the enhancements described in order to improve productivity and to minimize the amount of human intervention necessary to operate the entire system. The human element is not removed; its focus is merely shifted from dull, repetitive jobs to the more demanding tasks of system optimization.

DISCUSSION:

YOO: For real success in automation, I think that one of the most important factors is how accurately you monitor the blade condition. You mentioned checking the blade condition by blade deflection only. Maybe there are some other factors that influence the real quality of the blade other than blade deflection. In other words, possibly, monitoring the center of the ID blade, etc.

LEWANDOWSKI: Centering of the ID blade is usually a setup procedure. I imagine there is a possibility that it would shift in operation, but I have never heard anyone complain about that happening. As for monitoring other variables to determine the condition of the blade, yes, there are other variables that are important. One that we worked with to some extent is blade torque. We find a clear correlation between slice quality and the amount of torque required by the slicing process. We have done some work on measuring the force required at the cutting blade. The paper that was presented on Monday, the source of data was STC and it goes back a number of years where we had originally done work in this area. We are active in this area now and we are aware of other parameters that may be useful in determining blade condition, and we intend to make use of them.

DAUD: Could you give us a price estimate as to how much it will increase the saw price?

LEWANDOWSKI: No. As you get to a higher level of automation there has been less work done. Many of the machine improvements that I talk about do exist or are in the design stages and we can give you a price on them if you are interested. The real gains that you are going to see from automation are not at the machine level. They are going to be at the system level and they are going to make use of the ability to communicate from subsystem. When you put a sensor on the saw it only benefits you if it is on every saw. If you put it in another subsystem it can be used to a greater extent, more efficiently, and it would result in less overall capital expenditure. The system level is where automation is really going to pay off. It has benefits on the saw level, the enhancements I talked about to increase productivity for example, but the big gains will be seen at the system level and there really hasn't been all that much work done on that yet.

LIU: You mentioned that one of the items that you will be monitoring on your automated system would be the tensioning of the blade. I assume what you meant by that you would be able to monitor the actual tension of the blade _in situ_ while it's wafering. Is that what you meant?

LEWANDOWSKI: When you start losing hydraulic pressure the force you are applying to the blade is reduced, therefore the blade becomes more flexible.

KACHAJIAN: In further response to that question, we will also in time be monitoring the cutting force at the point of contact with the workpiece. Together with the actual blade deflection and the measuring of the cutting force we can determine if the cutting force increases or decreases and that could be a function of the loss of tension in the blade. If the blade is not tensioned properly it will not be cutting properly, and that will show up as an increased force.

LIU: Are you saying that we are losing tensioning on the blade because we are losing the hydraulic pressure itself, or is it just an indication of the blade being stretched during the wafering?

LEWANDOWSKI: Both. You can be losing hydraulic pressure; you do lose some tension because of blade yielding. You can retension, up to a point of course, and still cut effectively even though you have less tension due to yielding.

KACHAJIAN: The only time you can not recover really is when the core has been rubbed, and the steel has yielded dramatically in one direction. Then there is hardly anything you can do.

MORRISON: I suggest that you might monitor concentricity optically; a continuous monitoring might indicate whether you are getting a slip of tension or distortion of the blade.

I understand you people are building a multi-saw laboratory in-house and I am wondering how much of the type of systems you described in your presentation we can expect to see there and on what kind of a schedule.

LEWANDOWSKI: Saws that go into that laboratory will be equipped with just about all of the enhancements that are available today. We hope to have requirements for the centralized monitoring system defined by the end of the year and would be going into design at the beginning of next year. Again, this device is kind of a tricky one because we are selling to two different markets with widely varying requirements. Semiconductor is more of a batch-type process. They are cutting many different specifications on a slicing operation and they may have more of a need for this thing initially as strictly a monitoring type of device. In solar, I believe its real use will come when we are talking about integrating into a completely automated factory.

KACHAJIAN: The saws, unautomated, but ready for automation and design, will be in place by the third quarter of this year (and that is more than 10).

ILES: There is an old-fashioned way of dressing which I think involves mounting the ingots on a surface--a sort of a poor man's dressing--and as the blade came through each time, it at least cleaned the debris. Is that idea completely slipped away now or is it still an option?

LEWANDOWSKI: I would say that it is not an option simply because one of the things you want to avoid is excessive dressing. This is detrimental to bladelife. That is why it is important to develop a sensor or sensors that can tell you when the blade needs to be dressed, and dress it only when it needs to be dressed. The manner in which you dress it makes a big difference. If the blade is deflecting during a slice one way or another it indicates that it should be dressed on the opposite side and not on both sides. What you are suggesting would dress it both sides every time through.

N82 23673

WAFERING INSIGHT PROVIDED BY THE ODE METHOD

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ABSTRACT

Orientation-dependent-etching (ODE) can be used to slice silicon. The method has several possible advantages including high slicing yield (m^2/kg), plane parallel, thin slices, ready for processing and the chance of high throughput and low costs. There are limitations in the need for simple crystals, and in restricted depth of slicing. Analysis of the overall properties of the ODE method has added insight into the requirements of a successful wafering method.

BACKGROUND

Orientation-dependent (OD) slicing uses preferential etching down narrow slots in a silicon slab on form slices. This method of slicing was investigated to see if its advantages could be used to form more slices from high quality silicon crystals than can be achieved by mechanical slicing methods. In particular, an attractive feature was the possibility of forming thin slices (~50um), ready for cell processing; present methods for etching thin slices from already sliced silicon involve large losses of silicon. OD slicing has some limitations, which restrict the cell designs available. Attempts to overcome these limitations have led to study of different methods for processing the slices into cells and arrays.

ORIENTATION-DEPENDENT SLICING

OD etching has been used to form solar cell structures, including vertical multijunction cells (1), etched groove cells (2), and polka-dot cells (3). However, OD slicing requires formation of considerably deeper grooves.

Figure 1 shows a typical slicing sequence. (110) orientated slabs are cut from <111> orientated crystals. The slab thickness determines the eventual slice width, but there is no requirement for extreme accuracy in cutting the slabs. The slabs are chemically polished, and coated with SiO_2 and/or Si_3N_4 which act as masking layers during the OD etching. Using a slot-pattern mask and optical photolithography, a close-spaced, fine slot pattern is opened in the masking layers. An OD etchant (typically 30M KOH at 85°C) is used to etch down the slots; slices are formed when the slots are etched through. Figure 2 shows partial slicing with widespread slots ~450um deep.

Previous work (4) showed that for slots in the 111 direction and (110) faces, etch ratios (downward to sideways) as high as 400:1 could be achieved, and some reports (4,5) have quoted values as high as 600:1. These high ratios, which form deep, narrow slots require very accurate alignment (0.1°) of the slot direction with the (111) planes which are perpendicular to the (110) planes. These etch ratios are far in excess of the difference in bond densities for the different crystallographic planes, and a tentative explanation (6) involves preferential oxidation of (111) planes in the OD etchants. Accurate alignment has been achieved by extension of the fan-etch method (4) and once the fan-etch has shown the correct <111> directions of a typical slab from one ingot, subsequent slabs can be aligned with the slot-mask using precise mechanical adjustment.

The area yield, i.e. the slice area per starting mass of silicon, can be high if high etch ratios ($\geq$200:1) can be maintained. Figure 3 shows the m^2/kg obtainable for two slicing depths. Also, on this figure are indicated the range of m^2/kg available from present or projected mechanical slicing methods (multiple wires or saws) and sheet growth. Figure 4 shows how the etch ratio increases as the misalignment angle decreases. The etch rate down the slots (in the <110> direction) is fairly slow (~1um/min.), but despite this slow rate, a large number of slots can be formed simultaneously by etching several slabs at once. Using 10um wide slots, spaced 60um apart, 160 slices ~50um thick are obtained for each centimeter of slab width. Thus the areal output (cm^2/min) can be high. To form slices ~1mm thick requires etching for ~1000 minutes. This places severe requirements on quality of the masking layers.

Because the mechanical forces on the slices are small (none in slicing, mainly from the etchant motion or hydrogen pressure) it is possible to form very thin slices. Slices 50um thick have been the target, but thinner slices (down to 1um) have been formed. Typical slot widths are 10um, and for 200:1 etch ratio, a slice 1mm wide will involve a kerf loss ~20um. The slice faces are restricted to be (111) planes, giving chance of good parallelism for all slices formed. We had expected the slice faces to be very flat and they are flat and parallel. However, the prolonged exposure to the etchants forms etch figures on the slice faces (see Figure 5), probably arising from inherent bulk imperfections in the starting single crystal.

The OD slices are formed in silicon which has never experienced any mechanical processing. This is of interest, because it is believed that even after excessive etching to remove mechanical work damage, the effects of this damage can never be completely erased.

We have successfully OD sliced silicon and have found suitable combinations of slab preparation, masking layers, aligned slot formation and etchant conditions. However, we have also identified some practical limitations and they are discussed next.

Limitations in OD Slicing

There are several intrinsic limitations, including the need for starting single crystals, suitably oriented, the formation of very accurately aligned slots, and limited slice width (limitation on slot depth obtainable). We have also found some practical limitations as follows.

The thin slices formed must be supported during slicing to prevent breakage as slicing proceeds, and to prevent the need to handle many thin slices separately. Some support can be provided by masking the back surface of the slab, although it is difficult for this thin masking membrane to act as sole support. Several other methods have been used to give additional support. These methods include use of a heavily doped P+ layer, a few micrometers thick formed at the back surface to supplement the masking layers. These P+ layers (for concentrations $>6\times10^{19}\text{cm}^{-3}$) are attacked very slowly by the etchants, so that they act as a self-stopping membrane at the bottom of the slots. Such a stopping layer can also help to allow complete slot etching when the etch rate may differ in different slots. We have also studied the use of top surface support methods. By mask design, support struts can be left at intervals across the slot pattern. It is also possible to change the mask design to provide many mask bridges across each slot. There is some conflict involved in the need for slice support during formation, and the need for easy removal later in the process, and this will be discussed in the next section.

The slot width, slice thickness, and slot depth (slice width) values used were ~10um, ~50um, and ~1000um, respectively. We found several factors which gave variable etching in the deep slots. Because of capillary effects, it was observed that the etchant near the bottom of the slots could become depleted, thus slowing the etching rate. This etch depletion could also affect the oxidation rate of the (111) surfaces; if the slot faces are not protected, sideways etching can proceed by ledge exposure. In addition stresses at the top surface mask-silicon interface, or severe crystallographic defects on the etching slot faces, could also lead to sidways erosion. We did not find clear-cut connection between edge dislocations on the top slab surface or on the slice faces, and the occurence of excessive slot wall etching. No matter what the reason, this enhanced sideways etching formed very thin slices on parts of the slab, and often while the slots were etching deep, the slot pattern was "washed-out". Compounding these sideways etching problems was the formation of limiting surfaces near the bottom of the slots. These limiting surfaces were the family of (111) faces which are not at right angles to the (110) surface. (Figures 5,6.) These limiting surfaces slowed the etch rate, either requiring very long etch times to complete the slots, with greater chance of sideways etching, or they hindered methods developed to separate the completed slices.

We did form many slices ~1000-1250um thick, but the slicing was incomplete across the slab. These etching problems have slowed development of the slicing method. To avoid processing of many separate thin slices, we considered use of "matrix processing" wherein complete cells could be formed on the supported slices, before separation and use with spectral concentration (7).

COMMENTS ON OD SLICING

It is instructive to use the experience of the ODE slicing method, to add insight into the wafering requirements needed to meet the cost goals of the DOE solar cell programs.

Slicing is needed for grown or cast ingots of silicon. Present trends in these ingot technologies involve combination of reasonably pure starting silicon, growth to provide large grains (>mm size), and for reduced costs, growth of large ingots →100 kg per growth sequence for continuous Czochralski or FZ methods, →50kg for cast ingots. Clearly these large ingots should be processed as large slices, and failure to meet this requirement is the major disadvantage of the ODE method. As the cost of the starting silicon and the costs of growth are decreased, kerf losses can be accommodated, although the cost of generating ~50% scrap silicon will always be a heavy price to pay. Most casting methods give polycrystalline silicon, and ODE cannot be used in these cases; the mechanical methods have no similar limitations.

Present day technology (Czochralski crystals sliced by ID saws) shows that the slicing throughput is an early bottleneck in the whole cell processing sequence, and already much space and upkeep is required for the many ID machines needed. Assuming a working day of 20 hours, present ID machines can cut 4" wafers at ~2 m^2/day; at ≈0.7 m^2/kg yield, this means ≈3kg/machine/day. For the same working day, present Czochralski grower can generate at least 20kg per day and assuming ~50% kerf loss, requiring more than 3 slicing machines for each crystal grower. For all slicing methods, the slicing yield depends only on the sum of the (slice + kerf) thickness (Figure 7). It is clear that the yield rises rapidly as this sum decreases; also that for high yield it is important to reduce to slice thickness, as well as the kerf losses. To make such reductions, it is necessary to reduce the thickness of the slicing means, and to also reduce rate of slicing. This leads to methods for simultaneous formation of many slices at once to maintain a reasonable throughput. In this respect, the ODE slicing method can be regarded as the ultimate in simultaneous slicing, in that ≈100 slices can be formed per centimeter of silicon, and many centimeters can be simultaneously etched. Slicing to produce reduced kerf loss also tends to provide slices with less work damage. This has been demonstrated with damage depths ~25um for ID sawing, ~20um for MB sawing, and ~15um for MW sawing method; again the ODE method is the limiting case, with no damage produced.

Estimates of the practical limits for the various slicing methods show that the slice and kerf thicknesses fall off relatively slowly (with associated increase in the slicing yield) as the number of simultaneous cuts is increased. The results of these estimates are given in Table 1. Experience with the ODE methods shows that as more simultaneous cuts are made, reduced space is required for the equipment; if the throughput is similar to that of an ID machine, a similar number of machines will still be needed. Also, with increased number of simultaneous cuts to ensure effective slicing, the complexity may rise, and this added complexity (or the need for frequent maintenance) may add unwanted cost increments to the slicing process. When very high yields are obtained (resulting in thin slices), there may be the need for support of the slices, to avoid severe breakage. Also, to ensure lower overall costs, it is important that the slices formed should not be so thin that extra care in processing is required.

The ODE process had several other features which were favorable to large scale use. These included the need for only moderately complex methods (immersion in a solution below 100°C) an easily maintained condition (water bath), and modest equipment needs (large containers and exhaust fans). Also, there were two other possible features of interest. The OD etching process generates hydrogen, and it is possible that in a large scale process, this hydrogen could be collected, and used as fuel. Also, the etched silicon is left in the etching solution, and should be reasonably easy and economical to recover.

In conclusion, we have found that study of the ODE slicing method has focussed attention on the overall properties required of an effective slicing method. In its present state of development, ODE slicing is an example of a method which has many of the attractive features required, and yet cannot be regarded as a solution to meet the slicing goals of the DOE low cost silicon cell programs.

ACKNOWLEDGEMENTS

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REFERENCES

1. R.K. Smelzer, D.L. Kendall, and G.L. Varnell, Proceedings of the 10th IEEE Photovoltaic Specialists Conference, 1973, p.194.

2. R.L. Frank and J.L. Goodrich, Proceedings of 14th IEEE Photovoltaic Specialists Conference, 1980, p.423.

3. R.N. Hall and T.J. Soltys, ibid, p.550.

4. D.L. Kendall, Appl. Phys. Lett., Vol.26, 1975, p.195.

5. K.E. Bean, IEEE Trans. ED-25, 1978, p.1185

6. K.L. Kendall, Ann.Rev. Mater. Sci., Vol.9, 1979, p.373.

7. P.A. Iles and S.I. Soclof, Conference record of 15th Photovoltaic Specialists Conference, 1981 (to be published).

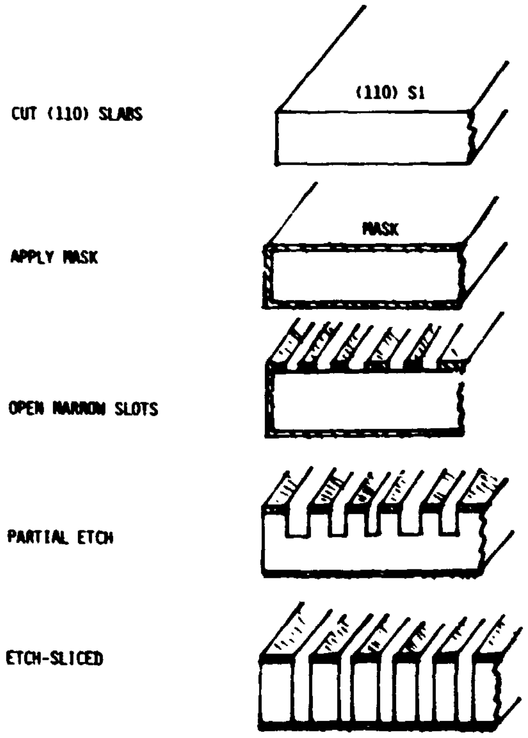

FIGURE 1

O.D. SLICING SEQUENCE

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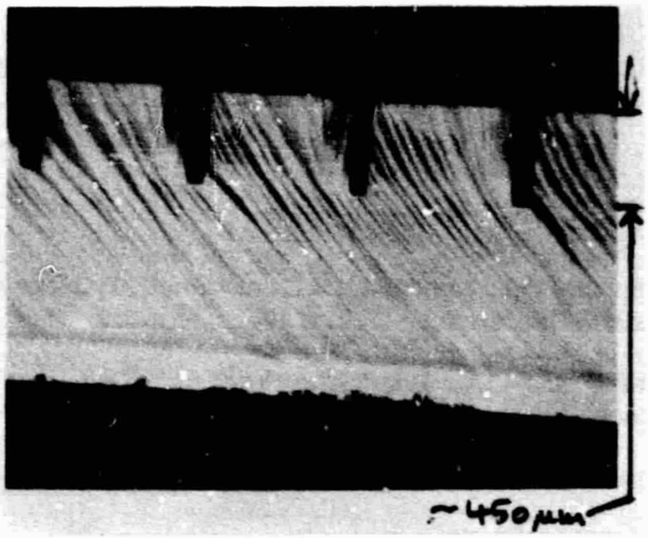

FIGURE 2

PARTIAL SLICING (SLOTS 0.5mm DEEP)

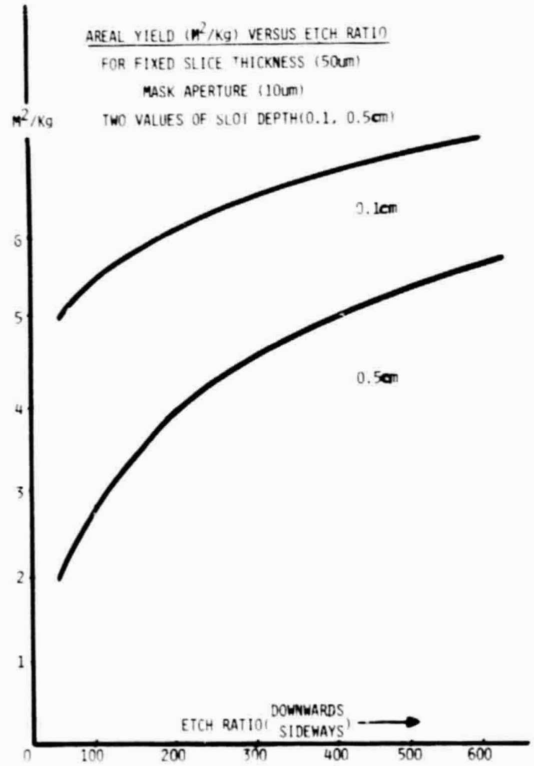

FIGURE 3

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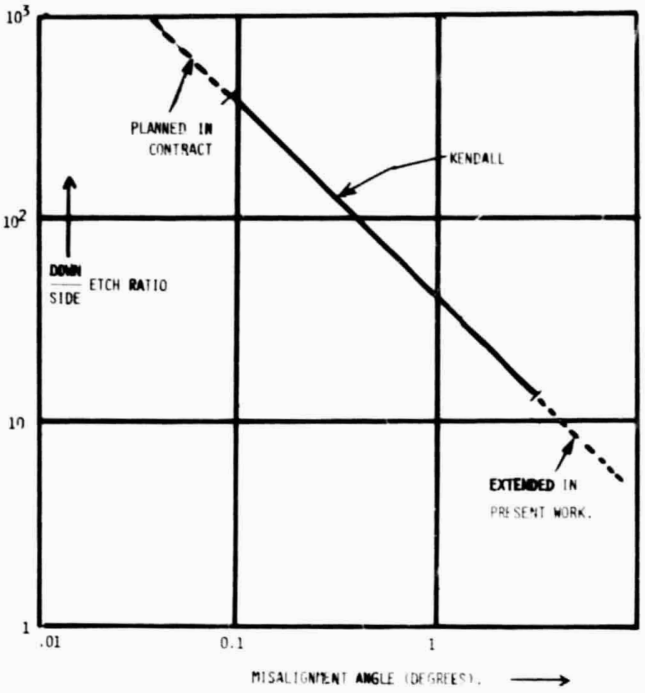

FIGURE 4

ETCH RATIO MISALIGNMENT ANGLE

(KOH ~85°C)

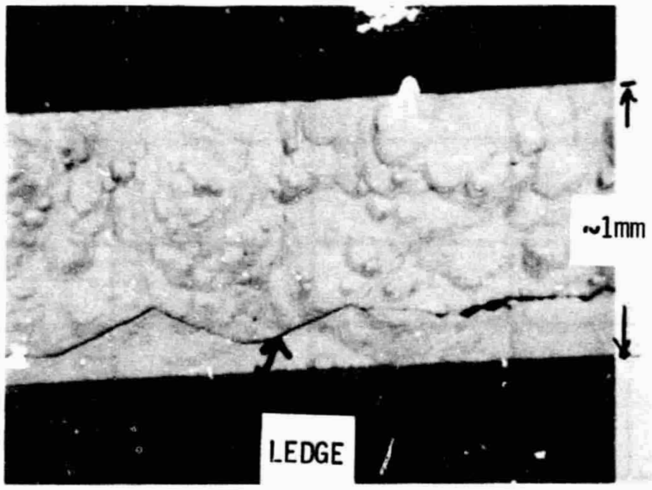

FIGURE 5

(111) FACE ETCH FEATURES

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FIGURE 6

LIMITING LEDGES ON (111) FACE (AT BOUNDARY BETWEEN OD ETCHED AND CLEAVED SECTIONS)

TABLE 1

COMPARISON OF VARIOUS SLICING METHODS

METHOD	NO CUTS	PLAUSIBLE MIN.S (mils)	PLAUSIBLE MIN.K (mils)	THROUGHPUT cm^2/min.	YIELD m^2/kg
ID	1	6-8	8-10	15	0.7-1
ID ADVANCED	3	6-8	8-10	45.	0.7-1
MBS	X00	6-8	6-8	*	0.8-1.4
MWS	Y000	4-6	5-7	*	1-1.8
ODE	Z000	2-4	1-3	*	4-6
RIBBONS	-	4-8	-	20-50 ø	2.1-3.2

* CAN ADJUST X, Y, OR Z TO GIVE 10-25cm^2/min.

ø RECENTLY 145cm^2/min. for EFG.

CHARACTERIZATION

Chairman: P.A. Iles, Applied Solar Energy Corp.

N82 23674 D24

EXIT CHIPPING IN I.D. SAWING OF SILICON CRYSTALS

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INTRODUCTION

This study is part of a general effort to understand the sawing process for silicon, in particular the internal diameter diamond sawing process (1). Fig. 1 illustrates the geometry schematically. An idealized process may be described as follows: a rotating annulus with diamond particles coating its inner rim is caused to move through the crystal in a perfect planar motion. The contact stresses and scraping action from the diamond particles causes multiple intersecting cracks and comminution of the silicon to be kerfed out.

In practice there are many deviations from the ideal process which cause defects in the slices. The present approach was to select one defect that was known to be caused by sawing and about which there existed some shop knowledge, then to try to understand that defect so that preventive action could be taken. The chosen defect occurs where the saw exits the crystal after cutting a slice and is therefore termed an "exit chip". Figure 2 shows a typical exit chip.

Exit chipping decreases the fraction of salable slices; if such slices are passed to a semiconductor slice processing facility, they generate fear of increased particle generation in handling. In addition, exit chipping may be accompanied by deeper-than-usual damage in the slice itself. Since slices with exit chips may be screened out, and surface removal procedures may be adopted to remove the extra damage depth, the phenomenon of exit chipping is merely a nuisance in the semiconductor industry.

To another industry -- low cost solar cells -- the exit chip may be very important indeed under another name: a "saw fracture". In this case the "exit chip" is more extensive, starting much farther back into the crystal because of the thinner slices and high cutting rates required for low cost. Table I shows a comparison of specifications for semiconductor slices and for low cost solar cell slices.

TABLE I. COMPARISON OF SLICE CUTTING SPECIFICATIONS

SPECIFICATION	CONVENTIONAL	LOW COST SOLAR CELL GOALS
DIAMETER	75-100MM	125MM
SLICE THICKNESS	25-30 MILS	10-11 MILS
KERF	11-16 MILS	5-6 MILS
CUTTING RATE	1-2 IN/MIN	3-4 IN/MIN
YIELD	HIGH	95%
BLADE LIFE	2000	4000
CORE	5 MILS	1-2 MILS

In the following discussion it should be evident that "exit chipping" or saw fracturing is a major problem to be overcome if these low cost solar cell goals are to be met.

DISCUSSION

Historically exit chipping is seen mostly in the (100) orientation. Unfortunately, this is the most desirable orientation for solar cells because of the added benefits of pyramidizing the surface (2). Positive blade deviation (bow) and excess hydraulic pressure are known to be deleterious influences. Backing by sacrificial silicon strips and using vacuum slice retrieval have helped reduce the problem at times. The middle slices in a group of 8 or 10 are sometimes more likely to show exit chipping. Other knowledge that bears on the subject is 1) that surface damage is predominantly microcracks oriented parallel to the abrasive path (1), and 2) that the inside (crystal side) of the wafer has the deeper damage (3).

Figure 3 shows an example of the fracture surface. The fracture surface consists of a collection of subfractures that originate in the kerf and move substantially as a single crack after starting at either edge. The fracture is roughly parallel to saw marks and lies approximately at the same angle from the slice as does the preferred cleavage plane (111). Even if the direction of cut is toward another azimuth than the standard ⟨110⟩ direction, the fracture parallels the saw marks and is composed approximately of {111} surfaces. Figure 4 shows a fracture surface near an edge of the slice, where there may be more or less connected sub-fractures paralleling the exit chip, but which did not develop into a full fracture. Figure 5 shows "sparkle", a reflection parallel to the exit chip that often accompanies it and implies deeper-than-usual damage to the area of the slice on which it occurs. The opposite side of the slice and the 90°-and 180° rotated slice show much less pronounced reflections. Figure 6 shows clustering of slices from surface tension when a slice retrieval unit is not used. If a saw is producing exit chipping, a series of slices decreasing in thickness will show increasing width of the exit chip.

An interpretation of the foregoing observations will now be given in terms of crack propagation as acted upon by the sawing stresses. Figure 7 shows a scale cross section of the I.D. saw kerf slot during the last part of the cut. The direction of crack travel and possible locations of exit chips are shown. Note that if the crystal orientation were ⟨111⟩, contact fractures from the diamond edge can readily form on planes parallel to the kerf slot (plane 1-6) and would be removed by the advancing blade. This explains why only (100) exit chipping is seen. Since the exit chips are roughly parallel to saw marks, the general locus of the crack must be determined by contact stresses although the exact locus depends on already existing subfractures located in the kerf region which are caused by more than one abrasive particle. The crack starts at either edge since these are weak areas in flexure. In the more extensive "saw fracture", the fracture plane often changes part-way across the slice to be other than parallel to the saw mark because the speed of the crack accelerates beyond the speed of the blade travel; i.e., outstrips the advance of the contact stress field.

With this picture of crack origin and propagation in mind, the influence of various external factors on the opening of the crack can be seen. These factors can be conveniently divided into two types: factors that wedge the crack apart and those that bend the slice away from the crystal.

Factors of the first type are: dull blade (abrasive particles not sufficiently exposed), excessive feed rates, blade eccentricity, and in-plane vibration. Figure 8 shows what happens if any of these factors rises above reasonable limits: the material to be removed builds up; contact stresses increase greatly, and microcracks lengthen accordingly. Since some of the cracks extend beyond the kerf slot into the silicon, the general damage to the slice is greater than is necessary. Such damage is directional: microcracks on one of the two sets of $\{111\}$ planes whose intersection is parallel to the blade travel propagate away from the slice as they progress, while the other set of microcracks propagate into the slice.

Factors of the second type are: lateral blade vibration, (1) excess hydraulic pressure (1), surface tension toward adjacent slices (4), bow (5), and flexure of the mounting strip (4). All of these factors can be seen through Figure 7 to be capable of contributing to the bending of the slice away from the crystal. Positive bow would apply a greater lever arm to a bending force than would negative bow, and would therefore be more deleterious. Even the weight of the slice would add to bending in the case of horizontal blades, which perhaps explains deeper damage in the case of horizontal saw (5). Lateral vibration of the saw blade is a main contributor to bending force and to dynamic stress pulses (6). If the major out-of-plane deflections occur at ν = 500-1000 times/sec (1), there would be sufficient time for cracks to move through the slice with only 5% of the time under tension: Crack penetration = $v/\nu \times 0.05 = 20\times10^3/1000 \times 0.05$ = 1mm, where v = crack velocity. (Crack velocity in abraded silicon accelerates from 20-40 to 1000 m/sec within approximately 0.05mm (7). A major contribution to inplane & lateral vibrations is the imbalance in the cutting head (8). Another is loss of blade tension. Factors of the bending type also introduce a further directionality to the damage: when the blade is far from the last part of the cut, the slice flexure away from the crystal favors crack propagation which damages the inside of the slice rather than the outside.

The foregoing considerations indicate how a conventional saw can be operated to minimize exit chipping; they also indicate design factors for a new generation of saws for cutting low cost solar cell slices. These factors are listed in Table II.

Another practical benefit of this study of exit chipping to present saw practice is that the depth or width of the exit chip may be used as a simple and convenient measure for studying the effects of various parameters on slice damage by the saw.

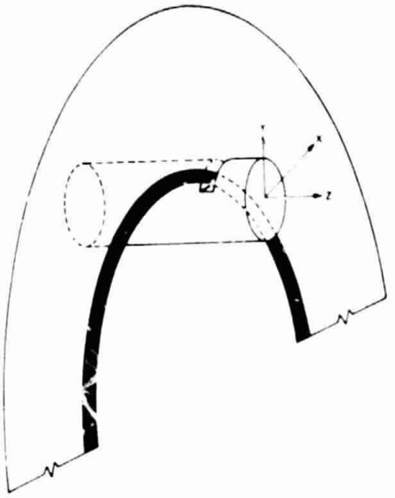

Fig. 1. I.D. saw geometry.

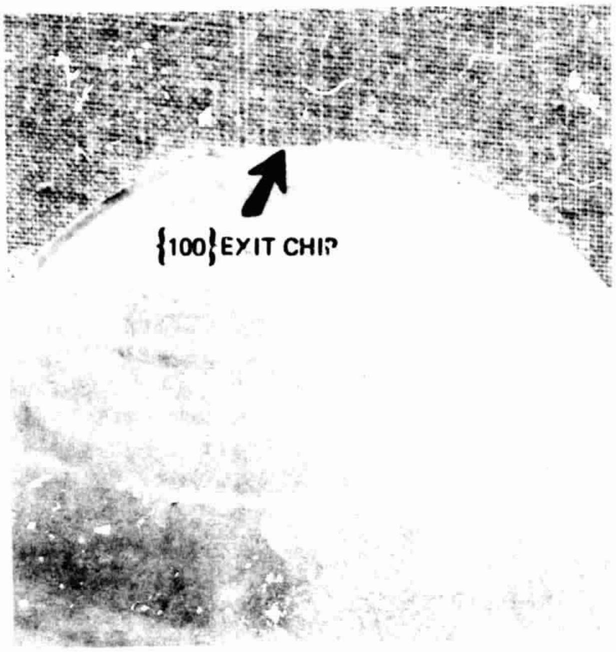

Fig. 2. $\{100\}$ exit chip. Direction of blade travel toward chip.

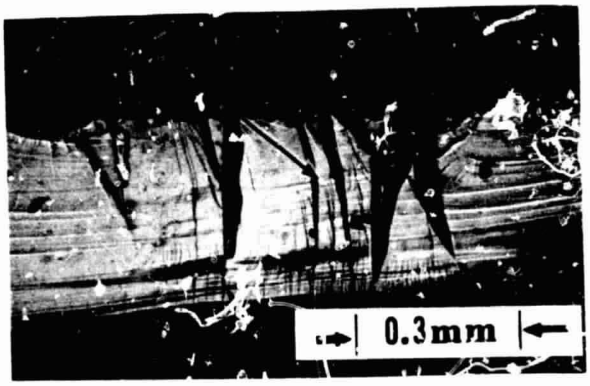

Fig. 3. Fracture surface of $\{100\}$ exit chip. Direction of blade travel toward bottom of page.

Fig. 4. Subfractures in slice surface paralleling exit chip.

Fig. 5. "Sparkle" : Reflection from slice surface parallel to exit chip.

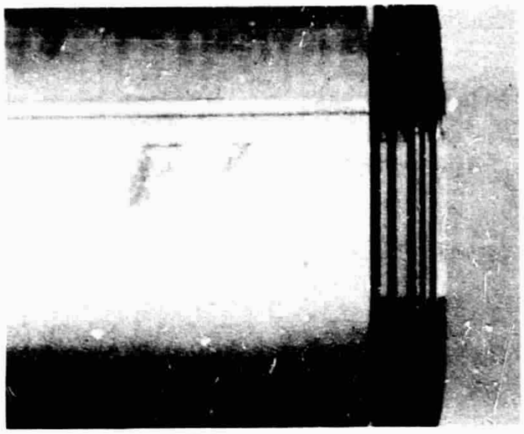

Fig. 6. Clustering of slices from surface tension.

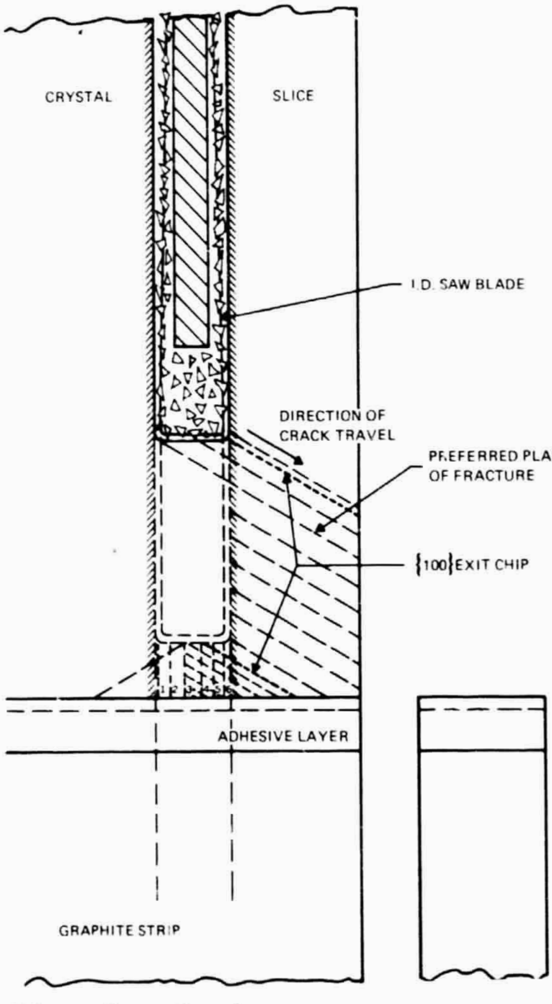

Fig. 7. Scale cross section of I.D. saw kerf slot.

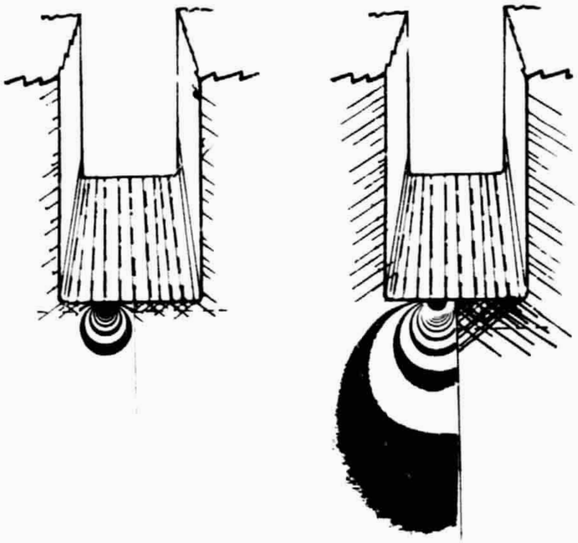

Fig. 8. Schematic diagram of stress fields caused by a single particle contact in kerf slot in the case of continuous (concentric) cutting (left), and intermittent (eccentric) cutting (right).

C-4

CONCLUSIONS

This study has:

- o Given a better understanding of exit-chip or saw-fracture formation, and of the I.D. sawing process for silicon.
- o Shown how to minimize the exit chip as a nuisance defect and obtain shallower damage as a bonus.
- o Indicated a serious problem in cutting low cost solar cell slices by present I.D. saws.
- o Pointed out desirable design features for new saws for ultra-thin slices.
- o Found a simple way to measure harshness of the sawing condition - measuring the size of the exit chip.
- o Explained why the crystal side of a raw slice has deeper damage then the outside.

TABLE II DESIRABLE CONDITIONS FOR MINIMIZING EXIT CHIPPING AND DAMAGE IN PRESENT SAWS AND A NEW GENERATION OF SAWS

PRESENT SAWS		NEW SAWS	
CONTACT FACTORS	BENDING FACTORS	CONTACT STRESS FACTORS	BENDING FACTORS
CONCENTRIC BLADE	BALANCED HEAD	MIN. SPRUNG WEIGHT & HEAD	SLICE BACKING
MIN FEED RATE (TRADE-OFF)	LOW HYDRAULIC PRESSURE	FORCE SENSITIVE FEED	BLADE DAMPENING (1)
AUTO SHARPENING	SLICE RETRIEVAL		
TENSION CHECKING AND CONTROL	SLICE TRACKING (BOW)		

REFERENCES

1. R.L. Meek and M.C. Huffstutler, J. Electrochem. Soc. 116 (1969) 893.
2. L.D. Dyer, J. Electrochem. Soc. 125 (1978) 256C.
3. G. Schwuttke, IBM Tech·Rep. 22.1741 (1974).

4. L.D. Dyer, Electrochem Soc. Ext. Abstr. 81-1, P 785.
5. P.S. Burggraf "Semiconductor International", Oct. 1979, P. 48.
6. B. Steverding and S.H. Lehnigk, J. Appl. Phys., 41, (1970) 2096.
7. J.H. Greenwood, Int. J. Fract. Mech. 8 (1972) 183.
8. G. Fiegl, DOE/JPL - 955282 79/3 (Oct. 1979).

DISCUSSION:

CHEN: Your paper is extremely interesting. I have a paper published in the Proceedings of the Electrochemical Society, an analytical model, which shows the edge chip due to the same P force, either wedging force or bending force from the blade. That model indicated the exit chip can be prevented by sufficient support because if your submounting strip under the ingot is not large enough when the force is great, the bending force would break up the wafer. A sufficient supporting of the wafer would prevent this exit chip. There is a relationship between the forces and thickness as a function of the width of the submounting.

DYER: People told me before that when they support the crystal all around with some sort of coating or something, that problem is helped. In our industry they want to get by with as little as possible. They wouldn't pay for a very big thing under there.

WOLF: It seems that without a sacrificial submount no wafer would come out without exit chips. If your feed force is pushing down, there will be a stress concentration on the corner. Just at the end; where this is weak enough it ultimately should snap off. There's no way of preventing it unless we have something underneath, which stiffens it, and prevents it from being bent down at the end.

DYER: Of course, we do have a fairly thick support under the thing. But you see all of these things have elasticity and the mounting medium, the glue that you put it on with, is not perfectly rigid.

If you look closely under a microscope at the edges of the slices, you'll see some degree of exit chipping on the (100) in almost all circumstances.

If it's only a tenth of the way through the slice, it's not important either to solar cells or to the industry because we grind away the edge for other reasons.

WOLF: I didn't quite understand this "clustering of the middle wafer" in a cluster of wafers ... how was this obtained, and what's the problem?

DYER: It was an interesting thing that they had noted. In sequence, first you cut a slice without a slice retrieval unit and leave it standing there. Then you cut the next slice and if there's sufficient liquid around, it is attracted to the first wafer and it moves over half the size of the kerf slot. Then the next slice moves over another half of a kerf slot. Eventually you reach a point at which the stress is high enough to help make this exit chip. Then you reach a point that the restoring force is so great that you can't make the surface tension connection with the next slice. So then it's free-standing again, and the next one attaches to it, and so on. They cluster in groups of anywhere from two to six or eight. Generally, four or five. With a slice retrieval unit, you get rid of that entirely.

REIMANN: I'd like to know the thickness of the wafers and what adhesive you used to mount the crystal?

DYER: The drawing I showed is as if the slices were 20 mils thick. That was 3-inch slices. Typically, people in the industry cut them a little thicker than that. The substrate and mounting strip can be any number of things. I know that we have used a bakelite-type plastic and graphite.

REIMANN: Which did you find better?

DYER: That depends. Better is not the case here. Which is cheaper? They both work.

KUAN: Did you find this exit chipping phenomenon occurs more often when you were slicing the end of the ingot or in the middle of the ingot?

DYER: There didn't seem to be any difference where you were in the ingot. Of course, you don't leave all those slices on at a time. You just take them off every once in a while. It's better to take them off one at a time. The various saw manufacturers have slice retrieval systems, if your operators will take the trouble to keep them working and if it means anything to them, which it apparently doesn't, because they don't work half the time.

MORRISON: Do you notice a difference in depth of damage from the top of a wafer to the bottom of a wafer? Admittedly, when you get to the bottom your whole lever forces are greater, but when you're at the bottom, you do have damping in the slot that might reduce the depth of damage. Have you measured depth of damage from top to bottom of a wafer?

DYER: I've seen both, actually. This is more complex than I've shown here. There are times when, for some reason, the vibrational situation seems to all of a sudden hurt the bottom part of the slice more than the top, and I've seen it where it's worse at the top also.

N82 23675 D25

FUNDAMENTAL STUDIES OF THE SOLID-PARTICLE EROSION OF SILICON*

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Abstract

The predictions of the theories of solid-particle erosion of brittle materials are compared to experimental results of studies in which angular Al_2O_3 particles with mean diameters D of 23-270 μm are used to erode (111) surfaces of silicon single crystals at impact angles α from 20-90° and velocities v from 30-150 m/s. The description of the steady-state erosion rate by a power law, $\Delta W \propto (v \sin\alpha)^n D^m$ must be modified to include threshold and plasticity effects. Furthermore the velocity exponent n depends on D. Results using abrasives of different sizes mixed together can be explained using a logarithmic-normal distribution. The results of transient experiments can be used to explain the synergistic effects which are observed using a biomodal distribution of abrasives.

I. Introduction

The erosion of materials by solid-particle impacts is an important process which may limit the service lifetime of components. Brittle materials have potential uses in many high-technology energy applications, e.g. valves in coal gasification plants, gas turbine blades, electrodes and regenerative heat exchangers for MHD applications, and photovoltaic devices. Therefore, understanding the erosion process in brittle materials is important. This paper will review the progress made in the last two years in understanding the erosion process in silicon single crystals, a material which not only has applications as photovoltaic devices, but represents an ideal brittle solid and, therefore, is important as a model material that should closely conform to theoretical predictions.

II. Theory

Material removal by impacting particles occurs by lateral crack formation i.e., subsurface cracks parallel to the impacted surface, which

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form primarily as a result of residual elastic-plastic stresses under a sharp indentor. Two models based on this experimental observation have been proposed to describe the erosion process in brittle materials. Both theories assume that the material removed is given by the area containing the lateral cracks times the depth of the lateral cracks, which is assumed to be proportional to the depth of penetration of the impacting particle. Both models assume that the lateral crack size c is proportional to the size of the radial cracks, i.e., cracks normal to the impacted surface, which form as a result of elastic-plastic loading stresses under a sharp indentor. In turn, the latter may be viewed as end-loaded half-penny cracks, the loading being due to the plastic zone expansion, where the plastic zone size is small compared to the final crack arrest size. Fracture mechanics gives $c \propto (P_{max}/K_c)^{2/3}$ for this situation with P_{max} being the maximum contact force and K_c the fracture toughness. The theories differ, however, in the calculation of contact stress $p_o \propto P_{max}/a^2_{max}$, where a^2_{max} is the contact area.

The quasi-static model of Wiederhorn and Lawn(1) calculates the force based on the conversion of the kinetic energy of the impacting particle modelled as a sharp indentor into plastic work. On the other hand, the model of Evans, et al.(2) neglects plasticity and the contact pressure is assumed equal to the dynamic pressure when a spherical particle first hits the surface. The depth of penetration is determined from the time of contact, and the mean interface velocity, both of which are calculated from a one-dimensional impact analogue. Both models predict that the steady-state erosion rate (weight loss [g]/total weight of abrasive impacting [g]) is given by $\Delta W \propto R^m v^n$, where R is the particle radius and v is the velocity. The exponents predicted on the basis of the two models are given in table 1. It may be seen that the only way to distinguish between the models lies in a determination of the velocity exponent, n.

TABLE 1. Predictions of erosion models.

Model	Particle Shape	m	n
Quasi-Static(1)	Sphere	2/3 (.67)	11/6 (1.8)
	Angular	2/3 (.67)	22/9 (2.4)
Pulse-Impact(2)	Sphere	2/3 (.67)	19/6 (3.2)
	Angular	2/3 (.67)	5

III. Experimental

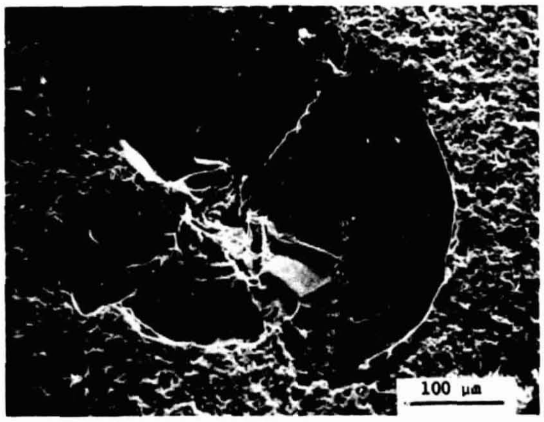
Angular Al_2O_3 particles were used to erode (111) Si single crystals using a slinger-type device.(3) The experimental details have been described previously.(4) Single impacts are examined using scanning electron microscopy (SEM). Erosion rates at a fixed impact angle, velocity, and particle size are determined from sequential weight-loss measurements.

IV. Results and Discussion

IV-1. Single Impacts

A typical SEM of a single impact produced at $\alpha = 90^\circ$ and v = 108 m/s using 270-μm Al_2O_3 is shown in Fig. 1. Each fan that orignates from the impact site is formed by propagating lateral cracks which periodically diverge up to the free surface, causing material removal. The lateral crack formation is considered in detail by Evans, et al.(2) High dislocation densities under the impact sites have been observed,(5) and this provides evidence for the importance of plasticity.

Further impacts produce overlapping damage sites until eventually a steady-state ΔW is achieved. Figure 2 illustrates a weight-loss curve measured for $\alpha = 90^\circ$, v = 108 m/s, using 37-μm particles to erode a surface previously eroded into steady state using large 270-μm particles. The erosion rate (the slope) initially decelerates as opposed to an accelerating ΔW which is always observed on pristine surfaces. The shape of the transient is therefore determined by the initial condition of the surface.



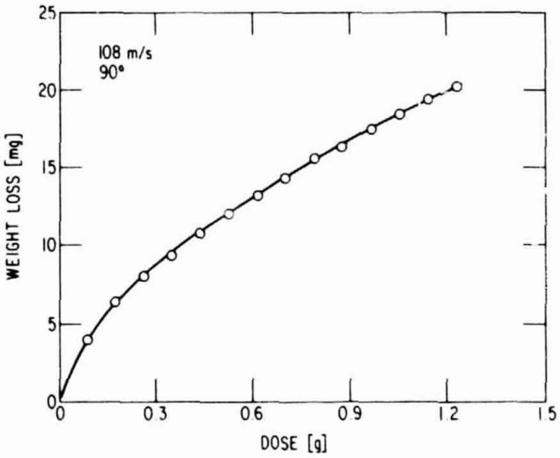


Fig. 1. (Left) SEM of single impact produced using 270-μm Al_2O_3 at v = 108 m/s and $\alpha = 90^\circ$.

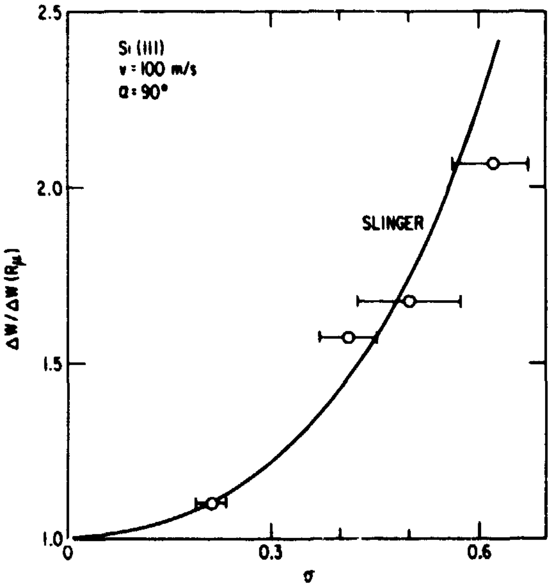
Fig. 2. (Right) Weight loss as a function of dose for 37-μm particles impacting a surface previously eroded into steady state (using 270-μm particles) at v = 108 m/s and $\alpha = 90^\circ$.

IV-2. Particle-size Dependence

The particle-size exponent m is close to the 2/3 predicted by the models for large particles. However, the relation greatly overpredicts ΔW for small particle sizes. This indicates that the expression must be modified to allow for threshold effects which seem to be manifest for smaller particles. If the data for erosion rate ΔW and particle size R of ref. 4 is plotted as $(\ell n\ \Delta W)/(1-R/R_0)^3$ vs $\ell n(R-R_0)^{2/3}$ to allow a comparison to the models that predict the volume removed per number of impacts, it is found that a velocity-dependent threshold size R_0 can be obtained such that the relationship $vR_0^{3/2} \approx (1280 \pm 200) \times 10^{-6}$ m^2/s is approximately valid. For $\alpha = 90^\circ$, $v = 100$ m/s, the threshold $R_0 \approx 6$ μm. The threshold can be related to a critical force required to propagate a crack, and the quasi-static model(1) predicts $vR_0^{3/2}$ = constant, while the pulse-impact model predicts vR_0 = constant. While the exact relation is difficult to evaluate, it appears from the data that the former relation is more reasonable.

IV-3. Particle-Size Distribution Effects

One of the difficulties which arise in the appraisal of threshold effects is that ΔW depends on the particle-size distribution.(6) Figure 3 shows the effect of particle-size distribution at $\alpha = 90^\circ$ and $v = 100$ m/s,



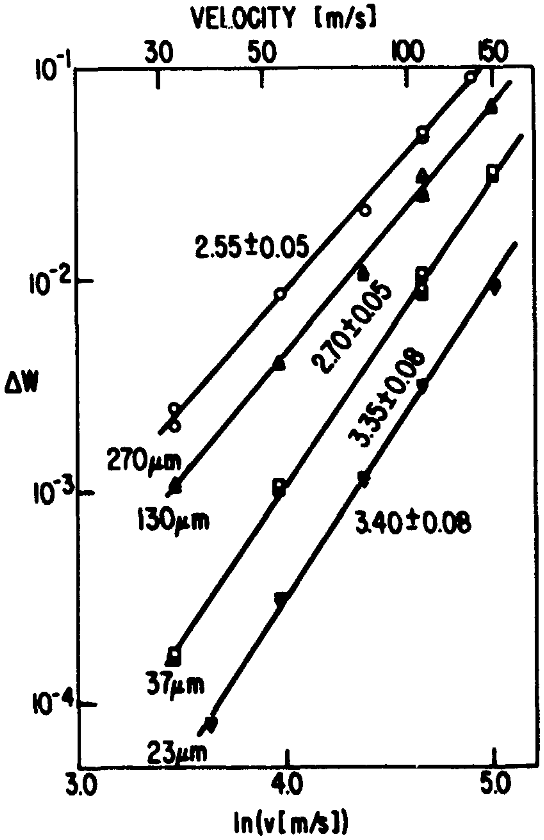


Fig. 3. (Left) The normalized erosion rate (measured steady-state rate/rate for $\sigma = 0$) as a function of the particle-size distribution σ.

Fig. 4. (Right) The logarithm of the steady-state erosion rate as a function of the logarithm of velocity for particle sizes of 23, 37, 130, and 270-μm.

as measured by the width of the distribution σ, on the normalized erosion rate (measured rate/rate for $\sigma = o$). The solid curve that is calculated from a logarithmic-normal distribution is seen to adequately describe the experimental results.

IV-4. Velocity Dependence

The dependence of ΔW on v has been systematically investigated.(7) The logarithm of the steady-state erosion is plotted as a function of the logarithm of velocity for four particle sizes in Fig. 4. Good fits to $\Delta W \propto v^n$ are obtained, but there is a dependence of the velocity exponent on the particle diameter D as shown in Fig. 5. The figure also shows data obtained on two different types of silicon carbide(8,9) which show that Si is not unique in this respect.

The velocity exponent varies from 3.4 for 37-µm particles to 2.55 for 270-µm particles. As seen from Table 1, no current model can explain this variation of n with D. It may be postulated that smaller particles have shorter contact times and therefore must be approximated using the pulse-impact model, while larger particles more nearly satisfy the quasi-static model. This predicts a trend in the direction observed. It is interesting to note that the velocity exponent obtained using large (1.58-mm diameter) spheres impacting MgO is ≈ 2.1,(10) in agreement with the trend predicted in Table 1. It is believed that the exponent for hot-pressed SiC is low because of the presence of weakened grain boundaries(9) which affect the erosion rate. In this respect polycrystalline MgO behaves like MgO single crystals(11) probably because the polycrystalline MgO was relatively pure.

IV-5. Angular Dependence

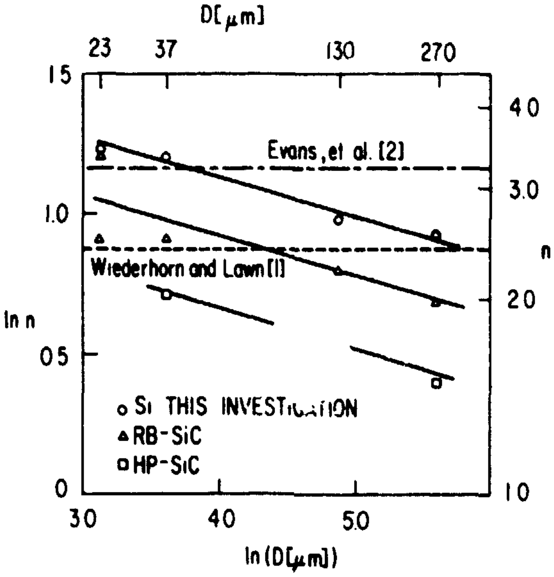
The power-law expression for ΔW is valid only for normal incidence for which ΔW is maximum for a brittle solid. For oblique impact angles the velocity v can be resolved into a normal component $v \sin\alpha$ and a tangential component $v \cos\alpha$. If frictionless contact conditions exist, only the normal component contributes to the erosion, and it can then be given by $\Delta W \propto (v \sin\alpha)^n$. Normalized data ($\Delta W(\alpha)/\Delta W(90^\circ)$) obtained for various velocities and particle sizes are shown in Fig. 6, where the solid line denotes $\sin^{2.6}\alpha$.

The assumption that the tangential component of v does not contribute to ΔW breaks down for $\alpha < 45^\circ$ where the actual losses are 2-4 times greater than those predicted by the model. The additional contribution to ΔW for smaller α can be rationalized if it is assumed to be due to the tangential velocity component that arises because of a plastic-deformation cutting process, which in a ductile material has a maximum for $\alpha \approx 20^\circ$.(12) This is consistent with TEM observations(5) which indicates that plasticity contributes to the erosion process.

IV-6. Synergistic Effects

The experimental conditions used in these studies cover the range of particle sizes, velocities, and impacts generally expected in service applications where the components are subjected to an erosive environment i.e. photovoltaic devices unprotected from a dust environment. The models, however, can not be assumed adhoc to apply to complex service conditions where, for example, several particle sizes or velocities are present simultaneously. The simplist assumption is to use a principle of linear superposition which requires that the damage processes occur independently of each other. This assumption is not in fact valid, and has recently been examined(13) in detail.

Figure 7 presents the results of an experiment designed to examine linear superposition for erosion using a mixture of two sizes of particles. The steady-state erosion rate in Fig. 7 is plotted as a function of the weight fraction of the 270-μm particles (f_{270}) in a mixture of 37-μm and 270-μm particles. The simple "law of mixing" given by $\Delta W = f_{270} \Delta W_{270} + f_{37} \Delta W_{37}$, where f_{37} is the weight-fraction of 37-μm particles and the ΔW's are the respective steady-state erosion rates obtained for that size of particles, is shown as the dashed line and is not a valid description.



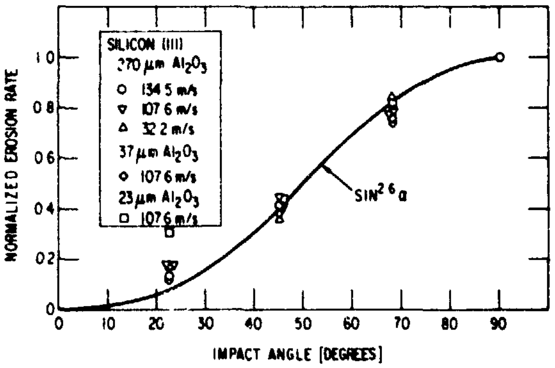


Fig. 5. (Left) The logarithm of the velocity exponent n as a function of the logarithm of the mean particle diameter D.

Fig. 6. (Right) The steady-state erosion rate normalized by ΔW for $\alpha = 90^{\circ}$ as a function of impact angle α.

As can be seen from Fig. 2 the erosion rate of the 37-μm particles impacting a surface pre-eroded with 270-μm particles is initially enhanced over the eventual steady-state rate. The enhanced (initial) erosion rate $\Delta W'_{37}$ may be used(13) to describe the results using $\Delta W = f_{270} \Delta W^{o}_{270} + f_{37} \Delta W^{o}_{37} + f_{270}(1 - f_{270})(\Delta W'_{37} - \Delta W^{o}_{37})$ where the superscript o is used to denote the rate for particles acting individually and the subscript denotes the size. This relation, which requires an accurate measurement of the transient erosion rate $\Delta W'_{37}$, is shown by the solid lines in Fig. 7 for

$6 \leq \Delta W'_{37}/\Delta W_{37} \leq 8$, the range estimated experimentally. The results support the predicted trend. It should be mentioned that in an actual service application the situation is most likely to be more complex, due to more complicated particle distributions.

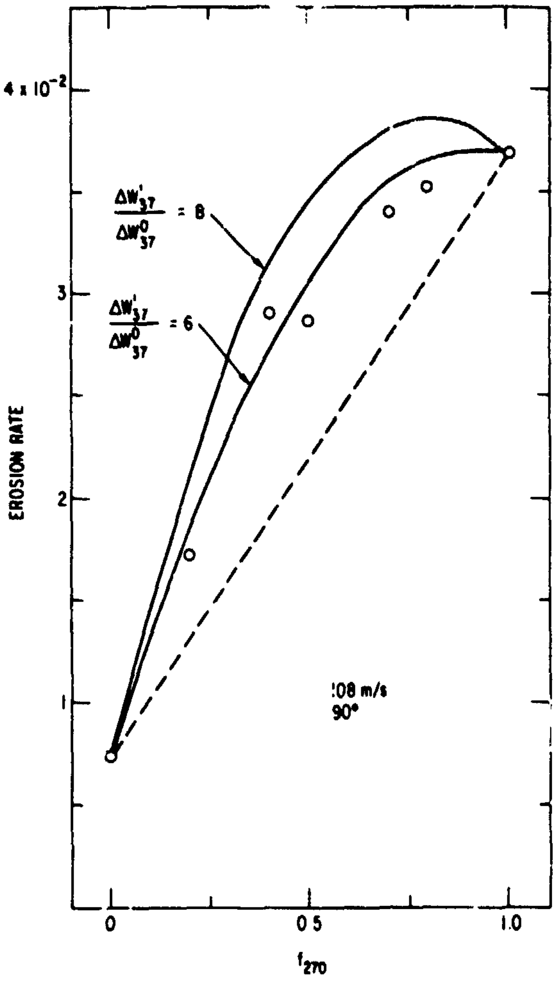


Fig. 7. The steady-state erosion rate obtained for mixtures of 37 and 270-μm particles shown as a function of weight-fraction of 270-μm particles. The dashed and solid lines are explained in the text.

V. Summary

The existing models adequately predict the functional dependence, on velocity and size of impacting particles, of the steady-state erosion rates in Si single crystals measured using angular Al_2O_3 particles if they are modified to include: 1. plasticity for small impact angles, 2. particle-size (and possibly velocity) threshold effects, 3. a particle-size dependent velocity exponent, and 4. a particle-size distribution effect. The above effects are known to exist, but further systematic experiments are needed to establish the phenomenology in other systems, and to provide a sound basis for the proper relationships needed in physical models. Theoretical work is needed to incorporate these effects into the models. Synergistic effects are known to exist, but our understanding of them is not complete, and it is certainly not possible to predict complex synergistic effects on the basis of our current knowledge. Finally, the projecticle properties (shape and hardness) have never been investigated. Microstructural effects in polycrystalline Si are also possible.

Acknowledgements

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References

1. S. M. Wiederhorn and B. R. Lawn, J. Am. Ceram. Soc., 62, 66 (1979).
2. A. G. Evans, M. E. Gulden and M. Rosenblatt, Proc. Roy. Soc., London, 361, 343 (1978).
3. T. H. Kosel, R. O. Scattergood and A. P. L. Turner, in Wear of Materials, edited by K. C. Ludema, et al., Am. Soc. of Mech. Engrs., New York (1979).
4. J. L. Routbort, R. O. Scattergood, and E. W. Kay, J. Am. Ceram. Soc., 63, 635 (1980).
5. B. J. Hockey, S. M. Wiederhorn and H. Johnson, in Fracture Mechanics of Ceramics, edited by R. C. Bradt, et al., Plenum, New York (1977).
6. D. B. Marshall, A. G. Evans, M. E. Gulden, J. L. Routbort, and R. O. Scattergood, Wear (in press).
7. R. O. Scattergood and J. L. Routbort, Wear, 67, 227 (1981).
8. J. L. Routbort, R. O. Scattergood, and A. P. L. Turner, Wear, 59, 363 (1980).
9. J. L. Routbort and R. O. Scattergood, J. Am. Ceram. Soc., 63, 593 (1980).
10. D. G. Rickerby and N. H. Macmillan, J. Mater. Sci., to be published (1981).
11. D. G. Rickerby, B. N. Pramila Bai, and N. H. Macmillan, J. Mater. Sci., 14, 1807 (1979).
12. I. Finnie, Wear, 19, 81 (1972).
13. R. O. Scattergood and J. L. Routbort, submitted to J. Am. Ceram. Soc.

DISCUSSION:

BOUJIKIAN: On your formula where DO was 12 microns--at that point your erosion sort of stopped--are the particles interfering with each other?

ROUTBORT: No. We are extremely careful to feed very slowly so that we get no interference of particles, in fact single streams of particles. What we cannot do of course, is to get particles 10 microns in diameter to erode. What you can do, however, is to calculate what the theoretical threshold should be and it turns out that in the case of silicon, the threshold is even less than we can measure in velocity. We have to go down to 10 meters per second. There the erosion rate is so slow that we couldn't measure it. So it's not a particle interference effect, it's probably a real threshold effect, but we haven't proved it unambiguously. The material removal rate is proportional to the particle size to the 2/3 power, and the velocity anywhere from the 2nd to the 4th power. It depends on particle shape, because that depends on the contact conditions. It depends on the hardness of the material. It depends on whatever model you use, it depends on the acoustic impedance of the target compared to the particle and it depends on the density of the impacting particle.

BOUJIKIAN: The hardness of the particle, therefore, comes into it.

ROUTBORT: The hardness of the target, not the particle. Yes.

CHEN: Your model is based on the complete brittle fracture model, brittle material, no plasticity occurred during the impact.

ROUTBORT: No. That's not quite right. Because you do assume that the kinetic energy of the indentor, if you will, is converted to plastic work in the plastic zone.

CHEN: No, I'm referring to the Weiderhorn paper about six months ago. He used a high-speed camera, and shooting the particle on the glass surface, he definitely showed there's a scooping. Showed the particle really pushed into the glass surface, and melted it...with energy so high it melted the surface and scooped part of the material out.RO

ROUTBORT: Many people observe intense shear zones where there's actually molten material. We have never observed it in silicon. You can indeed calculate that there's enough kinetic energy of the impacting particle to melt the material depending on the conductivity of the material. But we've never seen it.

HEIT: Are the abrasive particles directed against the work in an airstream?

ROUTBORT: No. That's not an airstream. It's under vacuum...the whole system. It's under vacuum because this arm is rotating at 10,000 rpm, and it doesn't rotate very well in air. The particles are mechanically accelerated out the end of the tube.

HEIT: How do you determine the weight loss of the silicon?

ROUTBORT: We do it sequentially, we put in a charge of 10 grams, we erode away, we stop, we open the vacuum, we take the samples out and weigh them, we put them back in.

HEIT: Is there any embedment of the abrasive?

ROUTBORT: Absolutely none. We've used dispersive X-ray analysis and there's no trace of aluminum; silicon yes, but none of aluminum. Alumina we find embedding in all of our metal work. In fact, many of our metal samples that we've run for various reasons or other gain weight due to embedding. The aluminum and nickel are both fairly soft, the abrasive particle is very sharp, it just sticks in.

WOLFE: I want to congratulate you on a marvelous piece of work that really helps to illuminate what is going on in this silicon removal area. You recommended looking at a higher-density particle like aluminum oxide rather than silicon carbide or such. I think there's probably a small difference. What you did is probably directly applicable to the something like sandblasting, while what we have is a backup of the particles with the tool, so the tool actually imparts the velocity onto the particle and so therefore the density of the particle is probably not as important as its hardness. I think the hardness comes in the size of the impact area. If you have a more ductile particle impacting, the impact area is probably larger, because the particle spreads out. When you have a very hard particle, the impact area is smaller, we have a larger force on a smaller area. I suspect that goes more rapidly to the cutting rate question than the density in this type of cutting we are doing here.

ILES: This is the first paper we've had where people are discussing the mechanics of erosion. It seems to me we've got liquid drops and we've also got particles of silicon from the kerf, coming at very high speed, loose, not bound on the diamond wheel. Are we in the range of speeds where we would expect to see some impact with silicon by silicon itself, which would perhaps modify the cut rates?

ROUTBORT: Do you have any idea what the velocities are?

ILES: I suspect it's in the range of 100 meters per second.

ROUTBORT: We have significant losses at 10 meters per second with hard particles.

ILES: I'm glad your talk opened up that sort of possibility. That's very interesting.

WOLF: Danyluk's experiments seem to indicate, in light of what you have been showing us here now, that depending upon what kind of lubricant we are using, we could get predominantly ductile erosion, or predominantly brittle erosion. Possibly one kind of hammering of the particles due to some tool vibration and so on, and the other kind, just pushes ductily the material away. Maybe we can learn to take advantage of these.

ROUTBORT: These things make a difference of a factor of 4 or so in erosion rate. At least the stuff we've studied. Now four is evidently enough for you people to make big savings.

N82 23676 D6

PRE AND POST ANNEALING OF MECHANICAL DAMAGE IN SILICON WAFERS

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ABSTRACT

Shaping operations of silicon, such as sawing, grinding, and lapping introduce micro-cracks and abrasion damage into silicon. The crystallographic nature of such defects in wafer surfaces before and after annealing is discussed. It is shown that dislocations and stacking faults are the annealing product of micro-cracks. Abrasion damage consists of shear loops. Frequently, such shear loops introduce sub-micron cracks due to dislocation pile-ups. Sub-micron cracks lead to stacking faults in the silicon surface during high temperature annealing. The electrical properties of such defects are discussed. It is shown that their presence reduces minority carrier lifetime in silicon. The effectiveness of damage removal techniques on silicon surfaces is also reviewed. Measurements are presented that indicate that silicon dioxide polishing of silicon removes damage with a minimum of damage propagation.

INTRODUCTION

Silicon wafers are produced from cylindrical single crystal ingots through mechanical shaping operations, such as grinding, sawing, lapping and polishing. The semiconductor industry has expanded considerable effort on the subject of producing damage free wafer surfaces. This has lead to numerous studies by many workers dealing with damage removal techniques, depth of damage measurements, crystallographic nature of damage, annealing properties of damage, electrical properties of mechanical damage and others.[1-10] Some of the highlights of such studies are reviewed in this paper.

INFLUENCE OF MECHANICAL DAMAGE ON ELECTRICAL PROPERTIES

Mechanical damage on silicon surfaces has significant influence on minority carrier lifetime and surface recombination velocities of carriers. This is illustrated in Figs. 1a and 1b for minority carrier lifetime. Both figures represent MOS C-t generation lifetime maps of silicon wafers. Figure 1a shows generation lifetime distributions for a "state of the art" silicon dioxide polished wafer. Average lifetime for this wafer is 400 μsec. The results shown in Fig. 1b were obtained by first lightly abrading half of a polished wafer surface and subsequently removing 10 μm of the abraded surface by chemical etching before MOS processing. The average lifetime in the damaged wafer half is 0.07 μsec as compared to 300 μsec obtained in the undamaged part of the wafer. This 4 order of magnitude decrease in lifetime in the damaged part of the wafer is due to dislocations and stacking faults.[10] Such defects are the annealing product of mechanical damage in silicon.[4,10] This subject is discussed in the next section of this review.

CRYSTALLOGRAPHIC STUDIES OF MECHANICAL DAMAGE

Detailed analytical studies of mechanical damage in silicon wafers are primarily hindered by the complexity of the defect state in the wafer surface encountered after conventional shaping procedures such as sawing and grinding.[4] The problem of damage complexity can be avoided by introducing mechanical damage into crystal surfaces in a controlled manner. This can be done most effectively using Impact Sound Stressing (ISS).[11] ISS of silicon wafers can reproduce the two basic features of mechanical damage in silicon such as micro-cracks and abrasion damage.[4] Using ISS a detailed study of mechanical damage in silicon surfaces was made and the pre- and post-annealing properties of cracks and abrasion on silicon surfaces were determined.[10] Some highlights of these studies are summarized in the following.

PRE-ANNEALING STUDIES OF CRACKS

A micro-crack in a silicon surface causes three different types of lattice distortion: (1) A rotation of both surface parts of the fractured wafer surface around an axis perpendicular to the surface, (2) A rotation of both surface parts of the fractured wafer surface around an axis parallel to the surface and parallel to the crack (bending), (3) Translation of the split crystal parts by a vector R mainly in (011) or (101) type directions for (001) surfaces in (111) or (011) planes (block slip).[10,12]

In general all three effects are present simultaneously. Thus the lattice distortions overlap and produce a rather complicated Moire pattern if observed in the transmission electron microscope (TEM). Simple patterns are seen for cracks lying in cleavage planes. Such Moires consists of pure translational fringes and the crack image looks very much like a stacking fault. This similarity is very striking if "closure" of the crack has taken place. This is always the case for areas close to the crack tip. Examples are given in the micrographs of Figs. 2.

TEM Moire patterns of crack tips can reveal many interesting facts about the crystallographic nature of cracks in silicon. For instance it can be shown that cleavage at room temperature does not introduce dislocations into the silicon because stresses around the crack tips are not plastically relieved. Consequently, crack tips in silicon represent stress centers which anneal out at high temperature. The annealing behavior of cracks is discussed in the next section.

POST-ANNEALING STUDIES OF CRACKS

Typical strain fields associated with crack tips before annealing are shown in Fig. 3. High temperature annealing of such cracks causes the formation of dislocations outside the crack area. An example is shown in the micrographs of Fig. 4 and reveals dislocation formation around a crack tip after annealing in nitrogen. Similar results are obtained for annealing in oxygen.

The simple equation $\theta = N.b/D$ can be used to estimate the number of dislocations necessary to relieve the strain connected with a crack in the lattice (θ = lattice tilt due to crack, N = number of dislocations, b = Burgers vector of dislocation, D = spacing between dislocations). The lattice tilt θ can be measured using the Kikuchi technique. For a tilt of approximately 0.15 degrees, it is calculated that only 6 dislocations are necessary to relieve the strain field connected with a micro-crack in silicon. This value is in good agreement with the experimental findings (Fig. 4).

Microcracks can be annealed out, specifically, if such splits are located in {111} planes. Assuming that "block slip"[12] governs crack formation it appears plausible that bonding between the silicon atoms in the vicinity of the crack tip is re-established through high temperature relaxation. Thus fairly large crack areas (micron range) can heal and 60° - and 90° - dislocations are the healing product of this process. Sub-micron cracks cause a much smaller displacement between the split crystal parts and stacking fault nucleation may occur directly through rebonding of the silicon atoms if the displacement "R" of the free crystal surfaces is of the right order of magnitude. This is shown very clearly in the TEM - micrograph of Fig. 5 and is an important mechanism for the annealing of abrasion damage as discussed in the next section.

PRE-ANNEALING STUDIES OF ABRASION DAMAGE

Abrasion of silicon surfaces introduces dislocation bands into the crystal. A typical example is given in Fig. 6. Such dislocation bands are composed of dislocation loops and appear in rows oriented along <100>, <110> or <120> directions. However, the intersections of all loops with the (001) surface is always a <110> direction indicating that the loops are located on {111} glide planes.

To understand the annealing properties of such dislocation bands Burgers vector determination of the dislocations were made before annealing. Accordingly, the Burgers vector of the loops is contained in the (111) or $(\bar{1}11)$ plane with Burgers vector (a/2) [011] or (a/2) [101]. Consequently, these dislocations are mixed dislocation loops which lie and expand in the {111} slip planes. Thus the loops are not prismatic dislocations, as generally assumed,[13] but are of the shear type.

POST-ANNEALING STUDIES OF ABRASION

Experimental evidence indicates that annealing of abraded silicon surfaces generates stacking faults (Fig. 7). The most frequently studied nucleation model for stacking faults relies on a dislocation reaction first pointed out by Hirsch[13] and assumes that mechanical damage produces prismatic dislocations which form stacking faults according to the reaction: $(a/2)[1\bar{1}0] \rightarrow (a/3)[1\bar{1}1] + (a/6)[1\bar{1}2]$. However, our measurements indicate that dislocation loops introduced through abrasive damage are shear loops. A shear loop cannot dissociate as required by the Hirsch reaction. Consequently, the generally accepted prismatic loop nucleation mechanism for oxidation induced stacking faults cannot explain stacking fault nucleation.[10]

An additional result from our abrasion studies is the finding that the dislocation bands due to abrasion contain dislocation pile-ups, on neighboring slip planes, which are separated by only 200A. The corresponding dislocation density can be estimated to be $10^{10}/cm^2$ or higher. Based on the work of Fujita[14], Cottrell[15], and specifically of Abrahams and Ekstrom[16] such dense dislocation pile-ups favor micro-crack formation. Consequently, we must assume that abrasive type of damage produces microcracks.

The contention that microsplits in the silicon surface-- caused by dislocation pile-ups -- act as sources for stacking fault generation during oxidation, is supported by experimental evidence (Fig. 8). We have observed many examples of small Moire patterns connected with high density dislocation clusters. Such patterns are only 2000A in size or even smaller and grow into stacking faults during oxidation.[10]

DAMAGE REMOVAL

It is interesting to note that the agreement between differently measured values of saw damage depth published in the literature[2,7] is quite poor, indicating certain difficulties with such measurements primarily related to the different measurement techniques. In this context it is also noteworthy to observe that polishing techniques are generally assumed to be equal in terms of "effectiveness" of damage removal. Actually, large variations in damage removal and damage propagation are characteristic for different polishing techniques. This is discussed in the following.

Three polishing techniques are compared: (1) Chemical polishing using nitric, acetic and hydrofluoric acid mixtures (fast and slow), (2) Chem-mech cupric ion polishing, (3) Chem-mech silicon dioxide polishing.

The comparison is based on the idea that first mechanical damage is introduced into highly perfect silicon surfaces in a controlled manner. Subsequently, the damage removal effectiveness of a polishing technique is measured as the amount of material necessary to be removed to again obtain a "perfect" surface. The damage is introduced through the technique of Impact Sound Stressing (ISS). The damage removal is monitored through generation lifetime measurements.[10]

The experimental findings that relate the effectiveness of damage removal to the polishing agents are summarized in Fig. 9.

It is evident that the more mechanical acting polishing technique - silicon-dioxide - is the most effective one for damage removal. The least effective polish is the slow chemical etch. This difference in damage removal rate between chemical and mechanical acting agents relates to crack propagation during polishing. Chemical etching requires removal of at least four times the original damage depth as a result of crack propagation during etching. Generation lifetime of the original surface is not recovered through chemical etching.[10]

SUMMARY

Basic properties of mechanical damage in silicon consisting of cracks and abrasion were studied using transmission electron microscopy. The crystallographic structure of mechanical damage was determined before and after high temperature annealing. The main findings include that stresses in silicon around crack tips are not plastically relieved at room temperature and that abrasion at room temperature introduces shear loops into the silicon. It was also found that cracks of micron size can be annealed out, specifically, if cleavage occurs on {111} planes. The healing products of such cracks are 60° and 90° dislocations. Sub-micron cracks transform into stacking faults during annealing. Likewise high concentrations of shear loops due to abrasion were found to anneal into stacking faults. No direct evidence of the stacking fault nucleation process was obtained. However, a one to one correlation between surface areas containing small cracks and stacking faults was made.

Measurements of damage removal on silicon surfaces through chemical-mechanical etching techniques are presented. It is shown that silicon dioxide repolishes damaged silicon surfaces most effectively.

REFERENCES

1. J. W. Faust, Electrochem. Tech., 2, 339, 1964.
2. E. N. Pugh and L. E. Samuels, J. Electrochem. Soc., 108, 1043, (1964).
3. R. Stickler and J. W. Faust, Electrochem. Tech. 4, 339, 1966.
4. R. Stickler and G. P. Booker, Phil. Mag. 8, 858, (1963).
5. T. M. Buck, The Surface Chemistry of Metals and Semiconductors, ed. H. C. Gatos, p. 107, John Wiley & Sons, Inc., New York 1960.
6. T. M. Buck, J. Electrochem. Soc. 109, 1220, (1962).
7. G. A. Wolff, J. M. Wilbur and J. C. Clark, J. Electrochem. 61, 101, (1957).
8. J. W. Faust, in Symposium on Cleaning of Electronic Device Components and Materials, ASTM Spec. Tech. Pub. 246, p. 66, Phil., PA (1959).
9. T. M. Buck and F. S. McKim, J. Electrochem. Soc., 105, 711 (1958).
10. G. H. Schwuttke, Technical Reports No. 4, 7, APRA Contract DAHC15-72-C-0274, published 1976.
11. G. H. Schwuttke, K. H. Yang, H. Kappert, phys. stat. sol. (a) 42, 553, 1977.
12. M. J. Hill and D. J. Rowcliff, J. Mat. Soc. 9, 1569 (1974).
13. P. B. Hirsch, NPL Conference, HMSO, London 1962, Discussion I, page 44.
14. F. E. Fujita, Acta Met. 6, 543 (1958).
15. A. H. Cottrell, Fracture, Wiley, New York 1959, page 24.
16. M. S. Abrahams and L. Ekstrom, Act. Met. 8, 654, (1960).

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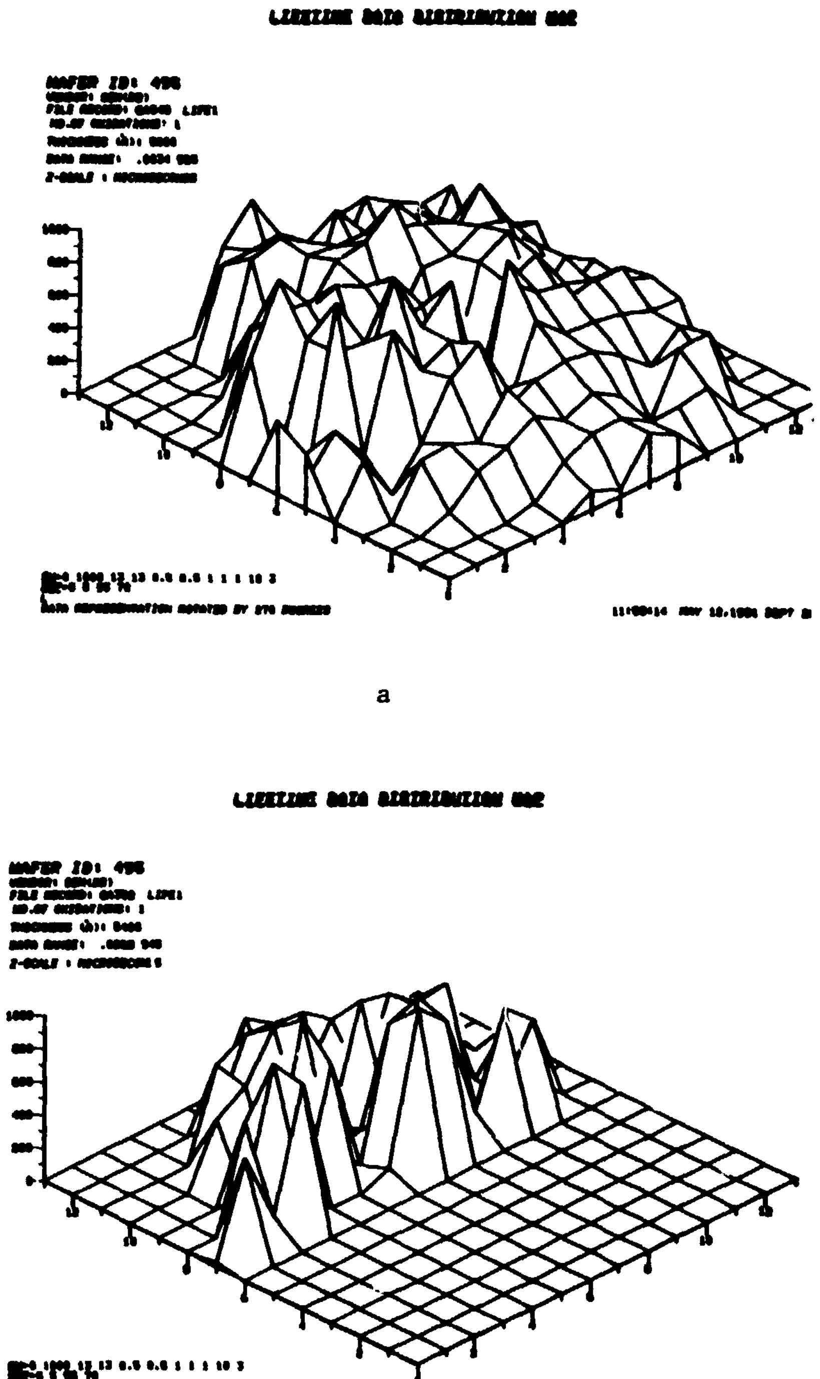

Fig. 1. Generation lifetime maps of silicon wafers. (a) Standard wafer after silicon dioxide polishing. (b) Same as (a) only one half of wafer surface contains residual mechanical damage. Note decrease of lifetime by 4 orders of magnitude in this part.

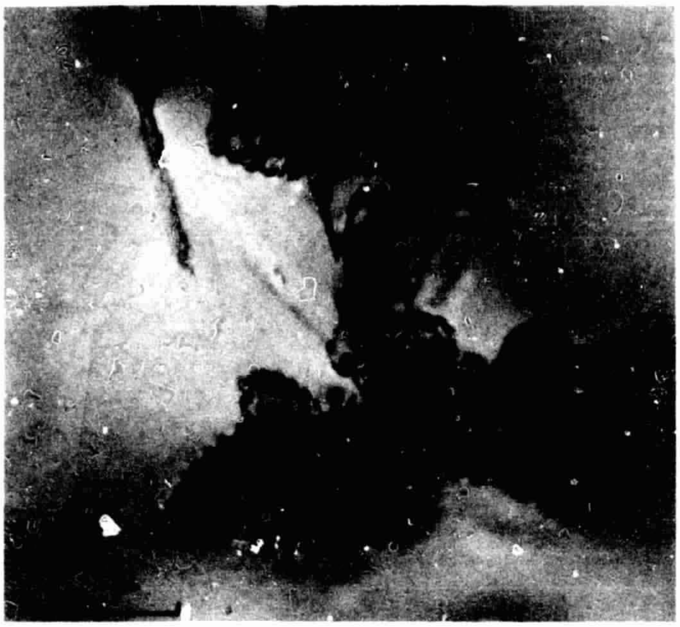

Fig. 2 Transmission electron micrograph of crack in silicon.

Fig. 3 Transmission electron micrograph of strain field associated with crack in silicon.

Fig. 4. Transmission electron micrograph of annealed crack showing dislocations

Fig. 5. Transmission electron micrograph of stacking fault nucleation through annealing of microcrack.

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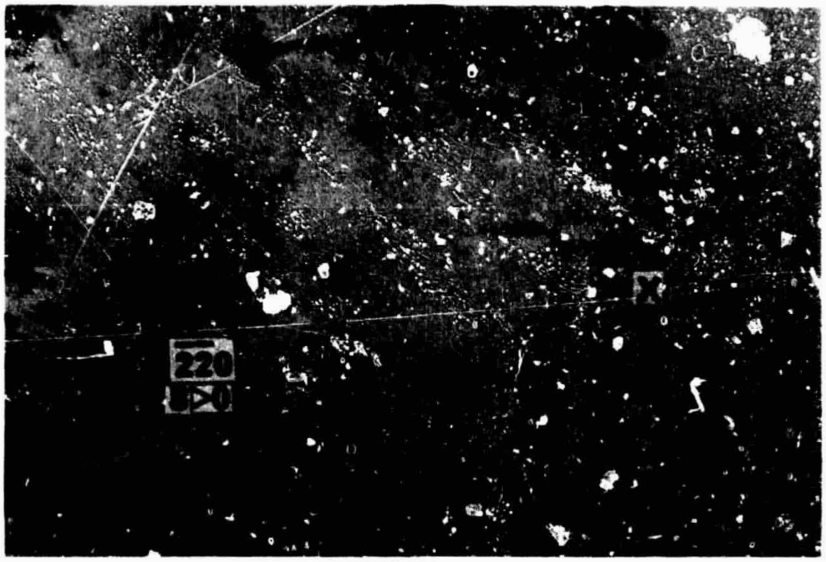

Fig. 6 Transmission electron micrograph of abrasion damage showing dislocation shear loops.

Fig. 7 Transmission electron micrograph of annealed abrasion damage showing stacking faults.

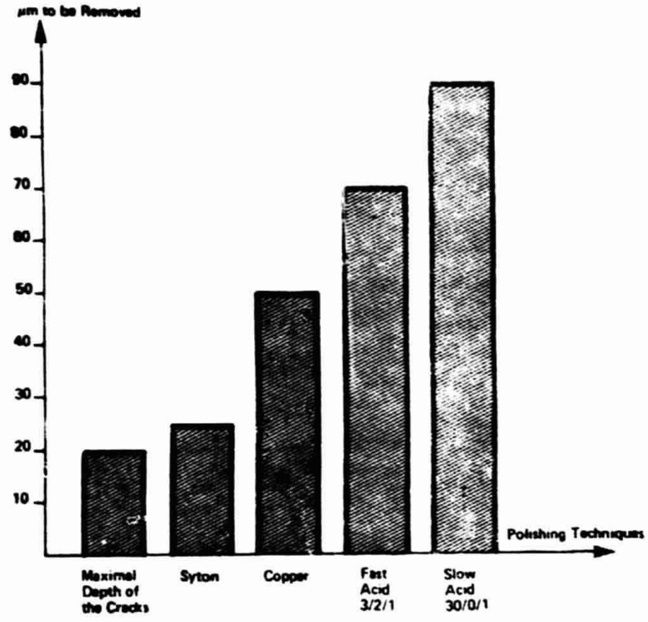

Fig. 8 Summary of damage removal effectiveness of different polishing techniques.

DISCUSSION:

KOLIWAD: One of the objectives we had in the work we did three years ago on the nature and the effect of damage on solar-cell efficiencies in the multiblade-sliced wafers was to verify whether, in fact, that damage has microsplits, and secondly of course to verify the effect of damage itself on efficiency. We did not look extensively into the existence of microcracks, but one of the ways we tried to identify them was doing exactly what he showed in the last viewgraph. We did remove the damage by Syton polish as well as by chemical etching. One of our conclusions was that for certain removal of damage, there was no difference at all on the efficiency of the cells from the polished wafers and the efficiency of the cells from the chemically removed wafers. So what we concluded was that maybe there were no microsplits in the multiblade-sliced wafers and of course depth of damage itself had an effect. We also concluded from the study that the efficiency increased up to the point where we had removed all damage, and then remained stable after that. So I would like to know if you have any thoughts on whether the simulation by ISS is general or is particular for the plunge cutting kind of technique?

SCHWUTTKE: I think the ISS allows you to do some real basic studies. It does not relate to any particular slicing or sawing technique. It allows me to put abrasion in a controlled manner into a surface, and I can do this before processing. It really doesn't matter what kind of device you use. It also allows me to put splits into the silicon surface, and since we know the annealing properties of this type of damage, you can make a prediction of what effect it might have on your device characteristics. I'd like to address what you said in your comment. When you did these measurements, you did not find any influence on solar-cell efficiency. I believe as long as you are satisfied with a 10% to 12% solar-cell efficiency, you are not addressing the key problem. If you are after a better than 15% solar cell, then the solar cell is much more lifetime-dependent. At higher efficiencies, this will be very important.

KOLIWAD: Of course we are comparing the wafers where the damage was removed first chemically and then polished. But the question I had was: are we right in assuming, since our efficiency did not change with respect to how we removed the damage, that there are no microsplits?

SCHWUTTKE: Multiblade slicing I would say, if done properly, and in a controlled way, is a gentler technique than ID slicing. Based on this I would say you have a better chance to end up with a good surface. A wire saw is basically a very gentle technique. I get concerned if I listen to comments like the last two days, that everybody puts his effort into speeding up multiblade cutting, multi-wire cutting, many miles per hour faster. So actually, you may approach an out-of-control process again, and then you will have other problems.

ROUTBORT: Does the formation of these shear loops depend on the dopant level of the silicon?

SCHWUTTKE: Not so much. We have investigated a wide range of doping, n-type and p-type, and in all cases, we find similar damage. Very much alike.

ROUTBORT: You know, these abrasion experiments are really nice because in the old days, in the late '50s, Hausner and Alexander deformed silicon at high temperatures, and they found precisely that the deformation characteristics depend on the surface finish at room temperature, because they are, of course, the source of all the dislocations.

SCHWUTTKE: I think it's a very neat way of studying damage in silicon. The intent of our experiments was to simulate, to get a handle on residual damage. We have two damage modes if you address ID saw damage. One is a uniform damage, which indicates that you have the controlled ID slicing process. Now if you find superimposed a nonhomogeneous damage mode, then you know that the process is out of control, and you are dealing with blade vibrations. The blade vibrations we found are highly undesirable because they are responsible for that tremendous variation in damage depths. This is based on cracking of the material. If you prepare your wafer surface, you remove the original saw damage, you are left with such splits. Originally you knew the semiconductor industry would deliver slices, and you had split concentration of 10^6 per square centimeter. It's unbelievable. Subsequently, we learned how to do a better job. Out-of-plane vibration is something that can be eliminated. Then you should be left with a very uniform damage depth, and so you are in a much better shape from the beginning. And this is how I interpret Kris Koliwad's experiment. He had a much better-controlled slicing process.

WOLF: I have two other questions . First, we heard from Larry Dyer earlier this morning about the split propagation in the (100) cutting direction. Would we be better off if we would be cutting the (111) direction, where the crack propagation is more in line with the saw normal force? Would we get less penetration sideways off these microcracks? The second part is, if we go to ductile deformation rather than to brittle erosion, where we deal more with plastic deformation, would we also get less damage in the wafers?

SCHWUTTKE: I think the application of lubricants of the type discussed in the first two papers on Monday is an important aspect of the slicing. Particularly if you want to go faster. These things will become very important. Orientation dependence in terms of hardness: silicon is a non-isotropic material, and is softest in the (111) plane. There are tradeoffs from that point of view.

DYER: Both your paper and the one preceding are fundamental to this field. They help us understand how to cut the silicon; everybody should appreciate that. From one of the statements of Jules (Routbort) and statements of yours, a person could get the impression that the plastic deformation or the formation of the shear loops is beneficial to removing silicon. In my view, that might be an incorrect way of looking at it, i.e., if we could prevent that, it would probably be better. Thus, we want the direct application of the stress to form the cracks, and all that any plastic deformation does is to absorb some of the energy temporarily and make it necessary to build up more stresses before the thing finally does the cracking that we want. Any plasticity will actually hurt.

"Would it better to have ductile behavior?" I doubt it very much. I think we want it to stay brittle.

SCHWUTTKE: You will have a trade-off. If you stay too brittle and you go too fast, you knock the hell out of silicon and that is no good either. If you want to go fast, you will be forced to use lubricants.

DYER: To me, if you try to cut fast through something and you try to make it ductile, you get through it all right, but the thing gets bogged down by grabbing onto the sides.

SCHWUTTKE: I'm not so much concerned about the ID saw. I think the guys have made a lot of progress in ID slicing. If I look at the equipment we threw out several years ago, and take a look at the equipment we are using today, it's like day and night. You probably find the same thing. You never would make a 100-millimeter slice and show your lifetime distribution is an average of 400. It's not exactly a plateau, but it's coming close to that. I think that is progress in technology. That was unthinkable just a few years ago. So slicing and combined chem-mech polishing has made a tremendous leap forward. Using these two techniques, the first a very tough one, the second the polishing technique, we can reestablish and bring back a basically perfect silicon surface. It's amazing that this can be done.

DYER: I make a distinction between the beneficial nature of having it brittle and having the very many, many cracks, very small in depth, and the type of brittle you're talking about, where you have big cracks going all the way through something. So we can actually use the brittle nature of it to our benefit.

SCHWUTTKE: Deformation at room temperature of brittle materials like silicon is advantageous because we were able to develop polishing techniques that will remove this type of damage. Your concern is if we go now to plastic deformation at room temperature, by the use of lubricants, we may lose that particular benefit. We may not be able to bring back a perfect surface, because the plastic deformation process will be out of control. If it is a brittle material, we seem to be able to control the plastic deformation to the contact point, and that is where the advantage is right now.

DYER: You show this difference between polishing by removal of the damage layer with the acid and with the polisher. Have you any idea why that is? Why that tremendous difference? Can you give us some physical insight?

SCHWUTTKE: Yes. I think it relates to the chemical potential around the crack tip. And if you use chemistry, then you lower the chemical potential and the crack continues to run ahead of the etching front. If you do a more mechanical polishing you don't encounter this problem; you don't propagate the crack. So Syton is just fantastic. Syton seems to be able to recover the crystal without crack propagations. We are just lucky.

UNO: We have the same problem. We do our chemical etching. Now what do you consider slow and fast? Is 25 microns per minute fast or slow?

SCHWUTTKE: That is fast. Slow, I'm talking about 2 microns per minute.

SCHWUTTKE: By the way, Peter (Iles), looking at your picture yesterday: you indicated that you had an uneven surface where you were cutting chemically through the wafer. You indicated that you thought that this may be related to internal defects present in the material. It is my experience, and I have seen such surfaces as you showed, it is due to bubble formation. And you also indicated that you have violent action of hydrogen. All that happens is that the hydrogen seems to form bubbles on the internal surfaces, and that's where you get your uneven etching.

CHEN: You have a beautiful TEM picture of the crack on the sample. Can you address, a little bit, the TEM sample preparation--what are the thicknesses of the samples you prepared?

SCHWUTTKE: We are fortunate, we have a 200 kilowatt electron microscope, so I can penetrate more silicon than with a 100 kV. It makes it simpler to display these cracks.

CHEN: Do you have any other simple method in use for crack examination?

SCHWUTTKE: I have shown you some pictures, but this is really tedious work, as the SEM pictures I showed you where those splits opened up. They are very tedious. It's very tough. The best way to find cracks is really the transmission electron microscope. Because you have two crystal faces, no bonding between, so you just chase the thing down till you see a Moire pattern, and you know you have a crack. To find these things--it took us weeks and months the first time, when we attacked the problem, to see this tiny Moire pattern--but once you know what to look for they suddenly pop out all over the place. As I said, we even come up with a million per square centimeter, but we never could find any before that. It's really a matter of knowing what to look for, like everything else, and then you suddenly see it.

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STATUS OF SEMI'S SOLAR-GRADE SUBSTRATE STANDARDS

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The primary purpose of the Semiconductor Equipment and Materials Institute, Inc. (SEMI), was to manage a local equipment and materials trade show that would attract Santa Clara County's semiconductor companies. Since its formation in 1970, however, SEMI has grown into an international organization providing multiple services to its members. It is guided by industry committees staffed by member-company representatives working to develop services beneficial to all.

The first step of SEMI's evolution from a trade-show organization into a full-service trade association occurred in 1973, with the formation of a Standards Committee. The committee explored the possibilities of an institute-organized industry effort to standarize specifications for materials, equipment and processes used in semiconductor manufacturing. The first Book of SEMI Standards (BOSS) was published in 1978.

The original Standards Committee evolved into seven major divisions:

(1) Chemical Division
(2) Equipment Division
(3) Packaging Division
(4) Photomask Division
(5) European Liaison
(6) Government Liaison
(7) Materials Division

Because participants in the wafering workshop are interested in solar-grade substrate standards, a breakdown of the areas of interest to that subcommittee in the Materials Division is given:

(1) Silicon Wafer
(2) Silicon on Sapphire
(3) Epitaxial Substrate
(4) Gadolinium Gallium Garnet Substrate
(5) Solar-Grade Substrates

The subcommittee approved the General Requirements document on the solar-grade substrate standards for balloting by industry on May 18, 1981. It now stands as an addition to the BOSS. This standard specification covers requirements for silicon slices (wafers) used in solar cell manufacture. Dimensional characteristics and crystal-structure defects are the only standardized properties set forth. Three classes of material are defined: polycrystalline, substantially monocrystalline and monocrystalline. These are defined as:

(1) Polycrystalline: does not meet requirements of another class. Minimum grain size of N times the slice thickness.
(2) Substantially Monocrystalline: not more than X grain boundaries per slice or Y mm total length of grain boundaries, or having no crystallites smaller than 0.Z of the width of the slice.*
(3) Monocrystalline: free of grain boundaries.

A complete purchase specification requires that additional physical properties be defined. These properties are listed with test methods suitable for determining their magnitude.

The Standards format consists of two specific documents: the first describes the general requirements of the specification that is applicable to all of the SEMI Standards. The second, which will be the SEMI Standard specification for that particular substrate, will describe the specific dimensional characteristics and crystalline structure.

A breakdown of the specific paragraphs of the general requirements specification and a statement of content follows:

(1) Preface: contains the general information as given above.
(2) Applicable Documents: the applicable ASTM Standards and DIN Standards that are required to measure specific properties, and statistical documents for test sampling, are listed.
(3) Definitions: the required definitions are stated specifically (e.g., define a "lot").
(4) Ordering Information.
(5) Dimensions and Permissible Variations.
(6) Materials and Manufacture: defines the structural class or growth method.
(7) Physical Parameters.
(8) Sampling.
(9) Test Methods.
(10) Certification.
(11) Packaging and Marking.

A specific example of a proposed slice specification, in this case for a square slice, is given in Table 1 and Figure 1.

In conclusion, the general requirements for a SEMI Specification for solar-grade silicon slices has been approved for balloting by industry. The results are expected to be published at the next meeting to be held in September. The definition of specific dimension and tolerance requirements for individual slices is still in committee.

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*Numerical Values of N, X, Y and Z are to be established in committee.

Table 1. Example of Proposed Square Cell Specification

I. Crystallographic	II Electrical	III Mechanical*	IV Visual
No limit for dislocation EPD, slip, lineage, or swirl Surface orientation on <100>± 3° Crystal orientation to growth lines 45° ± 8°	Boron dopant 0.5 to 2.0 ohm-cm.	Cell width, 100 ± 0.5 mm Cell diagonal, 125 ± 3 mm Flat length, < 74.9 mm Adjacent sides, 90° ± 0°20' Thickness, .37 ± 0.10 mm TTV, 50 μm maximum Warp, 60 μm maximum	Front and back surfaces, sawn. Saw marks, none on one side. Roughness, 1 micrometer RMS maximum Cracks, none. Chips, conchoidal, up to 6 each with a maximum length or radial penetration of 1.6 mm. Chips with both dimensions less than 0.25 mm are exempt. No conchoidal chips are permitted. No fracture or pointed apex chips of any size. Saw exit defects permitted on 5 percent of cells. No foreign matter visible to unaided eye permitted.

*See Figure 1.

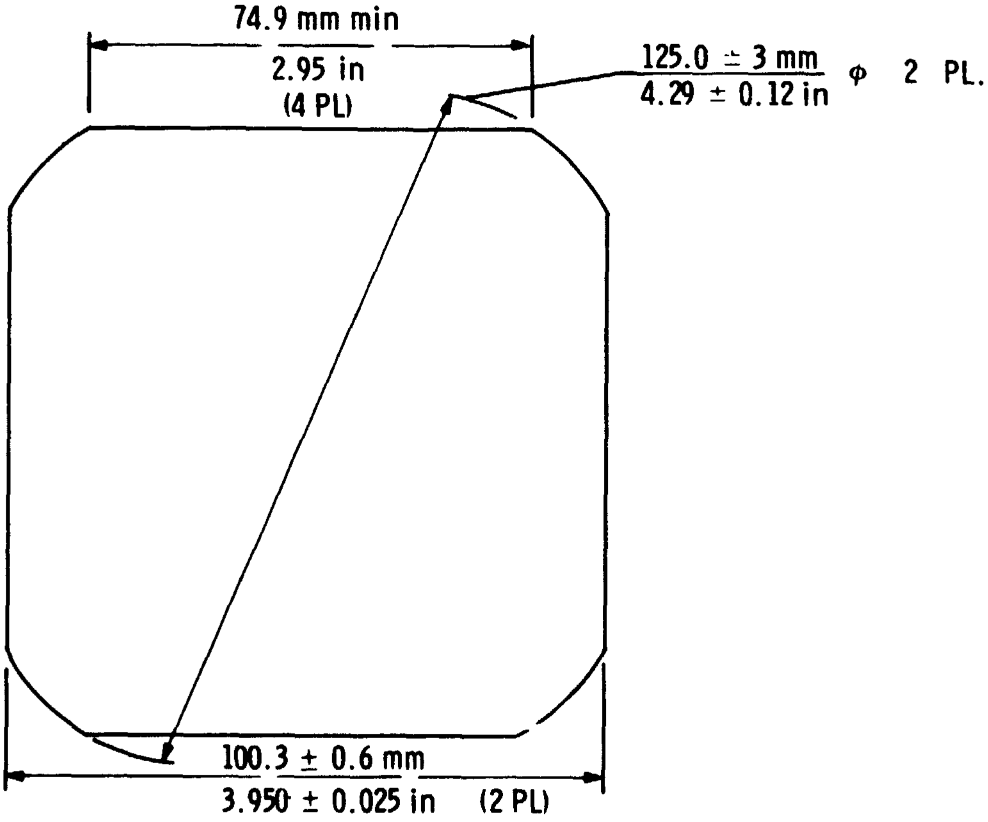

Fig. 1. Example of Proposed Square Cell Specification

DISCUSSION:

GALLAGHER: Remember that this is a strictly voluntary type participation and we definitely need more participation than we have now. There are usually three meetings a year. San Mateo, Boston, and the third one is usually held in Anaheim, in conjunction with the Nepcon show.

ILES: I should mention for the people in wafering, as a means of self-defense, you should keep an eye on these things. Once these specs get slipped in on you, you'll find they haven't heard your input and they don't know that some things are very difficult to do altogether.

It was interesting that many people came thinking they were going to hear all sorts of wonderful numbers on slicing speeds and wafers you can see through and things like that. It was very interesting that we were guided gradually and rather expertly into the microscopic aspects, and people may be going away thinking more about what's really happening in the process rather than cursing about the machine that rocks or bumps too much.

I think we even strayed into philosophy last night. I was listening to Tom (Lewandowski) from STC, and he was talking about the problem if you had 10 machines and there's a noise on one but no operator. Sounded like that old business about the tree falling in the forest and whether there's really a noise or not, depending on whether there's a human ear to hear it. I guess we can be satisfied that we can say "if we see a lot of chips on the floor, then we can tell the philosophers something happened." I think the ID people go away feeling that "Thank God that the blade, saw, wire people have some problems" and vice versa, so I think we've at least shared our problems and everyone feels a little better to know that the other guy has a different set of insurmountable problems, mainly based on low cost. I had a comment from someone who'd not been to any of the PIMs or any of the JPL meetings. He said he particularly appreciated the fact that there were so many disciplines presented here. I think the original fear of the steering committee was that we might find that some people would sit around bored to death while other people talked about stuff that they'd been hearing a lot of, but I think it is very good to have different viewpoints on all the questions. I'm sure JPL is going to focus all this work, and upgrade all this wafering thing, and I'll just finish by saying the success of this conference can be traced very accurately by just watching how well the ribbons do. If the ribbon people take over from us, then we haven't done our job in wafering.

INDEX OF AUTHORS AND SPEAKERS

(Editor's note: names of authors appear in capital letters; names of those who participated in discussions of papers appear with initial capitals only. Number in parentheses following an author's name indicate page on which his paper begins. Numbers not in parenthesis after a name indicate pages on which that person's participation in discussions is quoted.)

AHARONYAN, P.: (35); 43-45, 70, 73, 75, 228, 229.

Bosomworth, D.R.: 154.
Boujikian, J.M.: 69, 70, 73, 75, 119, 122, 289.

CHEN, C.P.: (47, 159); 59, 60, 76, 278, 289, 305.
COLLINS, E.R.: (243).

DANYLUK, S.: (89); 72, 99, 100, 123, 172.
DAUD, T.: (187); 69, 196, 209, 228, 257.
DYER, L.D.: (269); 22, 43, 59, 60, 69-71, 73, 99, 119, 172, 208, 222, 223, 226, 228, 241, 242, 248, 278, 279, 303, 304.

FALLON, D.B.: (101); 120, 121.
Farber, J.J.: 69, 70.
Frizell, W.M.: 71, 88 99, 100.
FUERST, F.P.: (211); 43, 209, 221, 222, 225-227.

GALLAGHER, B.D.: (307); 99, 119, 310.
Glyman, J.: 221.

Heit, A.H.: 71, 77, 153, 172, 289, 290.

ILES, P.A.: (29, 259); 69, 196, 224, 226, 290, 310.

Jacksen, N.: 152, 155, 241.
Johnson, C.M.: (61).

Kachajian, G.: 223, 224, 231, 257, 258.
KHATTAK, C.P.: (111, 233).
KOLIWAD, K.M.: (3); 70, 123, 222, 227, 302.
Koundakjian, V.: 72, 73, 227.
KUAN, T.S.: (81); 73, 88, 119, 122, 123.

Lane, R.L.: 43, 44, 72, 88, 127, 155, 172.
LEIPOLD, M.H.: (47).
LEWANDOWSKI, T.: (253); 257, 258.
Liu, J.K.: 88, 121, 122, 208, 209, 226, 257, 258.
LYNAH, F.P.: (133); 155, 225.

MACKEY, C.R.: (249).
MOKASHI, A.R.: (197); 208, 209.
Morrison, A.D.: 154, 208, 228, 258.

O'DONNELL, T.P.: (159); 172, 173.
Oswald, D.R.: 70, 208.

Reimann, G.T.: 279.
ROBERTS, E.G.: (61); 69, 70, 196.
ROSENFIELD, T.P.: (211).
ROSS, J.B.: (133); 172, 173.
ROUTBORT, J.L.: (281); 289, 290, 302, 303.

Saltzman, R.: 72.
SCATTERGOOD, R.O.: (281).
SCHMID, F.: (111, 233); 11, 22, 23, 45, 121, 152, 156, 157, 196, 209, 221, 224, 225, 227, 241.
SCHWUTTKE, G.H.: (291); 22, 23, 43, 59, 76, 122, 302-305.
SHIH, K.K.: (81).
SMITH, M.B.: (111, 233).
SOCLOF, S.I.: (259).
Surek, T.: 208, 221, 227.

Uno, F.M.: 208, 304.

VAN VECHTEN, J.A.: (81).

Wallitt, A.L.: 156.
WERNER, P.G.: (141); 22, 23, 43, 74, 75, 120, 121, 152-157.
WESTDORP, W.A.: (81).
WOLF, M.: (13); 22, 23, 69, 77, 100, 154, 177, 185, 191, 209, 221, 223-229, 278, 290, 303.

YERKES, J.W.: (25); 44, 59, 74, 76.
YOO, H.I.: (179); 70, 257.