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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:

$$v_c = 4.2\cdot10^{-6}\,\frac{v_t\,F_n}{k}\ [\mathrm{cm\ min^{-1}}]\quad (v_t \text{ in cm min}^{-1},\ F_n \text{ in g},\ k \text{ in } \mu\mathrm{m}) \qquad (1)$$

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.

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Table II THE KEY VARIABLES IN SILICON CUTTING

Independent Variables	Choices		Dependent Variables
Abrasive Arrangement	Fixed	Movable (Slurry)	Expendables
Location of Cutting Action	Edges of "Teeth"	Surface of Rolling Grains	(Tool with imbedded abrasive, or blade and slurry)
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	1931	1976	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

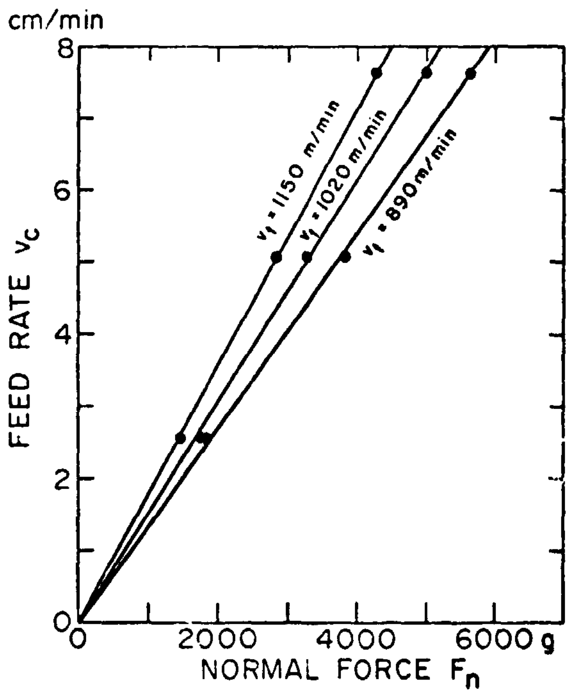
ATTRIBUTE	UNITS	SLURRY SAWING		FIXED ABRASIVE SAWING	
		MULTI-BLADE (VARIAN 686, M&B1, HOFFMAN PL-4)	MULTI-WIRE (YASUNAGA YQ-100)	MULTI-WIRE (CRYSTAL SYSTEMS FAST)	ID-BLADE (SILTEC AND STC
TANGENTIAL TOOL SPEED	M/MIN	12-50	72-82	60-150	800-1200
BLADE LOAD	G/BLADE	50-300	~100 AVE.	20-45	1500-6000
FEED 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

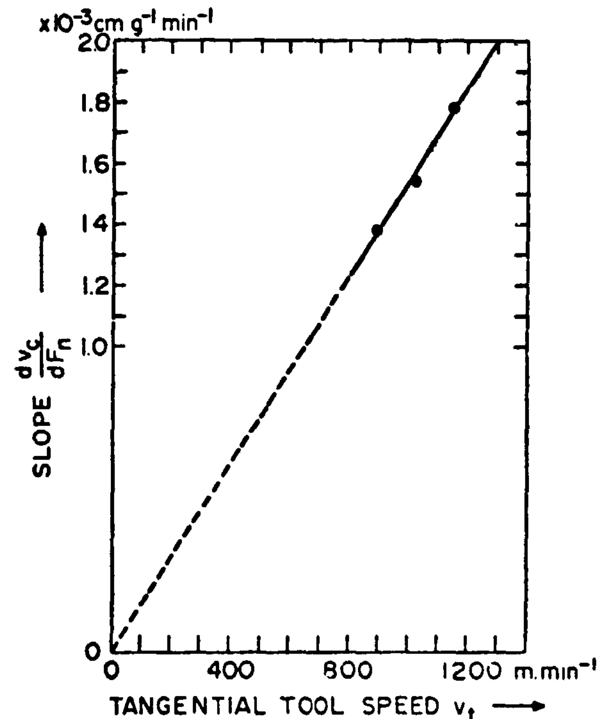
Table V COMPARISON OF EXPERIMENTAL FEED RATE WITH FEED RATES CALCULATED FROM GENERAL SILICON CUTTING EQUATION

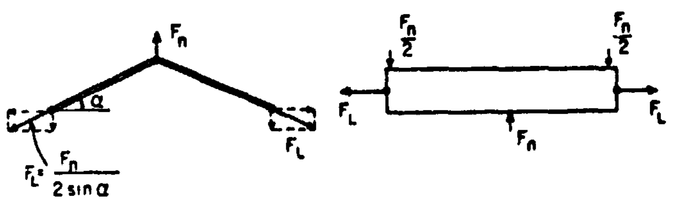
METHOD (CONTRACTOR)	MBS SAW (VARIAN)				YASUNAGA YQ-100 (SOLAREX)				FAST (CRYST. SYST.)			ID SAW (STC)
RUN #	2-1-02	2-3-04	2-5-14	2-7-06	3	8.4	11	14	2-002	328-SX	448-SX	(REF)
INGOT DIA. (CM)	10	10	10	10	8	8	7	6	10	10	10	9.8
NO. BLADES	150	137	150	940	75	75	80	75	114	144	167	1
PARAMETERS	LAB SAW #600 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	9900	102,000
F_N (G)	85	85	113	85	102	102	104	102	37.8	42.4	32.5	3270
K (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.[illegible]	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	33.0[illegible]	[illegible] 21	119.75	8.54
Lost Si	76.-	51.-	60.-	46.-	82.-	79.-	64.-	71.-	4[illegible].-
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	3[illegible]0	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 those are contact problems that involve fracture which has been almost ignored in most of the saw literature and a lot of the discussions. I [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.