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SLICING OF SILICON INTO SHEET MATERIAL

Silicon Sheet Growth Development for the
Large Area Silicon Sheet Task of the Low
Cost Silicon Solar Array Project

Fifth Quarterly Report
March 21, 1977 to May 27, 1977

S. C. Holden
J. R. Fleming

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Lexington Vacuum Division
Varian Associates
Lexington, Massachusetts

MASTER

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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By

S. C. HOLDEN

J. R. FLEMING

July 7, 1977

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JPL Contract No. 954374

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1.0 SUMMARY

Varian has demonstrated the multiblade slurry technique capable of slicing 10 cm ingot into wafers 0.25 mm thick with only 0.20 mm kerf loss and 98% yield. The total silicon requirement represents an ingot to sheet conversion of $0.95 \text{ m}^2/\text{kg}$.

Full production slicing tests have demonstrated the cost of MS slicing to contribute \$40-\$50/ m^2 , with "best effort" estimates for today's configuration to be \$30-\$35/ m^2 . By reducing material cost, and increasing the specific capacity of a saw to slice 900 wafers simultaneously, the long-term cost of MS slicing is estimated to be less than \$10/ m^2 .

The conversion of ingot to sheet is shown to be the most valuable contribution of slicing technology. At today's ingot costs, and with the thin wafer, low kerf loss slicing techniques demonstrated, the silicon material represents 5 to 10 times the cost of the wafering process in finished silicon wafers.

Increasing the number of blades used in MS slicing from 100-150 to 225-300 has resulted in a reduction of yield to 33-70% for thin slicing, or an increase in wafer thickness to 0.30 mm slices. The limitation is intrinsic misalignment of multiple blades. A technique to correct this condition is presented and forms a key element in low cost slicing.

Analysis of blade material accuracy shows that straightness and flatness specifications can be relaxed. The success of the blade alignment technique will allow lower thickness accuracy requirements. The goal is to use blade materials 50% as costly as used presently, reducing the cost of this expendible material.

2.0 INTRODUCTION

The purpose of this contract is for Varian Associates to explore the use of multiblade slurry wafering to slice ingot silicon into sheet material for use as solar cells. This report marks the completion of the first contracted effort to develop and evaluate MS slicing. Since the initiation of the work, Varian has achieved significant reductions of the slice thickness and kerf loss required for 10 cm ingot slicing.

The achievement of ERDA cost goals require modifications to the existing MS wafering process. These modifications have been identified as a result of Phase I of this work. A recent contract extension, Phase II, is a program to demonstrate ingot slicing cost goals for 1982 - 1986 using process knowledge gained under Phase I. The objective is an MS wafering saw capable of converting ingot to sheet at a rate of $1.0 \text{ m}^2/\text{kg}$ with an add-on cost of less than $\$10/\text{m}^2$.

3.0 CUTTING TESTS

During the past quarter, cutting tests with multiblade slurry (MS) slicing were completed for Phase I of the contract. These involved cutting with thin blades and full production demonstration of cutting with conditions and techniques developed for cost effective slicing of 10 cm diameter silicon. Also reported is a cutting test using zirconia-alumina rather than silicon carbide as an abrasive in MS slicing. A summary of cutting tests is shown in Table 1.

3.1 High Slurry Mix, High Load - Test #2-026

A standard 10 cm silicon ingot was cut using a 0.96 kg/liter mix of #600 SiC abrasive and a cutting force of 225 grams per blade (each twice normal). Total cutting time was 13.5 hours and cutting efficiency was high, peaking at 1.69. The test was intended to test the match of cutting load and abrasive concentration in MS slicing. Previous tests where load was increased without a change in abrasive mix, a reduction of cutting efficiency was noted. In this case, cutting efficiency compared favorably with standard conditions (0.48 kg/liter and 113 grams per blade). The result was a reduction of cutting time which nearly scaled with the increase in load (two times). However, even though a relatively thick spacer (0.40 mm) and standard (0.20 mm) blades were used, and slice thickness was nearly 0.36 mm, only 26% of the wafers survived the cutting operation. Blade wear was comparable to standard cutting (wear ratio of 0.045).

3.2 Thin Blade, High Cutting Force - Test #3-034

0.15 mm thick blades were used again in slicing a 10 cm ingot, with 0.40 mm spacers, a slurry mix of 0.36 kg/liter and a cutting force of 140 grams per blade (85 used previously). Cutting time

TABLE 1

SLICING TEST SUMMARY

(Phase I - Complete)

PARAMETER \ TEST	2-026	3-034	3-035	3-036
MATERIAL	Si {100}	Si {100}	Si {100}	Si
LOAD (gram/blade)	226.8	141.75	85.05	113.40
SLIDING SPEED (cm/sec)	60.1	60.7	60.0	60.7
NUMBER OF BLADES CUTTING	76	80	118	97
ABRASIVE (grit size)	#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)	7.6	7.6	7.6	7.6
MIX (kg/liter)	.96	.36	.36	.48
KERF LENGTH (cm)	10	10	10	10
INGOT HEIGHT (cm)	10	10	10	6.19
BLADE THICKNESS (cm)	.020	.015	.015	.015
KERF WIDTH (cm)	.0262	.0224	.0213	.0223
ABRASIVE KERF LOSS (cm)	.0058	.0071	.0061	.0071
AREA/SLICE (cm ²)	77.42	77.42	77.42	56.39
CUTTING TIME (total hours)	13:30	19:45	29:30	26:15
EFFICIENCY (full test)	1.11	1.02	1.10	0.698
(typical)	1.33	1.22	1.45	.7735
(maximum)	1.6927	1.7458	2.0966	1.1299
ABRASION RATE (full test)	.1503	.0878	.0559	.0479
(cm ³ /hr/blade) (typical)	.1806	.1046	.07373	.0531
(maximum)	.2299	.1497	.1066	.0775
PRODUCTIVITY (full test)	5.73	3.92	2.26	2.15
(cm ² /hr/blade) (typical)	6.89	4.67	3.46	2.38
(maximum)	8.77	6.68	5.00	3.48
SLICE TAPER (cm)	+.00080	+.00157	+.00153	+.00013
ABRASIVE UTILIZATION (cm ³ /kg)	21.13	50.71	71.12	45.91
OIL UTILIZATION (cm ³ /liter)	20.28	18.25	25.60	22.04

TABLE 1 (cont.)

SLICING TEST SUMMARY

(Phase I - Complete)

PARAMETER \ TEST	P-003	P-004	P-005
MATERIAL	Si {100}	Si {100}	Si {100}
LOAD (gram/blade)	113.40	85.05	85.05
SLIDING SPEED (cm/sec)	60.2	59.6	57.8
NUMBER OF BLADES CUTTING	225	271	234
ABRASIVE (grit size)	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)	7.6	7.6	7.6
MIX (kg/liter)	.48	.36	.36
KERF LENGTH (cm)	10	10	10
INGOT HEIGHT (cm)	10	10	10
BLADE THICKNESS (cm)	.020	.015	.015
KERF WIDTH (cm)	.0262	.0198	.0216
ABRASIVE KERF LOSS (cm)	.0059	.0046	.0064
AREA/Slice (cm ²)	77.42	77.42	77.42
CUTTING TIME (total hours)	25:20	35:15	32:00
EFFICIENCY (full test)	1.18	0.861	1.068
(typical)	1.38	1.12	1.37
(maximum)	1.6617	1.2829	1.5259
ABRASION RATE (full test)	.0801	.0435	.0523
(cm ³ /hr/blade) (typical)	.0939	.0566	.0671
(maximum)	.1130	.0648	.0747
PRODUCTIVITY (full test)	3.06	2.20	2.42
(cm ² /hr/blade) (typical)	3.58	2.86	3.11
(maximum)	4.31	3.27	3.46
SLICE TAPER (cm)	+.00141	+.00298	+.00083
ABRASIVE UTILIZATION (cm ³ /kg)	125.11	151.83	143.03
OIL UTILIZATION (cm ³ /liter)	60.05	54.66	51.49

was 19.8 hours, slice thickness was 0.33 mm and yield was 100%. Wafer accuracy was good, but kerf loss savings from 0.20 mm blades was only about 0.03 mm, indicating a slightly excessive loss of silicon (0.02 mm). This test did indicate the possibility of stable cutting with 0.15 mm blades.

A heating mounting block was used in #3-035, allowing immediate demounting of wafers after cutting is completed. Normally, after slicing, blades must be withdrawn through the sliced ingot in order to facilitate demounting. It was felt that this would cause breakage of thin slices, consequently the new technique was devised. It appears that the technique is successful in avoiding unnecessary breakage of thin slices (approx. 0.25 mm thick).

3.3 Thin Blades, Thin Wafers - Test #3-035

0.15 mm blades were used with 0.30 mm spacers to slice a 10 cm silicon ingot. Blade force of 85 grams and slurry mix of 0.36 kg/liter was used with #600 SiC. Cutting time was 29.5 hours with a peak efficiency of 2.10, higher than similar cutting with a lower slurry mix. Wafer yield was over 98% with 118 blades cutting. Slice thickness was 0.24 mm, and kerf loss was only 0.21 mm. The total silicon used per slice was 0.45 mm, the lowest to date. This corresponds to a conversion of 10 cm silicon ingot to sheet of 22.2 slices per cm of ingot, or $0.95 \text{ m}^2/\text{kg}$ of starting silicon ingot.

3.4 Thin Blades, Abrasive Concentration - Test #3-036

A partial 10 cm silicon ingot (25% of top cropped from another cutting test) was cut with 0.15 mm blades and 0.30 mm spacers. A higher cutting force (113 grams) and abrasive mix (0.48 kg/liter)

was used to duplicate test #3-035. Total cutting time for the smaller ingot was 26.2 hours, indicating that cutting rate was much less than with #3-035. The only suspect was a minor variation in the abrasive particle size, as similar results were observed with the same batch of #600 SiC abrasive in other cutting underway at the same time in the Varian slicing laboratory. The effect of a small reduction in abrasive particle size on cutting rate was seen in early cutting tests. Since, the process seems to be sensitive to particle size, variations in cutting rate must be expected due to minor changes in abrasive grading.

3.5 Zirconia-Alumina Abrasive - Test #2-042

$Zr_2O_2 - Al_2O_3$ abrasive was obtained to substitute for the standard #600 SiC. The abrasive appeared rather rounded and almost porous under SEM examination. The particle size was comparable to the silicon carbide, and a cutting test was run. A 10 cm silicon ingot was cut with 0.20 mm blades and 0.30 mm spacers. The abrasive mix was increased to 0.60 kg/liter to adjust for the 25% higher density of the zirconia-alumina and provide for an abrasive particle packing similar to that used with standard silicon carbide cutting. At 113 grams per blade (standard for 0.20 mm blades), the cutting efficiency was only 20% that seen with SiC abrasive. Severe breakage occurred with the thin slices, and the cut was aborted after completing 1.5 cm of depth into the 10 cm ingot in 12 hours.

The zirconia-alumina had been tried because in standard abrasive applications (grinding belts, etc.), it has shown greatly improved lifetime over silicon carbide and other abrasives. However, for MS slicing, the small scale shape of the particles seems to be a more significant criterion. The cleaved silicon carbide particles effectively concentrate cutting stresses to provide fracture of the silicon, and thus facilitate cutting.

The zirconia-alumina was more rounded, with no sharp edges. The cutting forces are more distributed in contact with the silicon, and silicon fracture was significantly suppressed. Perhaps only in the case of MS slicing, particle shape is most critical, and other abrasive material characteristics are likely not important.

The rounding of fresh zirconia-alumina was far more apparent than silicon carbide particles used to their "full" lifetime.

3.6 Full Production Demonstration - Test #P-003

0.20 mm blades and 0.30 mm spacers were used to slice a 10 cm silicon ingot, using the full saw capacity of 225 blades (0.20 mm thick and 6.35 mm high). 113 grams of blade load and 0.48 kg/liter of #600 SiC abrasive resulted in a cutting time of 25.33 hours. Slice yield was only 76%, resulting from a collapse of the spacers within the blade package upon tensioning. At 80% full tension, the sound of collapsing spacers was heard, but the test was continued. The collapse was not disastrous to the cutting process, but did seem to cause the reduction of slice yield and poor slice accuracy. The average wafer thickness was 0.246 mm compared to earlier results with thicknesses of 0.251 mm. The difference appears to be related to the larger package size, and a correspondingly higher average blade misalignment.

3.7 Full Production Demonstration, Thin Blades - Test #P-004

A full bladehead capacity of 300 0.15 x 6.35 mm blades with 0.30 mm spacers was used to cut a 10 cm diameter silicon ingot. The available ingot length was 12.4 cm, allowing 271 wafers to be cut simultaneously. Cutting time was 35 hours, and wafer thickness was 0.25 mm, with a kerf loss of 0.20 mm. However, the wafer yield after cleaning was only 33%. With only 115 blades cutting, the same conditions had resulted in nearly 100% yield. This supports an

earlier conclusion that blade alignment is the limiting factor in MS slicing with the present machine configuration.

In all cases of successful thin wafer slicing, a change to larger numbers of blades results in an increase in slice breakage, a reduction of slice accuracy, and a slight increase in kerf loss. The effect is more severe when thin (less stable) blades are used. In the Fourth Quarterly Report, it was shown that the cumulative packing tolerance of blades and spacers was expected to result in longitudinal blade misalignment from 200 to 500 microns. A vertical misalignment is expected as well. This misalignment will reduce the load carrying capacity of the blade, perhaps to a point where blade overturning will occur readily and cutting action cannot be sustained. It was shown in the Third Quarterly Report² that theoretical buckling load of a perfectly aligned blade is 10 times the loading actually experienced in MS slicing. Longitudinal misalignment (runout) can set up lateral loads on wafers during a cutting operation, and with thin slices (0.25 mm thick) fracture can easily occur.

An increase in number of blades, a reduction of blade thickness or tension or length (lower blade stability) can all limit the thickness to which slices can be cut. The fundamental problem source is the stacking of blade thickness variations, and the cure will be addressed in the extension (Phase II) of this contract.

3.8 Full Production Demonstration, Thin Blades - Test #P-005

P-004 was duplicated, except that a thicker (0.35 mm) spacer was used with the 300 0.15 mm blades. Ingot length allowed 234 wafers to be cut simultaneously. Cutting time was 32 hours and 83% of the wafers survived the cutting/cleaning process. This improvement was due to the 0.05 mm thicker wafers (0.30 mm) and their higher strength, but it still shows the tradeoff presently required for large numbers of blades simultaneously. This run completed the cutting tests for the initial contract (Phase I).

4.0 WAFER CHARACTERIZATION

Tables 2 and 3 show mechanical and non-contact thickness and bow characterizations of wafers from cutting tests performed in the last quarter. Also included in Table 3 are tests #2-001 and the first large diameter test #1-001. Both #2-001 (using 0.20 mm thick blades), and test #3-035 (0.15 mm thick blades) have reasonable wafer accuracy. The fact that 0.25 mm thick, 10 cm silicon wafers were sliced with nearly 100% yield is an indication of accurate cutting by itself.

However, both of these tests used only 100 to 150 blades in a package. When a full package was used in the production demonstrations, the accuracy of wafers decreased. The 0.20 mm blades suffered less from the use of a large (225 blades) package than did the 0.15 mm blades (300 blades). The reduction in accuracy coincides with the poor wafer yields seen in the production demonstrations.

The 0.25 mm wafer thickness is near to a lower bound for the slicing of 10 cm silicon wafers. The thin slices have a tendency to fracture under even the light cutting loads used in multiblade slurry sawing, and handling of these thin slices is liable to cause a further reduction of yield.

The tests of the last quarter demonstrate clearly that the mechanism of slicing failure for these very thin wafers is the combination of stability of blades and the misalignments characteristic of a large package of blades and spacers. Successful cutting of 0.25 mm slices was achieved with an intermediate number of both 0.15 and 0.20 mm thick blades. The thinner blades are expected to have 75% of the load carrying capability, or stability of the 0.20 mm blades (see Third Quarterly Report). The misalignment of blades is a result of the stacking of small thickness variations of blades and spacers across the package. This misalignment was described in the Fourth Quarterly Report as both longitudinal runout, causing side loading on slices and vertical misalignment reducing the load

TABLE 2

WAFER THICKNESS CHARACTERIZATION
(Mechanical Measurement)

TEST		<u>2-026</u>	<u>3-034</u>	<u>3-035</u>	<u>3-036</u>
THICKNESS (AVE)	cm	03485	03366	02441	02339
STD. DEVIATION	cm	00196	00157	00135	00185
TOTAL VARIATION (AVE)	cm	00546	00340	00320	00272
STD. DEVIATION	cm	00249	00127	00155	00109
STD. DEVIATION (AVE)	cm	00206	00135	00119	00094
STD. DEVIATION	cm	00104	00053	00610	00041
VARIATION (AVE WAFER)	cm	00137	00183	00196	00107
TAPER (AVE WAFER)	cm	00079	00157	00152	00013
BOW (AVE)	μm				
TAPER (AVE)	μm				
WAVINESS (p-p) (10^{-2}m)	μm				
ROUGHNESS (p-p) (10^{-4}m)	μm				
ROUGHNESS (RMS)	μinch				
STEPS	μm				
DAMAGE DEPTH ($<10^4/\text{cm}^2$)	μm				

TABLE 2 (cont.)

WAFER THICKNESS CHARACTERIZATION
(Mechanical Measurement)

TEST		<u>P-003</u>	<u>P-004</u>	<u>P-005</u>
THICKNESS (AVE)	cm	02456	02600	02921
STD. DEVIATION	cm	00264	00279	00414
TOTAL VARIATION (AVE)	cm	00549	00483	00744
STD. DEVIATION	cm	00274	00302	00231
STD. DEVIATION (AVE)	cm	00203	00216	00318
STD. DEVIATION	cm	00112	00117	00107
VARIATION (AVE WAFER)	cm	00196	00338	00460
TAPER (AVE WAFER)	cm	00152	00300	00213
BOW (AVE)	μm			
TAPER (AVE)	μm			
WAVINESS (p-p) (10^{-2}m)	μm			
ROUGHNESS (p-p) (10^{-4}m)	μm			
ROUGHNESS (RMS)	μinch			
STEPS	μm			
DAMAGE DEPTH ($<10^4/\text{cm}^2$)	μm			

TABLE 3
SUMMARY OF WAFER CHARACTERIZATION
(Non-Contact Gauging)

TEST		<u>1-001</u>	<u>2-001</u>	<u>3-035</u>
SLICE	Diameter (cm)	(10)	10	10
	Area (cm ²)	82.6	77.4	77.4
	Thickness (μ)	565	245	244
VERTICAL TAPER	Average (μ)	57	49	39
	Maximum	100	58	74
	Minimum	22	35	16
HORIZONTAL TAPER	Average (μ)	7	16	13
	Maximum	12	24	19
	Minimum	1	9	6
VERTICAL BOW-TOP	Average (μ)	63	94	57
	Maximum	108	107	100
	Minimum	30	77	23
HORIZONTAL BOW-TOP	Average (μ)	19	34	57
	Maximum	45	53	79
	Minimum	8	17	15
VERTICAL BOW-BOTTOM	Average (μ)	24	80	46
	Maximum	40	96	59
	Minimum	10	59	29
HORIZONTAL BOW-BOTTOM	Average (μ)	17	39	49
	Maximum	43	59	64
	Minimum	2	25	24
VERTICAL BOW-CL	Average (μ)	78	170	97
	Maximum	135	192	136
	Minimum	23	133	42
HORIZONTAL BOW-CL	Average (μ)	36	72	106
	Maximum	90	110	142
	Minimum	9	29	39

TABLE 3 (cont.)

SUMMARY OF WAFER CHARACTERIZATION
(Non-Contact Gauging)

TEST		<u>P-003</u>	<u>P-004</u>	<u>P-005</u>
SLICE	Diameter (cm)	10	10	10
	Area (cm ²)	77.4	77.4	77.4
	Thickness (μ)	246	260	291
VERTICAL TAPER	Average (μ)	47	53	74
	Maximum	89	98	118
	Minimum	18	16	34
HORIZONTAL TAPER	Average (μ)	11	11	6
	Maximum	24	22	13
	Minimum	3	4	2
VERTICAL BOW-TAPER	Average (μ)	97	44	95
	Maximum	165	88	236
	Minimum	42	14	25
HORIZONTAL BOW-TOP	Average (μ)	79	52	71
	Maximum	108	75	112
	Minimum	45	25	24
VERTICAL BOW-BOTTOM	Average (μ)	113	51	111
	Maximum	160	78	148
	Minimum	87	21	85
HORIZONTAL BOW-BOTTOM	Average (μ)	72	50	71
	Maximum	95	78	120
	Minimum	34	31	33
VERTICAL BOW-CL	Average (μ)	205	79	194
	Maximum	327	127	360
	Minimum	140	37	85
HORIZONTAL BOW-CL	Average (μ)	152	101	143
	Maximum	193	144	229
	Minimum	80		

carrying ability of the blades and increasing their tendency to wander through the ingot. This misalignment is expected to increase as the square root of the number of blades in the package.

When the number of blades was increased for a particular processing technique, the yield and accuracy both fell. In the case of the less stable 0.15 mm blades, the reduction of yield was more dramatic. By increasing the wafer thickness from 0.25 mm to only 0.30 mm, the effect of the increased misalignment was reduced dramatically. Thus the limit of multiblade slurry sawing is presently defined by wafer strength (thickness), blade stability (thickness), and blade misalignment (number) in combination. A technique of resolving this limit is discussed in Section 5.3.

The results from #3-035 and #2-001 indicate that the thin slices produced with MS slicing nearly meet the ASTM specifications for 10 cm silicon wafers. One important point to note about the bow measurements is that a .25 mm thick silicon slice has been estimated to "droop" or bow under its own weight by 10 to 20 microns. It is, however, impossible to omit this effect from the results of Table 3.

5.0 DISCUSSION

Multiblade slurry sawing has proven successful in using a minimum of silicon to produce a slice. The current slice spacing is 0.45 mm per slice, with 0.25 mm wafer thickness and 0.20 mm kerf loss. This improvement is significant to achieving the ERDA silicon sheet cost goal of approximately \$30/m². The scaling of this achievement from a relatively small production scale to a large-scale, low cost silicon sheet production technique is not without obvious problems. The fundamental limitation is now felt to be the alignment of blades in a multiblade wafering saw. In order to make multiblade slurry wafering of silicon more cost effective, a second phase of the contract has been undertaken. In this Phase II, Varian will design, build and test a large capacity multiblade slurry saw, having the potential for slicing silicon with an add-on cost of less than \$10/m², and to use thin wafer, low kerf loss processing which can convert ingot to sheet at a rate of 1.0 m²/kg. There are definite technical problems with the scale-up which have been identified in Phase I and will be investigated in Phase II.

5.1 Economic Analysis of MS Slicing - Ingot Conversion to Sheet

The contributed costs of multiblade slurry wafering of silicon ingot can be logically broken down into two discrete elements. The most significant is the ability to convert costly ingot silicon into sheet material (wafers).

The important factor in this conversion is the length of silicon ingot required to produce a slice that is usable for high efficiency solar cells. This slice must be of a thickness that can be handled without impacting the yield of the cell processing steps. For the present, this contract effort is geared toward the minimum thickness slice that can be produced from 10 cm silicon ingot, and still survive the cutting operation. As near to 100%

slice yield as possible has been sought. The remaining silicon material used per slice from the ingot is lost in abrasion debris (kerf loss). 10 cm silicon slicing has been carried out with a total silicon requirement of 0.45 mm per slice (0.25 mm slice thickness, 0.20 mm kerf loss).

The conversion of ingot to sheet can be described in cost terms by the total ingot length per slice, X_I (cm), the cost of usable silicon ingot, C_I (\$/kg), the wafering yield, Y_W , and the area yield, Y_A (83% for hex cells from round ingot), to give the silicon material cost of the sheet, C_M .

$$C_M(\$/m^2) = 23.3 \times \frac{C_I(\$/kg) \times X_I(\text{cm/slice})}{Y_W Y_A} \quad (1)$$

Figure 1 shows the sheet cost assuming various starting ingot costs in terms of slice to slice spacing. At today's best cost for 10 cm Czochralski ingot of \$250 per kg, the resulting sheet cost is \$260 - \$290/m² using the most effective slicing under this contract. The assumed goals for 1982 and 1986 sheet cost can be met with tentative ingot cost goals and the present state-of-the-art with multiblade slurry wafering. Improvements in yield are anticipated to make this conversion goal realistic. It is clear from Figure (1) that the most significant contribution of ingot wafering will be to increase the number of slices per length of ingot. Even as the cost of ingot drops from today's level to the 1986 goal of approximately \$20/kg, this conversion rate effects the most significant cost in sheet silicon production.

5.2 Economic Analysis of MS Slicing - Add-on Costs

The cost of the wafering process itself is comprised of four fundamental elements: 1) A mixture of abrasive and oil (slurry) is used to a maximum useful lifetime (number of slices cut). The slurry becomes loaded with silicon debris and after a period of time, cutting rate decreases, and more significantly, wafer breakage occurs. 2) A package of multiple blades and spacers is made from precision strip 1095 steel, hardened to 250-300 kpsi tensile strength. The associated costs are materials (steel), and assembly. The package is worn out during the cutting operation, and must be replaced periodically. 3) An operator is required to mount and install the ingot to the saw; install, tension and align a blade package; provide minor attention during the cutting cycle; demount the finished wafers; and change abrasive slurry. Except for the minor attention, the operators input does not depend at all on the duration of the cutting cycle. 4) The machine depreciation is the only factor having a direct cost associated with cutting time.

Table 4 shows a cost analysis of a series of cutting test demonstrations shown for Phase I. In these analyses, the actual wafer yields and number of wafers produced are considered. A column showing today's "best" case is also included, neglecting the lower yield resulting from slicing large numbers of very thin wafers. For this case the cost of silicon ingot is neglected. The important point to note is that ingot cost and slice spacing are far more significant today than the actual cost of the slicing operation.

The cost elements of MS slicing are calculated in a very simplistic, but meaningful fashion. The total area, A , produced during the cutting cycle is given by the number of slices cut (N), the ingot diameter in cm, d_I , and the wafering and area yields, Y_W and Y_A .

TABLE 4

ECONOMICS OF MS SLICING

		<u>P-001</u>	<u>P-002</u>	<u>P-003</u>
<u>INGOT PARAMETERS</u>				
Length	cm			
Diameter	cm	10	10	10
Cost	\$/kg	250	250	(250)
<u>SAW PARAMETERS</u>				
Spacer Thickness	cm	0.05	0.036	.03
Blade Thickness	cm	0.02	0.02	.02
Number of Blades		225	225	225
<u>BLADES</u>				
Height	cm	0.635	0.635	.635
Blade Cost	\$/lb.	5.40	5.40	5.40
Spacer Cost	\$/lb.	2.10	2.52	2.60
Fab & Assy	\$/blade	0.05	0.05	.05
Life	# cuts	1	1	1
<u>SLURRY</u>				
Volume	liters	7.6	7.6	7.6
Mix	kg/l	0.48	0.36	.48
Abrasive Cost	\$/lb.	1.95	1.95	1.95
Oil Cost	\$/gallon	2.50	2.50	2.50
Life	# slices	225	225	225
<u>LABOR</u>				
Set-up Time	hrs.	0.5	0.5	0.5
Work Mount	hrs.	0.2	0.2	0.2
Demount	hrs.	0.3	0.3	0.3
Attention	hrs.	0.5	0.5	0.5
Machines/Operator		10.0	12.25	13.2
<u>CAPITALIZATION</u>				
Machine Cost	\$	20K	20K	20K
Depreciation Time	yrs.	7	7	7
Usage	days/yr.	300	300	300
Usage	hrs/day	24	24	24
Down-Time	%	5	5	5
Maintenance	\$/yr.	0	0	0
<u>RESULTS</u>				
Wafering Yield	%	94	94	.76
Area Yield	%	100	100	.94
Slicing Time	hrs.	19.0	23.5	25.3
<u>COSTS</u>				
Sheet Materials	\$/m ²	\$433.78	\$347.02	\$407.68
Wafering Cost	\$/m ²	\$ 44.78	\$ 43.70	\$ 54.60
Blades	\$/m ² (%)	\$ 13.77(31)	\$ 13.58(31)	\$ 17.66(32)
Slurry	\$/m ² (%)	\$ 12.43(28)	\$ 10.08(23)	\$ 12.40(23)
Labor	\$/m ² (%)	\$ 13.55(30)	\$ 13.55(31)	\$ 15.84(29)
Capitalization	\$/m ² (%)	\$ 5.03(11)	\$ 6.49(15)	\$ 8.70(16)
Total Sheet Cost	\$/m ²	\$478.56	\$390.72	\$462.28

TABLE 4 (cont.)

ECONOMICS OF MS SLICING

		<u>P-004</u>	<u>P-005</u>	<u>3-035</u>
<u>INGOT PARAMETERS</u>				
Length	cm			
Diameter	cm	10	10	10
Cost	\$/kg	(250)	(250)	(250)
<u>SAW PARAMETERS</u>				
Spacer Thickness	cm	.03	.035	.030
Blade Thickness	cm	.015	.015	.015
Number of Blades		271	234	118
<u>BLADES</u>				
Height	cm	.635	.635	.635
Blade Cost	\$/lb.	7.95	7.95	7.95
Spacer Cost	\$/lb.	2.60	2.40	2.60
Fab & Assy	\$/blade	.05	.05	.05
Life	# cuts	1	1	1
<u>SLURRY</u>				
Volume	liters	7.6	7.6	7.6
Mix	kg/l	.36	.36	.36
Abrasive Cost	\$/lb.	1.95	1.95	1.95
Oil Cost	\$/gallon	2.50	2.50	2.50
Life	# slices	271	234	118
<u>LABOR</u>				
Set-up Time	hrs.	0.5	0.5	0.5
Work Mount	hrs.	0.2	0.2	0.2
Demount	hrs.	0.3	0.3	0.3
Attention	hrs.	0.5	0.5	0.5
Machines/Operator		18.1		
<u>CAPITALIZATION</u>				
Machine Cost	\$	20K	20K	20K
Depreciation Time	yrs.	7	7	7
Usage	days/yr.	300	300	300
Usage	hrs/day	24	24	24
Down-Time	%	5	5	5
Maintenance	\$/yr.	0	0	0
<u>RESULTS</u>				
Wafering Yield	%	.33	.833	.983
Area Yield	%	.94	.94	.94
Slicing Time	hrs.	35.2	32.0	29.5
<u>COSTS</u>				
Sheet Materials	\$/m ²	\$845.02	\$371.96	\$283.68
Wafering Cost	\$/m ²	\$121.00	\$ 52.02	\$ 72.03
Blades	\$/m ² (%)	\$ 42.46(35)	\$ 16.91(33)	\$ 14.25(27)
Slurry	\$/m ² (%)	\$ 25.35(21)	\$ 11.63(22)	\$ 19.55(38)
Labor	\$/m ² (%)	\$ 30.29(25)	\$ 13.90(27)	\$ 23.35(45)
Capitalization	\$/m ² (%)	\$ 22.90(19)	\$ 9.58(18)	\$ 14.88(29)
Total Sheet Cost	\$/m ²	\$966.02	\$423.98	\$355.77

TABLE 4 (cont.)

ECONOMICS OF MS SLICING

		<u>TODAY'S BEST</u>	<u>GOALS</u>
<u>INGOT PARAMETERS</u>			
Length	cm		
Diameter	cm	10	12
Cost	\$/kg	0	(20)
<u>SAW PARAMETERS</u>			
Spacer Thickness	cm	0.30	0.30
Blade Thickness	cm	0.15	0.15
Number of Blades		300	900
<u>BLADES</u>			
Height	cm	.635	1.0
Blade Cost	\$/lb.	7.95	2.00
Spacer Cost	\$/lb.	2.60	2.00
Fab & Assy	\$/blade	.025	.002
Life	# cuts	1	2
<u>SLURRY</u>			
Volume	liters	7.6	15.0
Mix	kg/l	0.36	0.36
Abrasive Cost	\$/lb.	1.95	1.95
Oil Cost	\$/gallon	2.50	1.00
Life	# slices	300	900
<u>LABOR</u>			
Set-up Time	hrs.	0.5	0.5
Work Mount	hrs.	0.2	0.2
Demount	hrs.	0.3	0.3
Attention	hrs.	0.5	0.5
Machines/Operator		15.5	15.5
<u>CAPITALIZATION</u>			
Machine Cost	\$	20K	30K
Depreciation Time	yrs.	7	12
Usage	days/yr.	300	300
Usage	hrs/day	24	24
Down-Time	%	5	5
Maintenance	\$/yr.	0	0
<u>RESULTS</u>			
Wafering Yield	%	95	95
Area Yield	%	100	100
Slicing Time	hrs.	30	30
<u>COSTS</u>			
Sheet Materials	\$/m ²	0	\$22.07
Wafering Cost	\$/m ²	32.71	8.08
Blades	\$/m ² (%)	10.51(32)	2.04(25)
Slurry	\$/m ² (%)	7.48(23)	2.80(35)
Labor	\$/m ² (%)	8.94(27)	2.07(26)
Capitalization	\$/m ² (%)	5.78(18)	1.17(14)
Total Sheet Cost	\$/m ²	32.71	\$30.15

$$A(m^2) = \frac{\pi}{40,000} d_I^2(cm) N Y_W Y_A \quad (2)$$

Blade costs are calculated from the steel cost at today's prices and the actual cost of low-volume hand assembly (\$.05 per blade). The steel cost (\$/lb) is different for the spacer and blade stock. Generally, a large fabrication and slitting premium per pound of steel is paid for the thinner and narrower blades. For the "best" case, an assembly cost of \$0.025 per blade was assumed to reflect larger scale automated package assembly techniques. The blade height and thickness in cm, t_B and h_B , the spacer thickness, t_S , in cm, the cost of blade and spacer material, C_B and C_S (\$/lb) and the cost of package assembly in \$/blade, C_P , gives a total package cost. Incorporating the number of times the package may be used through a particular ingot size, L_B (number of cuts), and the total area produced per slice, A/N (Equation 1), gives the add-on cost of blades, C_B .

$$C_B(\$/m^2) = \left(\frac{40,000}{\pi} \right) \frac{.609 t_B h_B C_B + 0.94 t_S C_S + C_P}{d_I^2 Y_W Y_A L_B} \quad (3)$$

Life of a package is given as once through a 10 cm ingot. Two passes have been made with an 0.635 cm high blade, but increased slice breakage occurred during the end of the second cut. However, a 12 cm should be sliced through with the same blade with no detrimental effects (44% more area).

The abrasive slurry is a volume, V_O (liters) of oil and, for the present, #600 SiC abrasive in a mixture, M_A (kg/liter). The cost of oil, C_O (\$/gallon), and the cost of abrasive, C_A (\$/lb) have been assumed to be today's costs with no volume reductions. The life of the slurry seems to depend on the contamination of silicon debris in the oil (kg of Si/liter of oil), however, a life

in terms of number of slices actually produced is used in Table 4.

$$C_S (\$/m^2) = \frac{40,000}{\pi} \frac{V_o \left[C_o / 3.8 + 2.2 M_A C_A \right]}{L_S d_I^2 Y_A Y_W} \quad (4)$$

Where C_S is the add-on cost of the expendible slurry, and the area per slice A/N (m^2) is included from Equation (1).

Labor input to the sawing operation is estimated by four elements, blade package installation and alignment, T_1 , work mounting and preliminary operations, T_2 , workpiece demounting and cleanup, T_3 and operator attention, T_4 . The package installation time, T_1 , is scaled by the number of runs per package, L_B . Labor was charged at \$4.00 per hour with supervision at 50% of direct labor and overhead at 100% of direct labor, for a total labor cost of \$10/hour of direct labor. A factor of 75% actual labor efficiency was used. The add-on labor cost, C_L ($\$/m^2$) is given by

$$C_L (\$/m^2) = \frac{\$10/hr.}{.75} \frac{40,000}{\pi} \frac{(T_1/L_B + T_2 + T_3 + T_4)}{N d_I^2 Y_W Y_A} \quad (5)$$

The number of saws handled by each operator, N_M , is given by the total slicing time, T_S , plus additional delays for setup, work mounting and demounting; the total labor input per machine cycle and the 75% efficiency factor.

$$N_M (\text{saws/operator}) = .75 \frac{T_S + T_1 + T_2 + T_3}{T_1 + T_2 + T_3 + T_4} \quad (6)$$

The machine capitalization cost is typically the smallest component of MS slicing costs. It depends on the output of the saw (area/run),

and the operation cost per run. The machine cost, C_o (\$) is depreciated over a period of T years. Yearly maintenance is C_M (\$/yr) and the saw is used for U_D (days/yr) and U_H (hours/day), with a maintenance down time factor U_M (%/year). The capitalization cost, C_c (\$/m²) is given by:

$$C_c (\$/m^2) = \frac{(C_o / T + C_M) (T_S + T_1 + T_2 + T_3)}{(U_D U_H) (1 - U_M / 100) N d_I^2 Y_A Y_W} \frac{40,000}{\pi} \quad (7)$$

The capitalization cost is the only element of MS slicing which depends on the slicing rate (T_S). The other cost factors are input only once into the operation, and do not depend on slicing time. In fact, efforts to increase cutting rate can increase the rate of blade wear, reduce the wafer yield or increase the minimum slice spacing. These effects are more costly than the associated reduction of capitalization cost. With high ingot costs, the slicing operation is only 10-15% of the finished sheet silicon cost. Most critical is the minimum slice spacing and high wafer yield. Notice that test #3-035 yielded the lowest sheet cost even though the wafering cost was twice as high as necessary due to the low number of wafers produced (118).

The final column of Table 4 shows the specific goals for a cost effective MS slicing process. The major change is a three to fourfold increase in the machine capacity of wafers while maintaining the slice spacing, X_I , of 0.45 mm. This reduces the specific (\$/m²) labor and machine costs. Problems associated with this change will be discussed in Section 5.3. Blade stock with similar hardness characteristics can be purchased for less than \$2.50 per pound. However, higher thickness and other tolerances must be accommodated. Blade and slurry life have also been assumed to increase. There are process improvements which must be achieved in order to meet 1986 sheet silicon cost goals, the most significant of which is an improvement in intrinsic blade alignment for multiblade slurry sawing.

5.3 Technique of Blade Alignment

It was previously described that very small (approximately .1 micron) variations in blade and spacer thickness could result in rather significant (10 to 50 micron) vertical and horizontal misalignments of blades when accumulated over hundreds of components as in a typical multiple blade package. The blade used to cut very thin slices with a minimum of kerf loss must be capable of very accurate passage through the ingot without exerting loads on the very delicate slices. The blade is also constrained to be relatively unstable due to its narrow width, and is susceptible to load induced distortion. With even a small degree of blade misalignment, these conditions are worsened. It is the misalignment of blades that limits the MS process, and thinner blades of larger numbers of components will increase the tendency of blades to wander.

Figure 2 shows a schematic of a blade package. The alignment of any blade from the reference blades is determined by the differences between four sets of component sizes. Since the errors are additive, significant misalignment occurs. Figure 3 shows a schematic of a misaligned blade and a corrective procedure devised to minimize blade misalignment even with large numbers of blades. The blade package is relied upon to roughly space and tension the blades. A set of four positioning combs determines the final location of a blade. The repositioning of a blade is small, thus loads are minor, but the four distances must be identical within a very small amount. By machining all four combs simultaneously, the variation between spacings is nearly zero and only depends on the run-out of the particular machining operation. In this way, improved alignment which does not depend on the package size is conceivable.

FIGURE 2

SCHEMATIC VIEW OF A BLADE PACKAGE

FIGURE 3
SCHEMATIC OF BLADE ALIGNMENT DEVICE

The effect may be to allow higher yield, thinner blades, higher cutting force, improved accuracy, thinner slicing by the MS technique. A preliminary design for this blade alignment device has been completed and ordered. It will be experimented with on a standard Varian slicing machine. If successful, it will allow the large capacity saw to be built under Phase II to duplicate or exceed thin slices and low kerf loss achieved on a smaller scale under Phase I.

5.4 Reduction of Blade Cost by Looser Tolerances

Much of the cost of the blade material is due to the very accurate dimensional and material specifications. It may be possible to reduce the cost of blades by specifying less accurate material.

One of the specifications is the "straightness". Nominally, the edges of the blade stock are straight when viewed perpendicular to the wide dimensions of the stock. Processing variations, however, result in these edges being curved. The amount of curve is the straightness. The standard groups of straightness are normal, accurate, and extra accurate (these groups are quantized below). Currently, blade stock is bought as extra accurate, costing 10-15% more than otherwise identical normal straightness stock. An analysis has been carried out on the effect of straightness with a view to saving the expense of extra accurate stock. The analysis concerns the deviation of a blade from the nominal cutting plane (defined by the lower corners of the end blades in a tensioned pack).

Analysis

Consider a blade with dimensions shown in Figure 4. Defining ρ as the radius of curvature at any point (initially ρ_0), and y_c as the y coordinate of the blade centerline taken through the

FIGURE 4

BLADE AND COORDINATES

point, geometrical considerations lead to a formula for the strain due to bending:

$$\epsilon_{xx}^b = \frac{y-y_c}{\rho} - \frac{y-y_c}{\rho_0}, \text{ all others zero} \quad (8)$$

Since the stress is uniaxial, the only strains due to tension are:

$$\begin{aligned} \epsilon_{xx}^t &= \Delta L/L \\ \epsilon_{yy}^t &= \epsilon_{zz}^t = \nu \Delta L/L \end{aligned} \quad (9)$$

And, assuming elasticity,

$$\sigma_{xx} = E \left(\epsilon_{xx}^b + \epsilon_{xx}^t \right) = E \left(\frac{y-y_c}{\rho} - \frac{y-y_c}{\rho_0} \right) + \frac{\Delta L}{L} \quad (10)$$

Considering a free body, moment equilibrium and simple beam theory and superposition lead to

$$\sigma_{xx} = (1-12(y-y_c)/h^2)E\Delta L/L \quad (11)$$

Equating Equations 10 and 11 and solving for $\frac{1}{\rho}$,

$$\frac{1}{\rho} = \frac{1}{\rho_0} - \frac{12 y_c \Delta L}{h^2 L} \quad (12)$$

It is possible³ to express ρ in terms of the first two derivatives of y with respect to x , y' and y'' . Defining the curvature in Figure 4 as positive,

$$1/\rho = -y'' / (1 + (y')^2)^{3/2} \quad (13)$$

If y' is very small, the relationship is simpler; ($1/\rho = -y''$). However, since the final equation will be solved numerically, there is no need to drop the nonlinear term. Substituting Equation 13 in Equation 12 and solving for y'' ,

$$y'' = \left(\frac{12 y_c \Delta L}{h^2 L} - \frac{1}{\rho_0} \right) (1 + (y')^2)^{3/2} \quad (14)$$

With boundary conditions

$$y = y_0 \text{ @ } x = \pm L/2 \quad (15)$$

Equations 14 and 15 comprise an ordinary boundary value problem. If the nonlinear term is dropped, an analytical solution does exist in the form of an infinite series⁴. It is more convenient to solve the problem numerically for the few cases of interest, especially since the blade thickness does not appear.

The solution is more convenient if Equations 14 and 15 are restated. First, since y is not initially known (because of Poisson contraction, $y_c \neq y + \text{constant}$), identify $y = y_c$ to solve for the centerline position. Second, shorten the interval by using symmetry to define the boundary condition $y'=0$ @ $x = 0$. Third, nondimensionalize by defining new variables

$$x^* = x/L \quad y^* = y/L \quad \rho_0^* = \rho_0/L \quad \beta = 12L\Delta L/h^2 \quad (16)$$

The restated problem is

$$y_c^{*''} = (\beta y_c^* - 1/\rho_0^*) (1 + (y_c^{*'})^2)^{3/2} \quad (17)$$

$$y_c^* = 0 \text{ @ } x^* = -0.5$$

$$y_c^{*'} = 0 \text{ @ } x^* = 0$$

The only remaining task in the formulation is to define ρ_0 . The straightness tolerance is stated in terms of the maximum deviation B from a chord of length A (usually 2.44 m or 8 ft.). Assuming the curve to be an arc of a circle,

$$\rho_0 = (A^2 + 4B^2)/8B \quad (18)$$

Values of A, B and ρ_0 for various tolerance grades are shown in Table 5. Values of $1/\rho_0^*$ and β are shown in Table 6. The values are all based on a length $L = 381$ mm (15 in) and extension $\Delta L = 2.54$ mm (0.1 in).

The problem was solved on an HP-97 calculator. The boundary value problem was converted to an initial value problem by a shooting method⁵ combined with a fourth order Runge-Kutta integration scheme. Resulting values of y_c^* @ $x^* = -0.5$ are shown in Table 7. A fourth order Runge-Kutta scheme was then used to calculate y^* between $x^* = -0.5$ and $x^* = 0.5$. A stepsize Δx^* , of 0.02 was used for all the integrations. Analysis of the problem with different stepsizes indicates that the results are at worst good to 3-4 significant figures.

The computations were carried out using various stepsizes ranging from $\Delta x^* = 0.02$ to $\Delta x^* = 0.001$. Analysis with different stepsizes and the symmetry of the results suggest that the results are good to at least three significant figures. (Ten decimal digit arithmetic was used for all calculations, with the results rounded after the calculations.)

Figures 5 - 7 show the position of the blade centerline, relative to a chord, after tensioning. It is interesting that tensioning does not significantly reduce the difference between the straightness grades even though a larger moment is developed in the less straight blades. This cannot be due to the relative magnitudes of extension stress and bending stress, since no extension stress terms appear in Equation 17.

TABLE 5

BLADE CURVATURE PARAMETERS FOR VARIOUS STRAIGHTNESS GRADES

	A m (in)	B m (in)	ρ_o m (in)
Normal	2.4384 (96)	11.906 (15/32)	62.429 (2457.8)
Accurate	2.4384 (96)	5.9531 (15/64)	124.85 (4915.3)
Extra Accurate	2.4384 (96)	2.7781 (7/64)	267.53 (10533)

TABLE 6
 NONDIMENSIONAL PARAMETERS FOR VARIOUS STRAIGHTNESS GRADES
 AND BLADE HEIGHTS

Blade Height h mm (in)	Straightness Grade		
	Normal	Accurate	Extra Accurate
12.700 (1/2)	$\beta = 72$ $1/\rho_o^* = 6.1029 \times 10^{-3}$	72 3.0517×10^{-3}	72 1.4241×10^{-3}
6.3500 (1/4)	$\beta = 280$ $1/\rho_o^* = 6.1029 \times 10^{-3}$	280 3.0517×10^{-3}	280 1.4241×10^{-3}
4.7625 (3/16)	$\beta = 512$ $1/\rho_o^* = 6.1029 \times 10^{-3}$	512 3.0517×10^{-3}	512 1.4241×10^{-3}

TABLE 7

NONDIMENSIONAL SLOPE, y_c^* , AT END OF BLADE

Blade Height h mm (in)	Straightness Grade		
	Normal	Accurate	Extra Accurate
12.700 (1/2)		3.5950×10^{-4}	1.6777×10^{-4}
6.3500 (1/4)	3.6472×10^{-4}	1.8237×10^{-4}	8.5109×10^{-5}
4.7625 (3/16)	2.6971×10^{-4}	1.3487×10^{-4}	6.2939×10^{-5}

FIGURE 5

CENTERLINE SHAPES OF 12.5 mm (1/2 in) HIGH BLADES UNDER TENSION

FIGURE 6

CENTERLINE SHAPES OF 6.4 mm (1/4 in) HIGH BLADES UNDER TENSION

FIGURE 7

CENTERLINE SHAPES OF 4.8mm (3/16 in) HIGH BLADES UNDER TENSION

The figures also show that the maximum deviation of a normal straightness tensioned blade from a chord is in the range $2.5 \mu\text{m}$ (10^{-4} in) to $25 \mu\text{m}$ (10^{-3} in). Currently, no attempt is made to align the blade ends on the cutting plane; the error due to normal straightness blades is likely to be smaller than the error due to misalignment. Therefore, we conclude that normal straightness blade stock can be used without any degradation in the cutting process, saving about 10-15% in the cost of blades. Cutting tests will be performed to check these conclusions.

5.5 Mechanical Wafer Testing

One of the objectives of Phase II is to adequately define the strength of wafers during the cutting operation, under various handling conditions and surface treatments. Preliminary analysis, design of a wafer testing machine, and construction of the machine have nearly been completed.

The silicon wafers are extremely brittle, and as such they obey statistical laws of fracture. We expect that a treatment similar to that of Weibull⁶ will provide an adequate description of fracture strength under various conditions. The parameters of the statistical strength distribution must be determined experimentally.

There is little data on the fracture strength of silicon (e.g., ref. 7), and what little there is has been determined in either tension or three point bending. We have decided, however, to conduct our tests in four point bending for several reasons.

One characteristic of a Weibull fracture distribution is that there is a strong size effect, since fracture strength is assumed to depend on the existence of flaws. It is more probable to find a large flaw in a large part than in a small part. Therefore, parameters derived from tests of parts near the size of the part of interest are more likely to be accurate, since the "extrapolation distance" is small. We, therefore, rejected three point bending because of the small volume subjected to maximum stress.

Tension testing was rejected because of the difficulty in gripping thin, brittle specimens securely and eliminating end effects. We chose four point bending as a test configuration because of the ease of specimen mounting and the comparatively large volume subjected to maximum stress.

The machine consists of a base plate with two knife edges and a crosshead carrying two more knife edges. The crosshead is carried on twin precision lead screws, which are driven by a motor-generator (with 1000:1 speed adjustment) through a precision anti-backlash gear train. The knife edges are designed to test a volume 25.4 mm (1 in) by up to 100 mm (4 in) by specimen thickness. The deflection of the center is sensed by a LVDT. Provisions have been made to mount a load cell if we decide that independent measurements of force and deflection are necessary.

The machine has been completed except for the LVDT mount and the motor control electronics. When the machine is completed, we will test wafers of various thicknesses and surface conditions. Hopefully, we will be able to characterize wafer strengths in order to specify cutting and handling procedures and to correlate damage with strength.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Conclusions of work performed under Phase I of the present contract are:

- MS slicing is capable of converting 10 cm diameter silicon ingot into 0.25 mm thickness wafers with 0.20 mm of kerf loss. The yield of $0.95 \text{ m}^2/\text{kg}$ was achieved with over 98% yield and 118 blades cutting simultaneously.
- The use of large numbers of blades requires a loss of wafer yield and accuracy, or an increase in wafer thickness to withstand increased blade misalignment. The misalignment is due to accumulated blade and spacer variations on the order of 0.1 micron for each component.
- MS slicing has been demonstrated to have a wafering add-on cost of $\$40\text{-}\$50/\text{m}^2$ for silicon sheet production. Large scale estimates of the present technique are an add on cost of $\$30\text{-}\$35/\text{m}^2$.
- By using low cost blades and increasing the machine capacity by 3 to 4 times, a slicing add-on cost of less than $\$10/\text{m}^2$ for sheet silicon is anticipated. However, a technique of precise blade alignment must be developed in order to avoid the resulting increase in blade misalignment.
- The most significant aspect of MS slicing is the ability to minimize both slice thickness and kerf loss. At 0.45 mm slice spacing, recently demonstrated, a conversion from ingot to sheet of nearly $1.0 \text{ m}^2/\text{kg}$ makes the 1986 silicon sheet cost goals realistic, if polysilicon and ingot growth developments result in ingot costs of nearly $\$20/\text{kg}$.

7.0 PLANS

Plans for the next three months include:

- Fabricate and test blade alignment device
- Evaluate slurry oils for low cost potential
- Test slurry lifetime characteristics, and test various improvement and enhancement techniques
- Finish preliminary design for large capacity MS saw
- Design and build laboratory saw for small scale slicing experiments
- Test low cost blade materials
- Fabricate and evaluate solar cells from MS slices
- Evaluate surface damage removal techniques

REFERENCES

- 1 S. C. Holden, SLICING OF SILICON INTO SHEET MATERIAL, FOURTH QUARTERLY REPORT, Varian Associates, ERDA/JPL 954374-77/1, March 27, 1977.
- 2 S. C. Holden, SLICING OF SILICON INTO SHEET MATERIAL, THIRD QUARTERLY REPORT, Varian Associates, ERDA/JPL 954374-76/4, December 27, 1976.
- 3 G. B. Thomas, CALCULUS AND ANALYTIC GEOMETRY, 3rd Edition, Addison-Wesley, 1966.
- 4 F. B. Hildebrand, ADVANCED CALCULUS FOR APPLICATIONS, Prentice-Hall, 1962.
- 5 B. Carnahan, H. A. Luther, J. O. Wilkes, APPLIED NUMERICAL METHODS, Wiley & Sons, 1969.
- 6 W. Weibull, A STATISTICAL THEORY OF THE STRENGTH OF MATERIALS, Ingeniör Vetenskaps Akademiens Handlingar, 151, (1939).
- 7 W. D. Sylwestrowicz, MECHANICAL PROPERTIES OF SINGLE CRYSTALS OF SILICON, Phil. Mag. 1, 1825 (1962).

APPENDIX I
(Phase I)

- Man-Hours and Costs
- Program Plan

MAN-HOURS AND COSTS
(Phase I - Complete)

During the reporting period of March 21, 1977 to May 27, 1977 (Phase I completion date), total man-hours were 512.7 hours and total costs were \$12,839. Previous expenditures were 4,064.1 hours and \$136,779. Final program man-hours were 4,576.8 hours and \$149,618 for Phase I of the contract.

SLICING OF SILICON INTO SHEET MATERIALS

Varian Associates
Lexington Vacuum Division
JPL Contract No. 954374
Starting Date: 1/9/76

Program Plan
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1. Background Parameter Study
 - 1.1. Establish standardized cutting format and data collection technique
 - 1.2. Modify saw, measure accuracy, build dynamometer
 - 1.3. Slicing tests - effects of load, speed, slurry, work configuration on rate, wear, wafer accuracy, etc.
 - 1.4. Wafer characterization
2. Theoretical Model
 - 2.1. Parameterize system performance from modified abrasive wear viewpoint
 - 2.2. Establish practical limits to theory - wafer accuracy and thickness, blade instability, abrasive blunting, etc.

Sch 1/22/76
Updated 6/17/77

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7. Evaluation

7.1. Cutting tests with final system

7.2: Economic evaluation, scale-up potential

7.3. Wafer characterization

8. Milestones

Sch 2/13/76
Updated 6/17/77

Achieve .010 Wafers
Evaluate $\langle 111 \rangle$ and $\langle 100 \rangle$ Slicing

Determine Surface Damage Characteristics
.010 Cutting Rate (Best Technique)
Achieve .005 Wafers

Max. Rate, Thin Wafers, Low Kerf Loss
Blade Package Assembly Technique

NOTE: In addition to the above Program Plan, the Lexington Vacuum Division of Varian Associates will attend the required meetings and deliver the required documentation and samples as per JPL Contract No. 954374.

SLICING OF SILICON INTO SHEET MATERIAL

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Updated 6/17/77

TOTAL HOURS: 4,260 PLANNED HOURS
HOURS TO DATE: 4576.8 INCURRED HOURS

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PROGRAM LABOR SUMMARY

SLICING OF SILICON INTO SHEET MATERIALS

Varian Associates
Lexington Vacuum Division
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PROGRAM COST SUMMARY

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APPENDIX II
(Phase II)

- Man-Hours and Costs
- Program Plan (Updated)

MAN-HOURS AND COSTS

(Phase II)

For the reporting period of May 19, 1977 (start of Phase II) to June 17, 1977, total program man-hours were 558.0 hours and total program costs were \$50,256. There were no previous expenditures for Phase II of the contract.

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
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SLICING OF SILICON INTO SHEET MATERIAL

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SLICING OF SILICON INTO SHEET MATERIAL

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SLICING OF SILICON INTO SHEET MATERIAL

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SLICING OF SILICON INTO SHEET MATERIAL

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SLICING OF SILICON INTO SHEET MATERIAL

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Phase II
Program Plan
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PROJECT MILESTONES (PHASE II)	1977								1978												1979					
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
REPORTS																										
Financial Package		▼	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽
Monthly Technical Progress		▼		▽	▽		▽	▽		▽	▽		▽	▽		▽	▽		▽	▽		▽	▽		▽	
Quarterly Technical Progress			▼			▽		▽			▽			▽			▽			▽			▽			
Interim Summary																										
Draft Final Report																									▽	
Final Report																									▽	
TRAVEL																										
Project Integration Meetings				▽			▽		▽			▽			▽			▽			▽			▽		
MAJOR EQUIPMENT																										
2 Test Saws	▼																									
Wafer Measuring Station	▼																									
Silicon Purchases		▽						▽						▽												

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division.

JPL Contract 954374

Starting Date: 1/9/76 (I) 5/19/77 (II)

Phase II

Program Plan

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PROGRAM LABOR SUMMARY

SLICING OF SILICON INTO SHEET MATERIAL

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Phase II
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PROGRAM COST SUMMARY

APPENDIX III

Engineering Drawings and Sketches

200 PITCH CUTTER ON .018-.016 CENTERS

200 PITCH ON STD. CENTERS

14 1/2° PRESSURE ANGLE

200 PITCH ON .018-.016 CENTERS

200 PITCH STD CENTERS

20° PRESSURE ANGLE

30° PRESSURE ANGLE .020 TOOTH SPACING

RACK TOOTH SPACING LAYOUT

NOTE- TOOTH TO TOOTH TOLERANCE .000
 ACCUMULATED IN 6.00" .00
 TO BE MADE IN SETS OF 4 AND MARKED
 CLEARLY TO KEEP IN SETS

BLADE ALIGNMENT FIXTURE

RACKS # I, II, III & IV TO BE LOCATED AS SHOWN
& BROUGHT INTO POSITION USING ADJUSTING SET SCREWS

RACK & RACK ADAPTERS (BLADE ALIGNMENT)

$$X_{nI}, X_{nII}, X_{nIII}, X_{nIV} = 0.020 \pm 0.001$$

FOR 1" TOOTH ALL FOUR RACKS TO BE IDENTICAL

$$X_n I + X_n II + X_n III + X_n IV \approx .0001 \quad (\text{Achieved By Cutting Four Packs Simultaneously})$$

No. OF TEETH

MAT'L-

RACK- (BLADE ALIGNMENT)

(4 REQ'D)

RACK SPACER (BLADE ALIGNMENT)

RACK ADAPTERS (BLADE ALIGNMENT)