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ASSESSMENT OF PRESENT STATE-OF-THE-ART SAWING TECHNOLOGY OF LARGE DIAMETER INGOTS FOR SOLAR SHEET MATERIAL

FIRST QUARTERLY REPORT

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By

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ABSTRACT

The objective of this program is to assess the present state-of-the-art sawing technology of large diameter silicon ingots (3" and 4" diameter) for solar sheet materials. During this period, work has progressed in three areas: (1) Slicing of the ingots with the multiblade slurry saw and the I.D. saw, (2) Characterization of the sliced wafers, and (3) Analysis of direct labor, expendable material costs, and wafer productivity.

Multiblade slurry slicing resulted in mechanical wafer yields of 95(%) for the 3" diameter ingot and 84(%) for the 4" diameter ingot (using a 230 blade package to cut 6" ingot in length). A slicing test with the I.D. saw was performed to obtain mechanical yield versus both wafer thickness and cut rate, and the result showed a good yield (above 95%) down to 7-8 mils of wafer thickness for the 3" wafers and 11-12 mils for the 4" wafers if the cut rates were reduced to one (1) inch per minute.

Thickness, taper, bow, and roughness (RMS) were measured to characterize the sliced wafers. Four inch wafers sliced with the multiblade slurry saw showed larger thickness variation (wafer to wafer) and more taper than 3" wafers. Wafers sliced with the I.D. saw indicated that bow and roughness increased as the cut rate increased from one (1) inch per minute to two (2) inches per minute. Comparison of the above parameters

showed the wafers cut with the I.D. saw had much smaller values and variations than those with multiblade slurry saw, indicating the need for less removal of silicon before solar cell formation.

An analysis of direct labor, expendable material cost and productivity for both sawing methods showed that the I.D. saw slicing technique is more favorable than multiblade slurry slicing techniques at present.

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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 been tried and some have seen limited 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.
- Multiwire saw, using slurry, or diamond particles plated to the wire
- 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 program is to assess the present state-of-the-art sawing technology of large diameter silicon ingots for solar sheet materials with main emphasis on the I.D. saw. Slicing by multi-blade slurry slicing and multi-wire abrasive slicing will be compared with I.D. slicing techniques.

During this reporting period, work has progressed in slicing of silicon ingots (3" and 4" in diameter) with multi-blade slurry (MBS) saw and internal diameter (I.D.) saw. Mechanical properties of the sliced wafers, such as thickness, taper, bow and roughness, are characterized, and two slicing techniques are compared for overall efficiency in:

1. Number of slices per unit length, or ingot to sheet conversion
2. Wafer productivity, expendable material cost and direct labor

These are the most important parameters which will ultimately influence the cost of the silicon sheet ($\$/m^2$).

2.0 SLICING EXPERIMENTS

2.1 Multiblade Slurry (MBS) Saw Slicing

Slicing experiments were conducted using a Norton wafering machine (Model 686). Since the reciprocating action of the heavy blade head introduces a shock, which might cause breakage of the slices in the ingot, the machine was mounted solidly to minimize the introduction of a shock to the ingot. A pre-assembled blade package from Varian was loaded in the blade head and aligned and tensioned. The blade packages with 230 blades (blade thickness 8 mils, spacer thickness 18 mils and blade depth 250 mils) were used to slice 6" ingot length for both 3" and 4" diameter ingots.

The slurry, which was a mixture of 12 lbs. of 400 grit SiC and 1.8 gallons of P.C. oil in a reservoir, was pumped through a single tube with two holes in it and this tube was reciprocating across the top of the work piece, providing a enough uniform distribution to the whole work piece. The slurry and debris from the ingots were drained into the pump reservoir and recycled during the slicing process. The load on the ingot per blade was 100 grams for the 3" ingot and 90 grams for the 4" ingot. Slightly less load was applied to the 4" ingot in an effort to provide good mechanical yield from a ingot of larger diameter. A stroke length of 6 3/4" and a stroke rate of 100 cycles/minute were used in this experiment. During the first five (5) minutes, a smaller load and a shorter stroke cycle were used for the better adjustment of blades to the ingot at the initial cutting stage.

The total slicing time was 10 hours for the 3" ingot and 20.5 hours for the 4" ingot, and the mechanical yields (the fraction of unbroken slices) were 95(%) and 84(%) for the 3" and 4" diameter ingot, respectively. In both cases, the breakage of wafers started to occur after slicing 2/3 of the ingot. This could be possibly due to the increased surface tension between wafers, the poor mechanical support and the increased mechanical shock due to the wear-out of the blades as the slicing progresses.

The detailed slicing conditions and their results are shown in Table 2.1.

2.2 Internal Diameter (I.D.) Saw Slicing

Slicing experiments were carried out using wafering machines from Silicon Technology Corporation (Oakland, New Jersey): Model STC-16 was used for slicing 3" ingot diameter and Model STC-22 for the 4" ingots. An I.D. blade was mounted on the blade mount, in which the blade was tensioned radially by hydraulic means. Proper tensioning of a new blade was obtained when the elongation

TABLE 2.1

MBS SAW SLICING CONDITIONS

Ingot Diameter, cm (inch)	7.62 (3")	10.16 (4")
Blade Package		
Number of Blades	230	230
Spacer Thickness, mm (mils)	0.457 (18)	0.457 (18)
Blade Thickness, mm (mils)	0.203 (8)	0.203 (8)
Blade Width, mm (inch)	6.35 (¼)	6.35 (¼)
Slurry		
Abrasive (400, SiC), Kg (lb)	5.4 (12)	5.4 (12)
Suspension Oil (P.C. oil), liter (gallon)	6.8 (1.8)	6.8 (1.8)
Mix, Kg/liter (lb/gallon)	0.79 (6.7)	0.79 (6.7)
Load on Blade, gram/blade	100	90
Blade Speed, cm/sec.	57	57
Wear Ratio	---	0.048
Productivity (Wafer)		
cm^2/Machine/Hour	1,005	771
cm^2/Blade/Hour	4.33	3.32
Yield, %	95	84
Yielded Wafer Area, m^2	1.0	1.58
Ingot Length, cm (inch)	15.24 (6)	15.24 (6)

of I.D. reached about 50 mils for the blade of STC-22. and 35 mils for the blade of STC-16. I.D. of a blade for STC-16 was 6" and the thickness of a diamond plated edge and core (stainless) of the blade were 11-12 mils and 4 mils, respectively. In the other case, I.D. of a blade for STC-22 was 8" and the thickness of diamond edge and core were 13-14 mils and 6 mils, respectively.

Since the main purpose of this experiment was to determine the limitations of wafer yields versus cut rate and wafer thickness, all other conditions were fixed to the normal mode of operation, a condition close to that used in the industry of current semiconductor manufacturing operations. Rotation speed of the blades was maintained at 1650 RPM for STC-22 and at 2100 RPM for STC-16. Coolant, which is a mixture of Rust-Lick and water, was supplied at the cutting edge with a flow rate of about 120-140 cc/min. In addition to this, water was continuously supplied at the exit edge for extra cleaning of the blades. To minimize the effect of the blade conditions on the wafer yields, a fixture dressing was applied to the cutting edge of the blade after every 50 slices for the 3" ingot and every 25 slices for the 4" ingot. This dressing includes five cuts of a alumina stick.

Ingots were mounted on a graphite fixture using epoxy in such a way that about one-sixth (1/6) of the periphery of an ingot was supported by the fixture. Both machines can accommodate an ingot of about 24" in length.

Two cut rates, one inch per minute (1 IPM) and two inch per minute (2 IPM), were chosen and the result of the slicing showed a good mechanical yield (above 95%) down to 7-8 mils of wafer thickness for the 3" wafers and 11-12 mils for the 4" wafers if 1 IPM of cut rate was used.

The detailed slicing conditions are given in Table 2.2 and the plots of mechanical yields versus wafer thickness and cut rate are given in Figure 2.1 for the 3" wafers and Figure 2.2 for the 4" wafers. Sample size for the plot was 50 for the 3" wafer and 25 for the 4" wafers.

TABLE 2.2

I.D SAW SLICING CONDITIONS

Ingot Size, cm (inch)	7.62 (3")		10.16 (4")	
Machine	STC-16		STC-22	
Blade				
I.D., cm (inch)	15.24 (6)		20.32 (8)	
O.D., cm (inch)	42.23 (16 5/8)		55.88 (22)	
Core Thickness, mm (mils)	0.10 (4)		0.15 (6)	
Diamond Thickness, mm (mils)	0.28~0.30 (11-12)		0.33~0.36 (13-14)	
Blade Rotation, R.P.M.	2,100		1,650	
Blade Return Speed, cm/min (inch/min.)	38.1 (15)		38.1 (15)	
Blade Stroke, cm (inch)	8.13 (3.2)		10.67 (4.2)	
Blade Dressing, After Number of Slices	50		25	
Coolant				
Flow Rate, cc/min.	120		140	
Mix Ratio, Water: Rust-Lick	80:1		80:1	
Cut Rate, Inch/Minute	1	2	1	2
Slicing Cycle, Minute/Wafer	3.4	1.8	4.5	2.4
Productivity (Wafer), cm^2/Machine/Hour	800	1,510	1,090	2,040

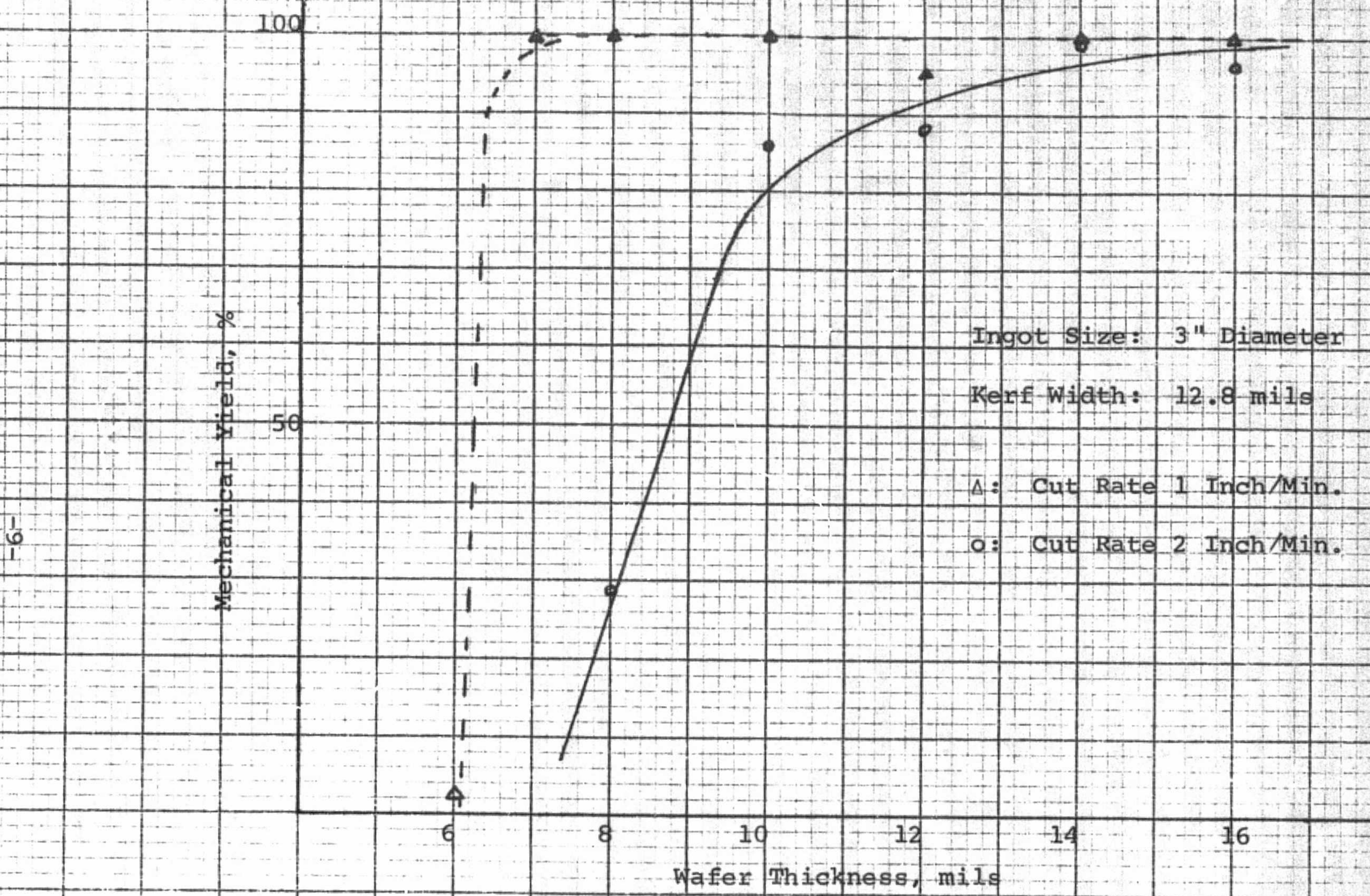


FIGURE 2.1 - Mechanical Yield Versus Wafer Thickness and Cut Rate of ID Saw; 3" Wafers

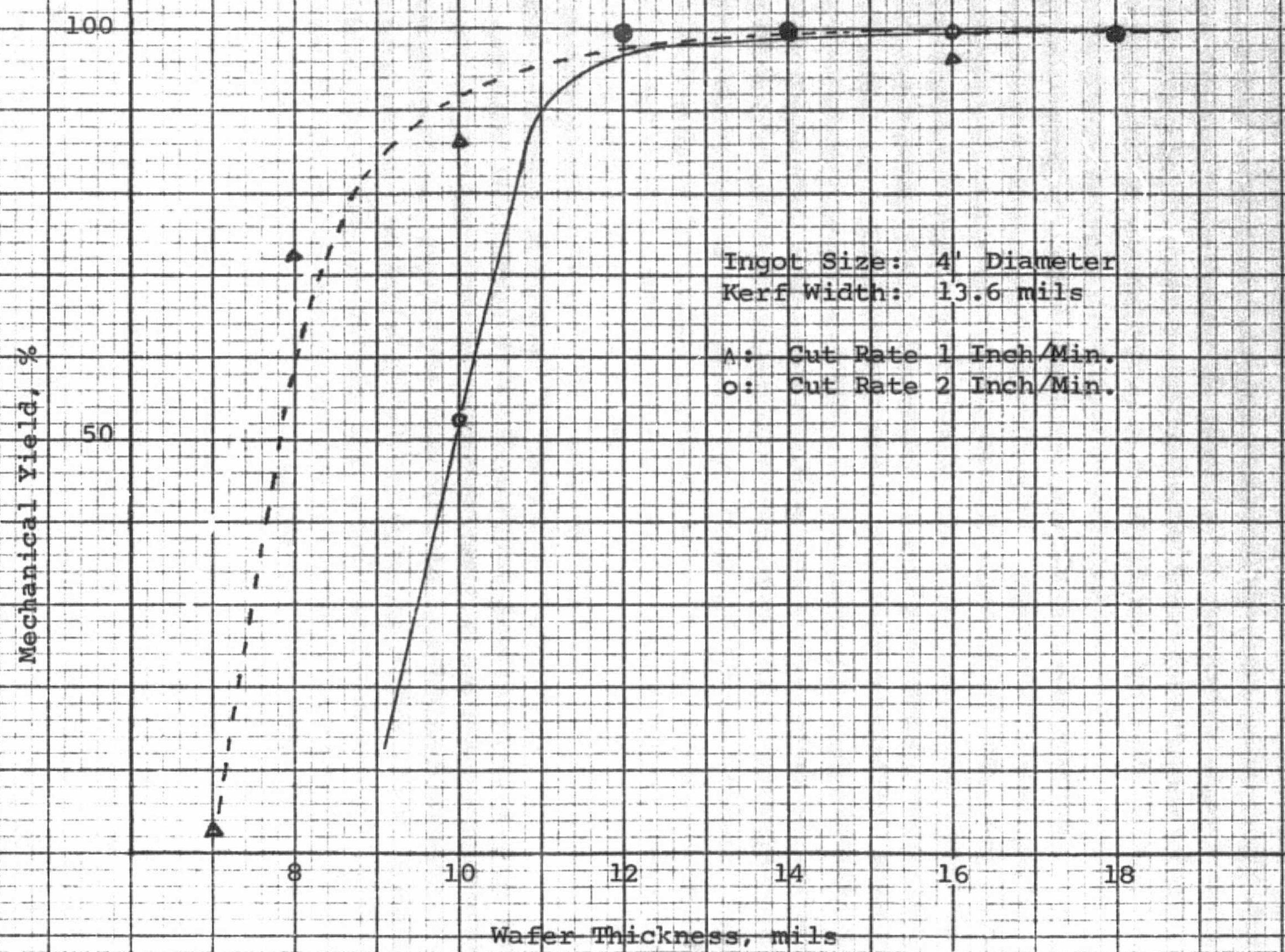


FIGURE 2.2- Mechanical Yield Versus Wafer Thickness and Cut Rate of I.D. Saw; 4" Wafers

3.0 CHARACTERIZATION

3.1 Wafers

General

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 gage (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 gage. 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). Surface profiles of the sliced wafers were obtained on a X-Y recorder using Dek-Tak (Sloan).

MBS Saw Wafers

From 60 slices of each ingot size, an average thickness of 13.2 mils for the 3" diameter ingot and 13.0 mils for the 4" diameter were obtained using the same blade package. Average bow indicated 1.1 mils for the 3" wafers and 0.81 mils for the 4" wafers, and average taper showed 1.7 mils and 2.4 mils for the 3" and 4" wafers, respectively. Taper is mainly due to the change in kerf loss, which is caused by the wear of abrasives and blade as the slicing progresses, consequently leading to thin wafers at the start and thick wafers at the last cutting edge of the wafers. Both sizes of the ingots showed an average roughness (RMS) of around 1.2μm.

Detailed characterization parameters of the sliced wafers are given in Table 3.1.

I.D. Saw Wafers

An average bow and roughness (RMS) of the 3" wafers cut at 1 IPM was about 0.52 mils and 0.37μm, respectively, while taper showed values less than 0.2 mils. Generally, an accuracy of taper was limited by the accuracy of thickness measurements using a dial gage. As the cut rate increased from 1 IPM to 2 IPM, average bow and roughness increased to 1.05 mils and 0.54μm, respectively. The 4" wafers showed similar values in taper and roughness (RMS). However, a slightly increased bow was observed from the 4" wafers, compared with the 3" wafers.

TABLE 3.1

CHARACTERIZATION OF WAFERS SLICED WITH MBS SAW

Ingot Size, cm (inch)	7.62 (3")	10.16 (4")
Yield, %	95	84
Thickness, mm (mils)		
Average	0.335 (13.2)	0.330 (13.0)
Standard Deviation	0.026 (1.02)	0.034 (1.32)
Range	0.264~0.422 (10.4~16.6)	0.241~0.417 (9.5~16.4)
Taper, μm (mils)		
Average	43.2 (1.7)	61.0 (2.4)
Standard Deviation	15.0 (0.59)	17.8 (0.70)
Range	7.6~76 (0.3~3)	22.9~127 (0.9~5.0)
Bow, μm (mils)		
Average	27.9 (1.1)	20.6 (0.81)
Standard Deviation	13.0 (0.51)	8.6 (0.34)
Range	7.6~58.4 (0.3~2.3)	6.4~38.1 (0.25~1.5)
Roughness (RMS), μm		
Average	1.20	1.20
Range	0.8~1.6	0.8~1.5

The characterization parameters are given in Table 3.2 for the 3" wafers and in Table 3.3 for the 4" wafers. Typical surface profiles of the wafers are shown in (a) and (b) of Figure 3.1. The wafers sliced at 2 IPM of cut rate (b) shows slightly increased surface roughness than the wafers sliced at 1 IPM of cut rate (a). However, a surface profile of a wafer sliced with MBS, (c) in the figure, show a significant increase in roughness at the surface compared with the wafers sliced with the I.D. saw.

Comparison of the Slice Parameters

The parameters obtained from the wafers of two different slicing type, MBS saw and I.D. saw, were compared for the evaluation of the mechanical quality of the sliced wafers. Similar thickness of the wafers sliced with the I.D. saw, 14 mils, were chosen for comparison with the MBS wafers.

Thickness variation, from wafer to wafer and within a single wafer, of the wafer sliced with the MBS saw was considerably higher than the wafers cut with the I.D. saw. Bow and roughness (RMS) also indicated that the MBS wafer showed about factor of two higher values than those of the I.D. wafers. In general, comparison of the characterization parameters showed that the wafers cut

TABLE 3.2

CHARACTERIZATION OF 3" WAFERS SLICED WITH I.D. SAW

Thickness, mils		16		14		12		10		8		7	
Cut Rate, Inch/Min.		1	2	1	2	1	2	1	2	1	2	1	2
THICKNESS, Mils	Average	16.1	16.0	14.0	14.0	12.0	12.0	10.0	10.0	8.0	8.0	7.0	
	S. Deviation	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.2	< 0.1	< 0.1	< 0.1	
	Range	16.0 ~ 16.3	16.0 ~ 16.1	14.0 ~ 14.1	14.0 ~ 14.1	11.9 ~ 12.1	11.9 ~ 12.1	9.9 ~ 10.1	9.7 ~ 10.1	7.9 ~ 8.1	7.8 ~ 8.0	7.0 ~ 7.1	
BOW, Mils	Average	0.37	0.93	0.37	1.4	0.6	0.9	0.67	0.63	0.59	1.4	0.52	
	S. Deviation	0.24	0.12	0.17	0.18	0.19	0.33	0.34	0.36	0.71	0.19	0.36	
	Range	0.05 ~ 0.75	0.7 ~ 1.1	0.1 ~ 0.75	1.3 ~ 1.8	0.15 ~ 0.85	0.6 ~ 1.5	0.15 ~ 1.15	0.1 ~ 1.3	0.1 ~ 2.15	1.2 ~ 1.7	0.2 ~ 1.2	

Continued...

TABLE 3.2

CHARACTERIZATION OF 3" WAFERS SLICED WITH I.D. SAW

Thickness, mils		16		14		12		10		8		7	
Cut Rate, Inch/Min.		1	2	1	2	1	2	1	2	1	2	1	2
TAPER, Mils	Average	0.2	0.1	0.1	0.1	0.1	0.2	<0.1	0.3	<0.1	0.1	<0.1	
	S. Deviation	<0.2	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.2	<0.1	<0.1	<0.1	
	Range	<0.6	<0.2	<0.2	<0.2	<0.2	<0.4	<0.2	<0.7	<0.1	<0.3	<0.1	
ROUGHNESS, μm	Average	0.4	0.4	0.37	0.57	0.4	0.69	0.35	0.55	0.34	0.51	0.38	
	Range	0.3 ~ 0.6	0.39 ~ 0.42	0.34 ~ 0.4	0.54 ~ 0.61	0.36 ~ 0.45	0.64 ~ 0.73	0.32 ~ 0.44	0.51 ~ 0.6	0.31 ~ 0.4	0.49 ~ 0.53	0.34 ~ 0.42	

TABLE 3.3

CHARACTERIZATION OF 4" WAFERS SLICED WITH I.D. SAW

Thickness, mils / Cut Rate, Inch/Min.		18		16		14		12		10		8		7	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2
THICKNESS, Mils	Average	18.0	18.3	16.1	16.2	14.1	14.1	12.2	12.0	10.1	10.2	8.1		7.0	
	S. Deviation	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.2	<0.1	<0.1	<0.3	<0.1		<0.1	
	Range	18.0 ~ 18.1	18.2 ~ 18.3	16.0 ~ 16.2	16.2 ~ 16.3	13.8 ~ 14.2	14.0 ~ 14.2	12.1 ~ 12.4	12.0 ~ 12.1	10.0 ~ 10.2	10.0 ~ 10.6	8.0 ~ 8.2		7.0 ~ 7.1	
BOW, Mils	Average	0.27	2.57	0.32	2.4	0.47	0.33	0.9	0.61	1.65	0.5	2.77		1.83	
	S. Deviation	0.12	0.61	0.21	0.54	0.29	0.16	0.44	0.6	0.46	0.23	0.45		0.39	
	Range	0.1 ~ 0.4	1.7 ~ 3.0	0.1 ~ 0.7	1.8 ~ 3.0	0.1 ~ 0.9	0.1 ~ 0.6	0.2 ~ 1.4	0.1 ~ 1.5	0.8 ~ 2.2	0.3 ~ 0.9	2.3 ~ 3.3		1.3 ~ 2.2	

Continued...

TABLE 3.3

CHARACTERIZATION OF 4" WAFERS SLICED WITH I.D. SAW

	Thickness, mils	18		16		14		12		10		8		7	
	Cut Rate, Inch/Min.	1	2	1	2	1	2	1	2	1	2	1	2	1	2
TAPER, Mils	Average	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.1	0.2	0.4	<0.1		0.1	
	S. Deviation	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1	<0.1	<0.1		<0.1	
	Range	<0.2	<0.2	<0.3	<0.2	<0.3	<0.3	<0.4	<0.3	<0.4	0.3 ~ 0.6	<0.1		<0.1	
ROUGHNESS, μm	Average	0.4	0.54	0.42	0.57	0.42	0.52	0.44	0.46	0.47	0.48	0.45		0.48	
	Range	0.38 ~ 0.44	0.48 ~ 0.58	0.38 ~ 0.46	0.55 ~ 0.59	0.36 ~ 0.54	0.43 ~ 0.59	0.34 ~ 0.50	0.39 ~ 0.55	0.4 ~ 0.52	0.45 ~ 0.54	0.4 ~ 0.48		0.4 ~ 0.54	

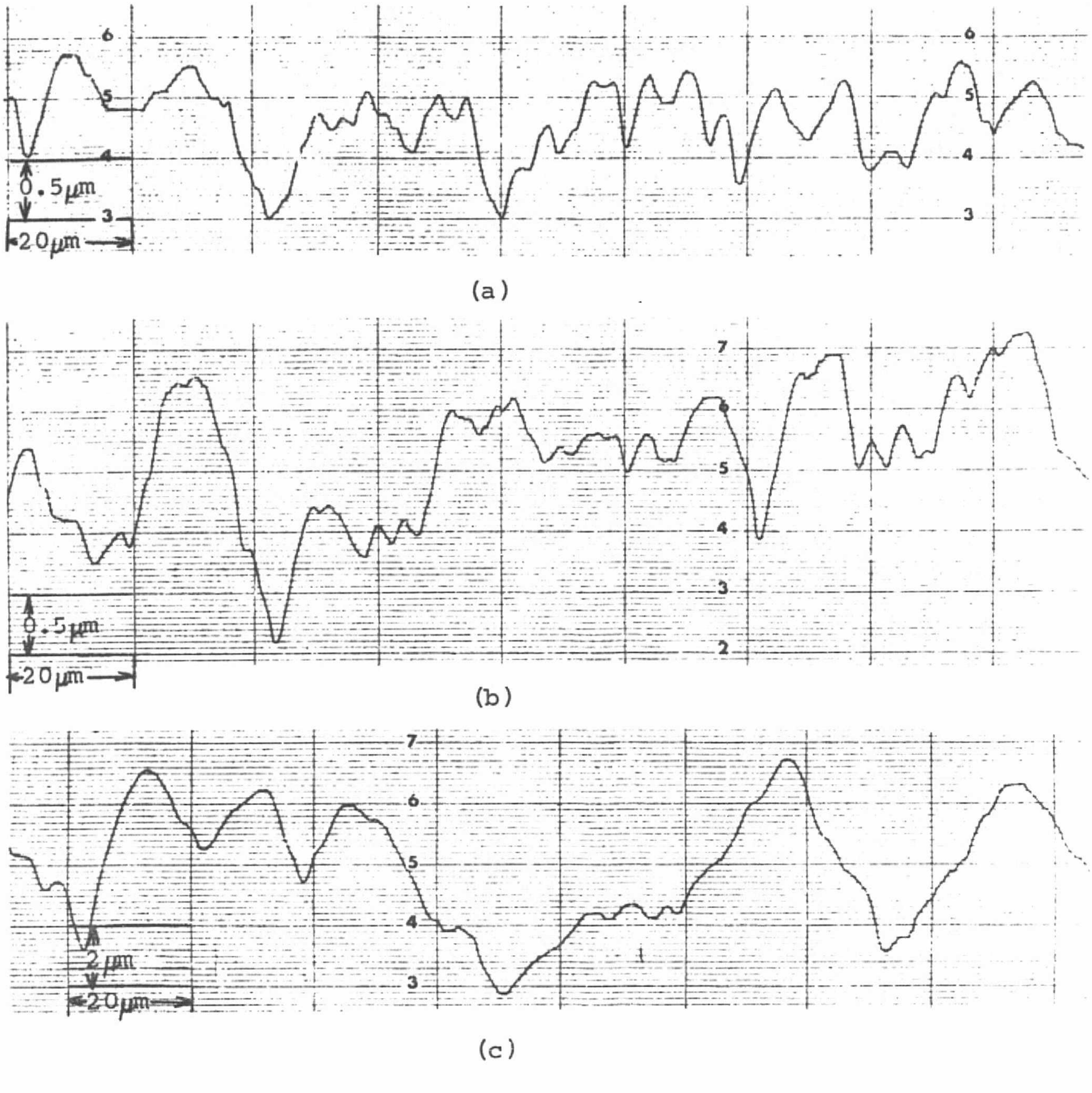


FIGURE 3.1

Typical Surface Profiles of the Sliced Wafers

(a) An I.D. saw wafer; 1 IPM of cut rate
(b) An I.D. saw wafer; 2 IPM of cut rate
(c) A MBS saw wafer

with I.D. saw had much smaller values and variations then those with the multiblade slurry saw, indicating the need for less removal of silicon before solar cell fabrication.

The detailed comparison of the parameters for two different slicing types is given in Table 3.4 for the 3" wafers and in Table 3.5 for the 4" wafers.

3.2 Blades

MBS Saw

The wear ratio, defined by the volume of the blade worn out divided by the volume of silicon removed during cutting, was about 0.048. After one slicing experiment with the 4" ingot, maximum wear of a blade width was about 2.6 (mm); corresponding to 40(%) wear of a new blade (new one 6.4 mm). The lifetime of a blade was considered to be 60(%) wear of the new blade[1].

I.D. Saw

Optical microscopic pictures were taken from both new and worn-out blades. Figure 3.2 gives magnified side views of the diamond plated edge. A new blade (a) shows higher concentration of diamond particles than a worn-out blade (b), which shows a excessive pull-out of diamond particles. A new blade shows a shiny background

TABLE 3.4

COMPARISON OF 3" WAFER PARAMETERS

Slicing Type		MBS	I.D. 1 IPM	I.D. 2 IPM
THICKNESS**	Average	13.2	14.0	14.0
	S. Deviation	1.02	<0.1	<0.1
	Range	10.4~16.6	14.0~14.1	14.0~14.1
BOW**	Average	1.1	0.37	1.4
	S. Deviation	0.51	0.17	0.18
	Range	0.3~2.3	0.1~0.75	1.3~1.8
TAPER**	Average	1.7	0.1	0.1
	S. Deviation	0.59	<0.1	<0.1
	Range	0.3~3	<0.2	<0.2
ROUGHNESS*	Average	1.2	0.37	0.57
	Range	0.8~1.6	0.34~0.4	0.54~0.61

* Measured in Micrometers
**Measured in Mils

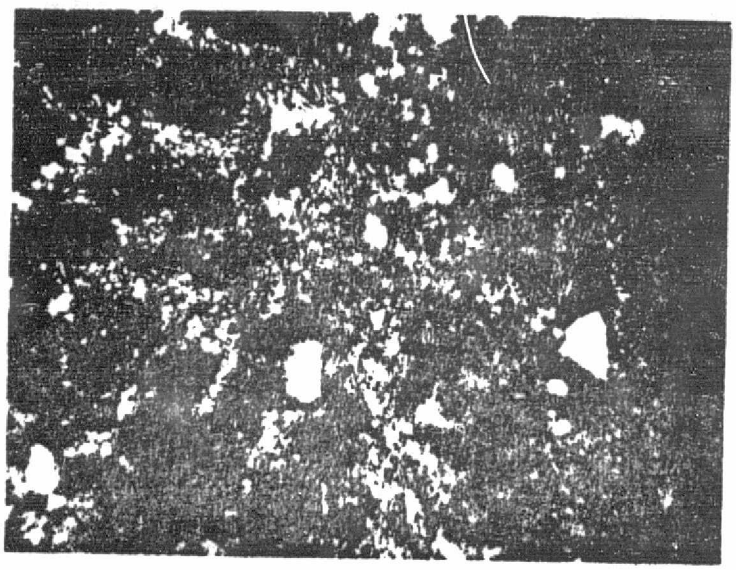
TABLE 3.5

COMPARISON OF 4" WAFER PARAMETERS

Slicing Type		MBS	I.D. 1 IPM	I.D. 2 IPM
THICKNESS**	Average	13.0	14.1	14.1
	S. Deviation	1.32	<0.2	<0.1
	Range	9.5~16.4	13.8~14.2	14.0~14.2
BOW**	Average	0.81	0.47	0.33
	S. Deviation	0.34	0.29	0.16
	Range	0.25~1.5	0.1~0.9	0.1~0.6
TAPER**	Average	2.4	0.2	0.2
	S. Deviation	0.7	<0.1	<0.1
	Range	0.9~5.0	<0.3	<0.3
ROUGHNESS*	Average	1.2	0.42	0.52
	Range	0.8~1.5	0.36~0.54	0.43~0.59

* Measured in Micrometers.
**Measured in Mils.

(a)



(b)

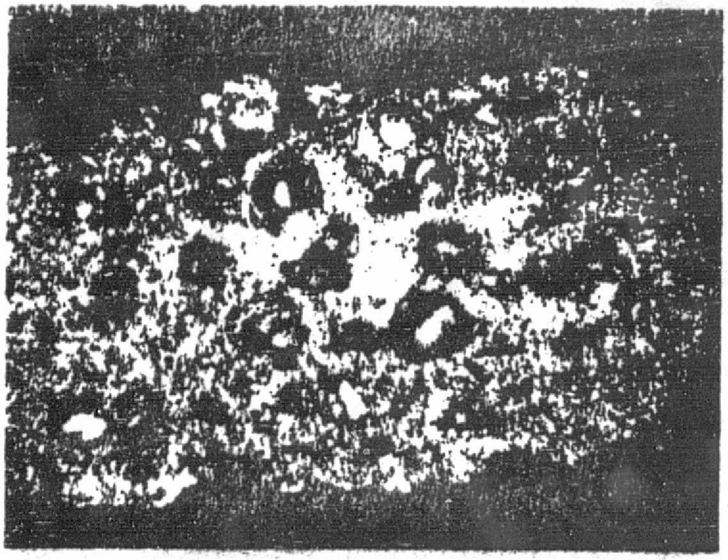
FIGURE 3.2

Side Views of Diamond Plated I.D. Blades
(200X Magnification)

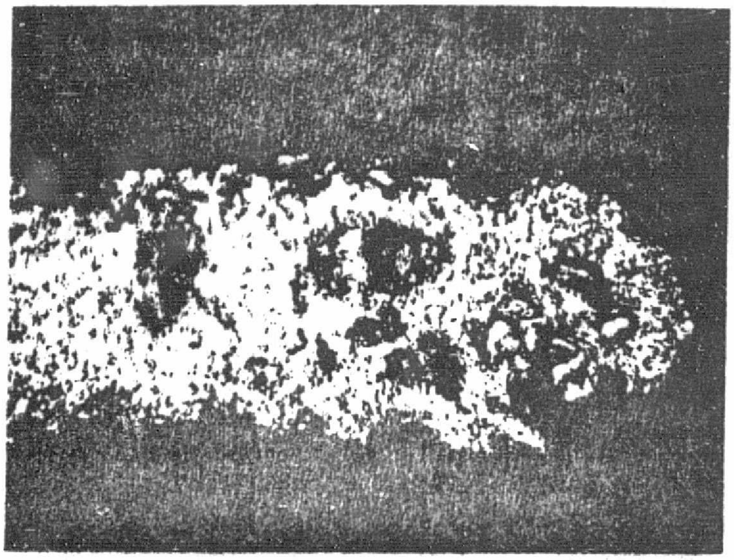
(a) A New Blade
(b) A Worn-Out Blade

matrix (Ni) while a worn-out blade shows a dull colored background which could be due to the glazing of the ingot fixing material, epoxy. This surface glazing might interfere coolant passage at the cutting edge of the blades, leading to fatigue of blade or lost of tensioning in the blade, and a breakage of wafers.

Figure 3.3 and Figure 3.4 give photographed sections of new (a) and worn-out blades (b). Figure 3.3 is a magnified picture of cutting edges, and a worn-out blade (b) shows considerable reduction in thickness and pull-out of diamonds from the sides. Figure 3.4 indicates significant wearing of core materials (stainless steel) from the worn-out blade (b), possibly due to excessive friction between the core and diamond particles pulled out or debris formed. This thin core might cause lost of blade tension when it is combined with excessive heat generation either due to high cutting rate or insufficient heat dissipation. This will cause vibration of the blade, eventually leading to breakage of wafers or saw marks on the wafers.



(a)

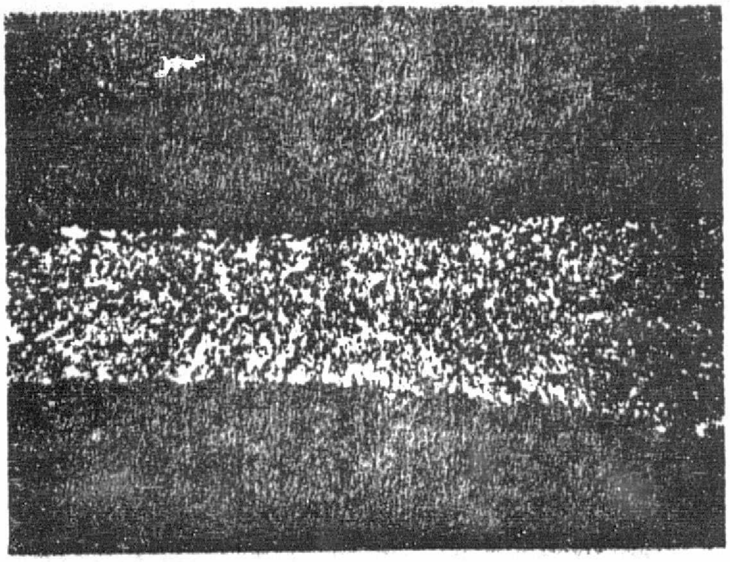


(b)

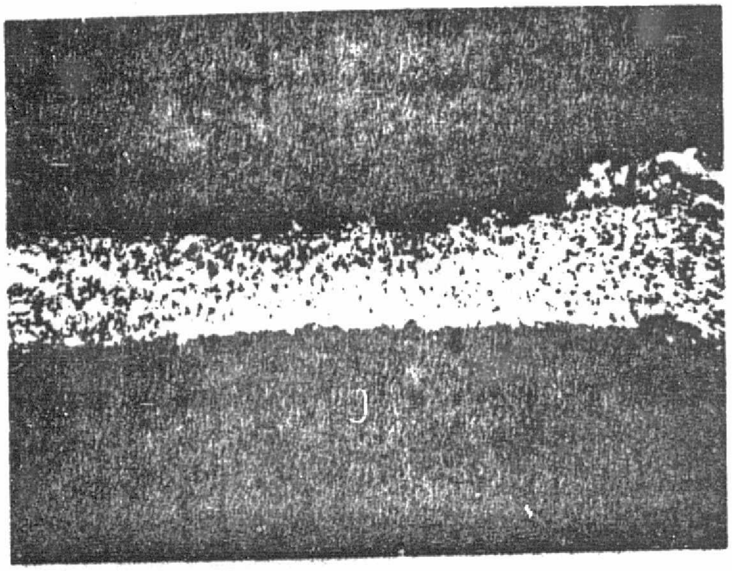
FIGURE 3.3

Cross-Sectional View of the Diamond Plated Cutting Edge of I.D. Blades
(200X Magnification)

(a) A New Blade
(b) A Worn-Out Blade



(a)



(b)

FIGURE 3.4

Cross-Sectional Views of Boundaries Between Diamond Plated Edge and Core of I.D. Blades
(200X Magnification)

(a) A New Blade
(b) A Worn-Out Blade

4.0 COST ANALYSIS

4.1 Parameters Influencing the Cost of Wafers ($\$/m^2$)

Two main sources leading to the high cost of silicon wafers can be identified; material (Si) cost and operation cost which is incurred during slicing operation. Parameters influencing the material (Si) cost can be further divided into wafer thickness, kerf loss, and mechanical wafer yield. In Table 4.1, some detailed parameters which will influence or limit the above three parameters are identified for both the multiblade slurry and the I.D. saw slicing techniques.

The cost of slicing operation can be divided into labor, overhead, interest, depreciation and expendable materials. Some factors influencing the above parameters are as follows:

Labor	- Productivity of a Machine - Other Operation Time, Such as Set-Up, Cleaning, Wheel Dressing Time, Etc.
Overhead	- Labor - Organization of a Company
Interest	- Price and Lifetime of a Machine - Productivity of a Machine
Depreciation	- Price and Lifetime of a Machine - Down-Time of a Machine - Productivity of a Machine

TABLE 4.1

Parameters Influencing Wafer Thickness,
Kerf Loss and Mechanical Wafer Yield

	MBS SAW	I.D. SAW
WAFER THICKNESS	<u>Blade Package</u> - Spacer Thickness - Number of Blades - Alignment and Tensioning <u>Slurry</u> - Abrasive Size - Density of Abrasive in Oil	<u>Cut Rate</u> <u>Ingot Mounting Fixture</u>
KERF LOSS	<u>Blade Package</u> - Thickness of Blades - Number of Blades - Alignment and Tensioning <u>Slurry</u> - Abrasive Size - Density of Abrasive in Oil	<u>Blade</u> - Thickness of Diamond Plated Edge - Blade Tensioning <u>Machine</u> - Accuracy of Travel Between the Blade and the Silicon Ingot
MECHANICAL WAFER YIELD	<u>Wafer Thickness</u> - Spacer Thickness <u>Cut Rate</u> - Speed and Load on Blade <u>Blade Package</u> - Thickness of Blade - Number of Blades - Alignment and Tensioning	<u>Wafer Thickness</u> <u>Cut Rate</u> <u>Blade</u> - Core Material - Diamond Plating - Dressing Conditions of of Blades - Tensioning and Centering of Blades - Blade History

Continued....

TABLE 4.1
Continued

	MBS SAW	I.D. SAW
MECHANICAL WAFER YIELD	<u>Ingot Mounting</u>	<u>Machine</u> - Accuracy of Travel Between the Blade and the Ingot - Relative Vibration Between Blade Edge and Ingot <u>Ingot Mounting</u> <u>Coolant Flow Rate and Position</u>

Expendable
Materials

- Wires or Blades
- Coolant or Oil
- Abrasive
- Ingot Fixture
- Miscellaneous Materials Like Dressing Material for Wheel Blades

From the above analysis, labor, overhead, interest and depreciation is strongly influenced by the productivity of a machine. Thus, the productivity of a machine, price and lifetime of a machine and the cost of expendable material are major factors which will influence overall operation cost of a specific slicing type of machine.

4.2 Analysis or Direct Labor and Expendable Materials for MBS Saw Slicing

To assess the cost of the multiblade slurry saw slicing, detailed analysis of direct labors and expendable materials were obtained based on the slicing experiments performed. Analysis of labor indicates that about 4 hours of direct labor was required for each size of the ingots, corresponding to 3.9 hour/m^2 for the 3" diameter ingot and 2.5 hour/m^2 for the 4" diameter ingot.

The analysis of the expendable materials shows the cost of about \$90 and \$150, corresponding to \$91/m^2 and \$97/m^2, for the 3" and 4" ingots, respectively. The following assumptions which might be conservative ones are adopted for the expendable material cost:

First, the blade package can be used 3 times for the 3" ingot and 1.5 times for the 4" ingot. This assumption was based on the lifetime of a blade mentioned in Section 3.2.

Second, the slurry was used only once. This may not be a proper assumption, but the past OCLI experience showed about 30(%) increased slicing time for the second cut when the same slurry was used, indicating decrease of productivity of the machine. Thus trade-off between the expendable cost and cost incurred due to productivity is required.

Slicing process for MBS saw is given in Figure 4.1 and detailed analysis of labor and expendable materials are given in Table 4.2 and Table 4.3, respectively.

4.3 Analysis of Direct Labor and Expendable Materials for I.D. Saw Slicing

A slicing process for I.D. saw slicing is shown in Figure 4.2. Analysis of direct labor indicated about 0.76 hour/m^2 for the 3" wafers and 0.64 hours/m^2 for the 4" wafers, and expendable material costs were about \$7/m^2 and \$6/m^2 for the 3" and 4" wafers, respectively. For the calculation of the blade cost, which is a main source of expendable material cost, lifetime of 3,000 cut for the blade for 3" ingots (STC-16 I.D. blade) and 5,000 cuts for the blade for 4" ingots (STC-22 I.D. blade) were adopted. Those assumptions on blade lifetime are conservative ones according to the past OCLI experience.

FIGURE 4.1

MBS SAW SLICING PROCESS

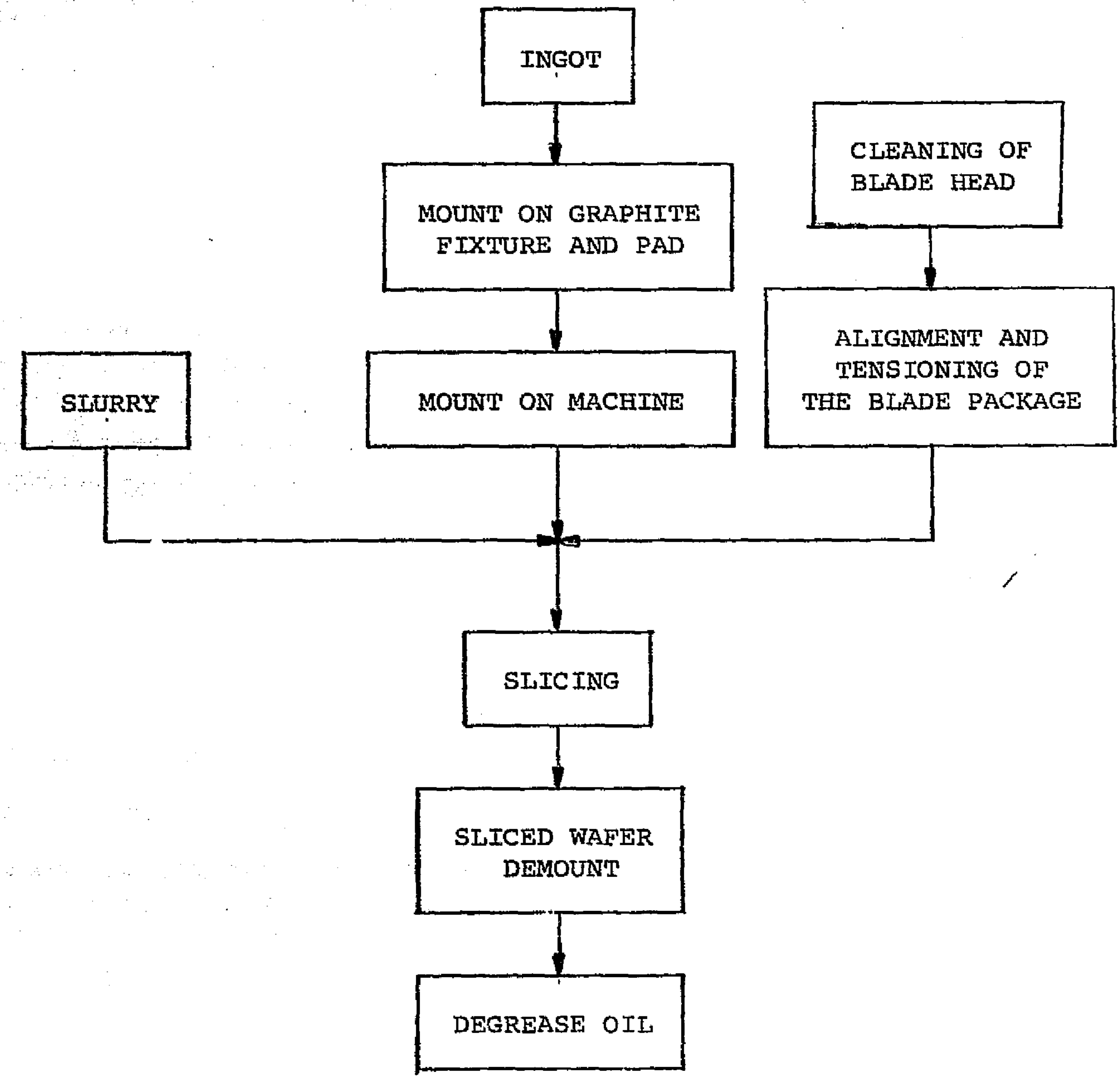


TABLE 4.2

ANALYSIS OF DIRECT LABOR, MBS SAW SLICING

Ingot Size, cm (inch)	7.62 (3") Hours	10.16 (4") Hours	7.62 (3") Hours/m^2	10.16 (4") Hours/m^2
Machine Set-Up				
Blade Head Cleaning	0.3	0.3	0.3	0.19
Blade Package Mounting	1.0	1.0	1.0	0.63
Work Piece Mounting				
Ingot on Graphite	0.25	0.25	0.25	0.16
Mounting on the Machine	0.25	0.25	0.25	0.16
Demount From Machine	0.20	0.20	0.20	0.16
Operator's Attention				
At the Start	0.1	0.1	0.1	0.06
In the Middle	0.05	0.1	0.05	0.06
At the End	0.25	0.25	0.25	0.16
Degrease Oil				
(Including Wafer Demount From Graphite Fixture)	1.5	1.5	1.5	0.95
TOTAL	3.9	3.95	3.9	2.5

TABLE 4.3

ANALYSIS OF EXPENDABLE MATERIALS, MBS SAW SLICING

Ingot Size, cm (inch)	7.62 (3")	10.16 (4")	7.62 (3")	10.16 (4")
	$		$/m^2$	
Ingot Mount				
Wax	0.25	0.25	0.25	0.16
Graphite	0.88	0.88	0.88	0.56
Blade Package	58.33	116.67	58.33	73.84
Slurry				
400 Grit SiC	16.20	16.20	16.20	10.25
P.C. Oil	8.53	8.53	8.53	5.40
Degrease				
Trichloroethylene (TCE)	7.00	10.50	7.00	6.65
TOTAL	91.19	153.03	91.19	96.86

ASSUMPTION

1. The blade package (230 blades, 8 mils blade thickness, 18 mils spacer and ¼" blade width): $175
2. 400 Grit SiC: $1.35/lb
3. P.C. Oil: $4.74/Gallon
4. Trichloroethylene (Technical Grade): $3.50/Gallon

Detailed analysis of direct labor and expendable material costs are given in Table 4.4 and Table 4.5, respectively.

A comparison of direct labor, expendable material costs and wafer productivity for these two slicing methods, MBS saw and I.D. saw slicing, were also made and given in Table 4.6. This table indicates that the I.D. saw slicing techniques is more favorable than the MBS saw slicing techniques at present. Better mechanical quality of the wafers sliced with the I.D. saw, as discussed in Section 3.1, gives an additional advantage over the MBS saw slicing techniques. The table also shows the conversion of silicon ingot to sheet forms, indicating around 0.65 m^2/Kg (or 1.54 Kg/m^2) for the wafer with both thickness and kerf loss of about 13 mils. However, I.D. saw can increase the conversion to 0.81 m^2/Kg (or 1.23 Kg/m^2) when thickness of a wafer reduced to 8 mils. Slight reduction in kerf loss can easily improve the conversion to 1 m^2/Kg (or 1 Kg/m^2).

FIGURE 4.2

I.D. SAW SLICING PROCESS

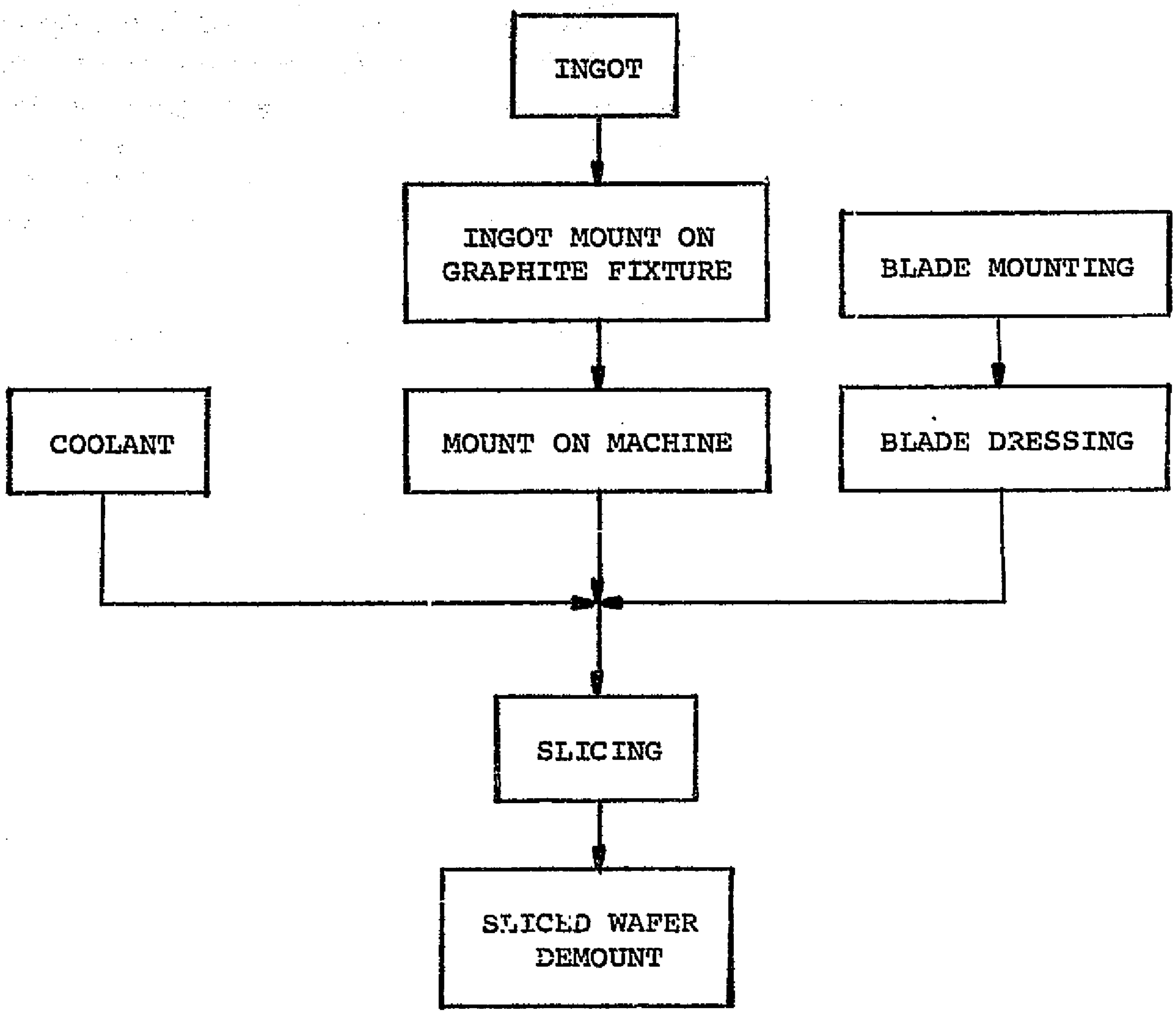


TABLE 4.4

ANALYSIS OF DIRECT LABOR, I.D. SAW SLICING

Ingot Diameter, cm (inch)	Hours/m²	
	(3")	(4")
Machine Time		
Blade Mounting	0.04	0.01
Blade Dressing	0.26	0.29
Work Piece		
Ingot on Graphite	0.07	0.08
Ingot Mounting on the Machine	0.01	0.02
Demount Sliced Wafers	0.29	0.16
Operator's Attention	0.09	0.08
TOTAL	0.76	0.64

TABLE 4.5

ANALYSIS OF EXPENDABLE MATERIAL, I.D. SAW SLICING

	$/m²	
	7.62 (3")	10.16 (4")
Ingot Mounting, (Epoxy and Graphite)	.97	.48
Blade	4.39	3.70
Blade Dressing Material, Alumina Stick	.62	.71
Coolant, (Rust-Lick)	1.04	.85
TOTAL	7.02	5.74

ASSUMPTIONS

1. Blade Cost

   6" I.D. Blade - $60/Piece
   8" I.D. Blade - $150/Piece

2. Blade Lifetime

   6" I.D. Blade - 3,000 Cuts
   8" I.D. Blade - 5,000 Cuts

3. Rust-Lick, (G-25-AH) - $3.65/Gallon

TABLE 4.6

SUMMARY OF IMPORTANT PARAMETERS FOR COST ANALYSIS

Slicing Type	Multiblade Slurry Saw	I.D. Saw		
		Cut Rate 2"/Min.	Cut Rate 1"/Min.	
Ingot Diameter, Inch	3 (4)	3 (4)	3 (4)	3 (4)
Wafer Thickness, mils	13 (13)	13 (13)	13 (13)	13 (11)
Kerf Width (Loss), mils	12.8 (13)	12.8 (13.6)	12.8 (13.6)	12.8 (13.6)
Wafer Yields, %	95 (84)	95 (100)	100 (100)	100 (95)
Material (Si Ingot), Kg/m^2	1.60 (1.83)	1.60 (1.57)	1.53 (1.57)	1.23 (1.53)
Wafer Productivity, cm^2/Machine/Hour	1,000 (770)	1,510 (2,040)	800 (1,090)	800 (1,090)
Direct Labor, Hour/m^2	3.9 (2,5)	0.76 (0.64)	0.76 (0.64)	----
Expendable Materials, \$/m^2	91.2 (96.9)	6.6 (5.4)	7.0 (5.7)	----

NOTE: 1. Machines used for the analysis were - Multiblade Slurry Saw: Norton 686
- I.D. Saw : STC-16 for 3" Ingot
- I.D. Saw : STC-22 for 4" Ingot

2. Yielded wafer area was considered for the calculation.
3. Parameters in parenthesis are for the 4" ingot.

5.0 DISCUSSION

5.1 Limitation of Multiblade Slurry Saws

The major advantages of multiblade slurry saw are claimed to be the ability to slice thin wafers with low kerf loss and the capability of slicing 100 to 300 wafers simultaneously. However, limits of wafer thickness (250μ) and kerf loss (200μ) are identified for present slicing techniques[2]. These are explained as a result of intrinsic misalignment in the major portion of the blade package (thickness of blade and spacer) used in multiblade slurry saw. Accumulation of small component errors is shown to result in 50 to 100μm misalignment of blades possibly resulting in fatigue of thin slices (<250μ). Statistical view of a blade package gives an expression for the runout (Δ) of blades as a function of number of blades (N) in a blade package under ideal conditions[3].

$$\Delta \ \alpha \ N^{\frac{1}{2}}$$

Other factors influencing blade alignment other than perfect stacking of the components (dirt, bent components etc.) will make the alignment worse. Measurements of blade misalignment indicated an average runout of 50μ in a 220 blade package[4].

Productivity of a multiblade saw, which is a product of number of blades in a blade package and productivity of a single blade (or cut rate), is also limited, at the present time. The number of blades are limited by the intrinsic misalignment. Productivity of a single blade is shown as a function of blade load, thickness and abrasive size (5). Increased blade load and decreased blade thickness increased a productivity of a blade while decreasing wafer yields and accuracy, and finer abrasives have caused a reduction of both kerf loss and productivity. Trade-off between wafer yield and productivity of the slicing machine is required for the best operation.

5.2 General Comments on MBS Saw Slicing

The following areas of disadvantages in operation of multiblade slurry saw were identified based on the past and present experience at OCLI:

1. Mounting of a blade package in the machine (specifically the blade head) is a time consuming process. This operation includes cleaning of the blade head and tensioning and alignment of the blade package. Typically it took about 1 to 1½ hours.

2. Once the blades are coming out of the ingots in the middle of the slicing, either due to mechanical failure or misjudgment of an operator, it is likely to loose all the slices.

3. Expendable material costs are high mainly due to the cost of blade package and slurry. This will be cleared by comparison with other slicing techniques.

4. Since P.C. oil was used for the suspension of abrasives in the slurry, an extra degreasing step, which requires labor and or organic solvent (TCE), is needed. Handling of slippery wafers before the degreasing could cause the breakage of the sliced wafers, especially of thin wafers.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Evaluation of the slicing experiments performed indicated:

- Mechanical factors such as thickness variation, taper, bow and roughness, were better for wafers sliced with the I.D. saw than for those with the MBS saw.

- Analysis of direct labor, expendable material cost and wafer productivity indicated the I.D. saw technique is more favorable than the MBS saw method at present. It might possibly be difficult for the MBS saw to meet LSSA goal (JPL-DOE) by 1986 without significant improvement in blade package and slurry cost. Improvement in blade package includes increase in number of blades in a blade package to increase productivity, overcoming of alignment problems associated with large number of blades in a simple way and development of low cost blade package. However, preliminary study indicated that the I.D. saw slicing technique will meet the sheet goal in 1982 ($80/m^2$) without any significant innovation of the slicing technology, and that given equivalent development to the proposed MBS techniques promises significant further improvements.

- Thickness limits that can be sliced with the I.D. saw were estimated to be around 6 mils for the 3" wafers and 7 mils for the 4" wafers. Good mechanical yields (higher than 95%) were obtained down to 7 mil wafers and 11 mil wafers from the 3" and 4" diameter ingots, respectively. Even at the slower cut rates, the slice productivity was considerably improved. When combined with other possible I.D. saw improvements (thinner blades to reduce kerf loss, ganged blades) the tests to date have shown good chance of significant impact on cost reduction for sheet formation.

- Since the ultimate goal of JPL-DOE project is expressed in unit of dollar per electrical peak output ($/Wp), the cost of silicon sheet ($\$/m^2$) has to be converted to $/Wp. Minimum $\$/m^2$ does not necessarily lead to minimum $/Wp because electrical quality of the sliced wafers and thickness dependence of solar cell output were not

- considered in formation of sheet, requiring an intermediate conversion factor (or a mechanical to electrical conversion factor); m^2/Wp. Thus,

$$\$/Wp = (\$/m^2) \times (m^2/Wp)$$

7.0 PLANS FOR THE NEXT PERIOD

Plan for the next period include:

- Cost analysis based on SAMICS
- Assessment of the multiwire abrasive slicing technique (Yasunaga wire saw)
- Reduction of kerf loss by using thinner I.D. blades; about 10 mils of kerf loss for the 3" wafers and 12 mils kerf loss for the 4" wafers.
- Looking for the potential improvement in mechanical yields of thin wafers (<10 mils) at high cut rate (>2 inches per minute) by adjusting operation parameters.
- Further characterization of the I.D saw blades
- Preliminary accelerometer results in an attempt to check mechanical vibration effects on the I.D. sawing process
- Overall comparison of I.D. saw with two other methods (multiblade slurry saw and multiwire abrasive saw) and recommendations for further works needed.

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TIME SCHEDULE