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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

By
S. C. Holden
J. R. Fleming

January 12, 1978

Work Performed Under Contract No. NAS-7-100-954374

Varian Associates
Lexington Vacuum Division
Lexington, Massachusetts

U.S. Department of Energy

Solar Energy

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Cost Silicon Solar Array Project

SEVENTH QUARTERLY REPORT

By

S. C. HOLDEN
J. R. FLEMING

January 12, 1978

Reporting Period September 19, 1977 to December 17, 1977

JPL Contract No. 954374

Varian Associates
Lexington Vacuum Division
121 Hartwell Avenue
Lexington, Massachusetts 02173

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1.0 SUMMARY

During the past quarter fabrication was begun on a prototype large capacity multiple blade slurry saw. Final concept and design is nearly complete on the bladehead which will tension up to 1000 blades, and cut a 45 cm long silicon ingot as large as 12 cm in diameter. The large blade tensioning force of 270,000 kg (600,000 lbg) will be applied through two bolts acting on a pair of scissor toggles, significantly reducing operator set-up time.

Poor wafering yields have caused concern in recent tests with MS slicing. The cause for poor yield, namely perimeter fracture of slices, also impacts the solar cell production yield of 10 cm diameter thin (250-350 μ) silicon slices. Recent tests with an "upside-down" cutting technique has resulted in 100% wafering yields and the highest wafer accuracy yet experienced with MS slicing.

Variations in oil and abrasive have resulted only in degraded slicing results. A technique of continuous abrasive slurry separation to remove silicon debris is described.

2.0 INTRODUCTION

Phase II of an effort by Varian to reduce the cost of multiblade slurry wafering of silicon for 1982 silicon sheet production cost goals involves construction of a large scale prototype MS wafering saw and numerous test programs to reduce the costs and improve the capabilities of the MS technique.

The standard form of the MS wafering technique has been shown to have cost effective potential for low cost solar array production. However, improvements in the technique cannot yet be formulated from basic understanding of the fundamental cutting technology. Recent experience has demonstrated that a more complete technical perception must be gained in order to effectively develop improvements.

An example of this dilemma is the lack of success of the multiple blade alignment device. It was felt that improved blade alignment with this method would result in significant process improvements. However, to date, no major improvements have been seen. A major objective of the next quarter will be to review the current technology understanding in light of recent results and formulate a modified approach.

3.0 CUTTING TESTS AND WAFER CHARACTERIZATION

Table 1 shows a summary of all MS slicing tests during this quarter. A severe reduction in slice yield has occurred during the second phase of this program. The slices which do survive the slicing operation have occasional cracks in the perimeter. The source of these cracks has not been explained or resolved despite efforts to modify slurry application, improvements in machine alignment and other changes. The one exception has been the upside down cutting tests where 100% yield was experienced.

It must be noted that most tests involve very thin slicing of 10 cm silicon wafers where a borderline survival condition may exist. Also wide variations in composition of the abrasive slurry has been explored and failures are not surprising.

3.1 Slurry/Oil Tests

The object of this series of cutting tests is to explore the use of lower cost abrasive mixtures in MS slicing. Broader particle size distributions may have effective cost leverage since fine gradations are more difficult to achieve. Oil tests are preliminary to tests involving oil viscosity and settling rate. This would indicate proper parameters for use with lower cost of recycled oils.

3.1.1 Mixed Abrasive: Test #2-3-05

For this test, the abrasive consisted of equal parts of #600 and #800 SiC. Other conditions were standard. This test was to investigate both reduction of kerf with mixed abrasive and the effect of the amount of spread in particle sizes.

Efficiency, abrasion rate, productivity and kerf loss were normal. The yield was very low, only 29%. Slice taper and bow could not be measured since the wafers activated the out-of-range warning on the measuring device.

TABLE I
SLICING TEST SUMMARY

PARAMETER	TEST	2-3-06	2-3-07	2-3-08	2-3-09
Material		100 Si	100 Si	100 Si	100 Si
Size	(mm)	100	100	100	100
Area/Slice	(cm ²)	78.54	78.54	78.54	78.54
Blade Thickness	(mm)	0.15 x 6.35	0.15 x 6.35	0.15 x 6.35	0.15 x 6.35
Spacer Thickness	(mm)	0.36	0.36	0.36	0.36
Blade Height	(mm)	6.4	6.4	6.4	6.4
Number of Blades		270	131	150	136
Load	(gram/blade)	85	85	85	85
Sliding Speed	(cm/sec)	63.76		61.15	64.44
Abrasive	(type/grit size)	#600 SiC	#600/800/ 1000 SiC	#600/800/ 1000 SiC	#600 SiC
Oil Volume	(liters)	7.6 Lub.	7.6 PC	7.6 PC	7.6 Lub.
Mix	(kg/liter)	0.24	0.18 Total	0.36 Total	0.12
Slice Thickness	(mm)	0.292		0.320	0.304
Kerf Width	(mm)	0.216		0.188	0.204
Abrasive Kerf Loss	(mm)	0.064		0.038	0.052
Cutting Time	(hours)	34.25	23.20	44.10	36.20
Efficiency	(full test)	0.93		0.656	0.81
	(typical)	1.15		0.812	1.06
	(maximum)	1.27		0.939	1.28
Abrasion Rate	(full test)	.050		.034	.044
(cm ³ /hr/bl)	(typical)	.062		.042	.058
	(maximum)	.069		.049	.070
Productivity	(full test)	2.29	3.39	1.78	2.17
(cm ² /hr/bl)	(typical)	2.87		2.23	2.84
	(maximum)	3.19		2.60	3.43
Yield		52/269 19%	4/130 3%	17/149 11%	16/135 12%
Slice Taper	(mm)	.065		.101	.078
Slice Bow	(mm)	.054		.107	.168
Abrasive Utilization	(cm ³ /kg)	251.3		81.1	239.2
Oil Utilization	(cm ³ /liter)	60.3		29.2	28.7
Blade Wear Ratio	(cm ³ /cm ³)	.054		.067	.064

TABLE I
(continued)

SLICING TEST SUMMARY

PARAMETER	TEST	2-3-10	2-4-04	2-4-05	2-5-03
Material		100 Si	100 Si	100 Si	100 Si
Size	(mm)	100	100	100	100
Area/Slice	(cm ²)	78.54	78.54	78.54	78.54
Blade Thickness	(mm)	0.15 x 6.35	0.15 x 6.35	0.20 x 6.35	0.15 x 6.35
Spacer Thickness	(mm)	0.41	0.41	0.41	0.41
Blade Height	(mm)	6.4	6.4	6.4	6.4
Number of Blades		131	271	78	125
Load	(gram/blade)	85	85	113.4	113.4
Sliding Speed	(cm/sec)		65.3	61.14	65.73
Abrasive	(type/grit size)	#600 SiC	#600 SiC	#600 SiC	#600 SiC
Oil Volume	(liters)	7.6 Lub.	7.6	7.6 PC	7.6 PC
Mix	(kg/liter)	0.06	0.36	0.48	0.48
Slice Thickness	(mm)		0.322	0.333	0.341
Kerf Width	(mm)		0.237	0.277	0.269
Abrasive Kerf Loss	(mm)		0.087	0.074	0.069
Cutting Time	(hours)	44.55	26.55	36.50	25.05
Efficiency	(full test)		1.25	0.87	1.13
	(typical)		1.53	1.42	1.30
	(maximum)		1.733	1.85	1.66
Abrasion Rate	(full test)		.069	.060	0.084
(cm ³ /hr/bl)	(typical)		.085	.098	0.097
	(maximum)		.096	.128	0.123
Productivity	(full test)	1.76	2.91	2.15	3.14
(cm ² /hr/bl)	(typical)		3.59	3.54	3.61
	(maximum)		4.06	4.62	4.58
Yield		5/130 4%	78/270 29%	42/77 55%	124/124 100%
Slice Taper	(mm)		0.044	.066	0.044
Slice Bow	(mm)		0.046	.057	0.030
Abrasive Utilization	(cm ³ /kg)		184.2	46.5	72.3
Oil Utilization	(cm ³ /liter)		66.3	22.3	34.7
Blade Wear Ratio	(cm ³ /cm ³)		.052		0.048

TABLE I
(continued)
SLICING TEST SUMMARY

PARAMETER	TEST	2-5-04	2-5-06	2-6-01	2-6-02
Material		100 Si	100 Si	100 Si	100 Si
Size	(mm)	100	100	100	100
Area/Slice	(cm ²)	78.54	78.54	78.54	78.54
Blade Thickness	(mm)	0.15 x 6.35		0.15 x 6.35	0.15 x 6.35
Spacer Thickness	(mm)	0.41		0.36	0.36
Blade Height	(mm)	6.4		6.4	6.4
Number of Blades		136		150	138
Load	(gram/blade)	85		127.6/85	85
Sliding Speed	(cm/sec)	65.21		63.42	
Abrasive	(type/grit size)	#600 SiC		#600 SiC	#600 SiC
Oil Volume	(liters)	7.6 PC		7.6 PC	7.6 PC
Mix	(kg/liter)	0.36		0.36	0.24
Slice Thickness	(mm)	0.330		0.287	0.300
Kerf Width	(mm)	0.229		0.221	0.208
Abrasive Kerf Loss	(mm)	0.076		0.068	0.056
Cutting Time	(hours)	65.55		22.55	12.35
Efficiency	(full test)	0.49		1.15	
	(typical)	1.33		1.59	
	(maximum)	2.06		2.00	
Abrasion Rate	(full test)	.027		.077	
(cm ³ /hr/bl)	(typical)	.073		.107	
	(maximum)	.114		.134	
Productivity	(full test)	1.20		3.48	
(cm ² /hr/bl)	(typical)	3.19		4.84	
	(maximum)	4.98		6.06	
Yield		96/135 71%		120/149 81%	0/137 0%
Slice Taper	(mm)	.090		.075	
Slice Bow	(mm)	.137		.020	
Abrasive Utilization	(cm ³ /kg)	89.4		95.3	
Oil Utilization	(cm ³ /liter)	32.2		34.3	
Blade Wear Ratio	(cm ³ /cm ³)	.048		.054	

TABLE I
(continued)

SLICING TEST SUMMARY

PARAMETER	TEST	2-6-03	2-6-04		
Material		100 Si	100 Si		
Size	(mm)	100	100		
Area/Slice	(cm ²)	78.54	78.54		
Blade Thickness	(mm)	0.15 x 6.35	0.15 x 6.35		
Spacer Thickness	(mm)	0.36	0.36		
Blade Height	(mm)	6.4	6.4		
Number of Blades		150	150		
Load	(gram/blade)	85	85		
Sliding Speed	(cm/sec)	63.24	62.23		
Abrasive	(type/grit size)	#600 SiC	#600 SiC		
Oil Volume	(liters)	7.6 PC	7.6 PC		
Mix	(kg/liter)	0.36	0.36		
Slice Thickness	(mm)	0.274	0.267		
Kerf Width	(mm)	0.234	0.241		
Abrasive Kerf Loss	(mm)	0.082	0.091		
Cutting Time	(hours)	28.20	30.50		
Efficiency	(full test)	1.21	1.16		
	(typical)	1.64	1.75		
	(maximum)	1.91	2.09		
Abrasion Rate	(full test)	.065	.061		
(cm ³ /hr/bl)	(typical)	.088	.092		
	(maximum)	.102	.110		
Productivity	(full test)	2.79	2.53		
(cm ² /hr/bl)	(typical)	3.76	3.82		
	(maximum)	4.36	4.56		
Yield		80/149 54%	99/149 66%		
Slice Taper	(mm)	.060	.079		
Slice Bow	(mm)	.059	.086		
Abrasive Utilization	(cm ³ /kg)	100.8	103.9		
Oil Utilization	(cm ³ /liter)	36.3	37.4		
Blade Wear Ratio	(cm ³ /cm ³)	.046	.047		

TABLE 2

WAFER THICKNESS CHARACTERIZATION SUMMARY

PARAMETER	TEST	2-3-06	2-3-07	2-3-08	2-3-09
SLICE	Diameter (mm)	100	100	100	100
	Area (cm ²)	78.5	78.5	78.5	78.5
THICKNESS	Average μ	292.1		319.5	303.7
	Std. Dev. μ	39.7		34.0	38.0
TOTAL VARIATION	Average μ	60.4		58.9	57.6
	Std. Dev. μ	21.2		18.3	37.0
STD. DEVIATION	Average μ	23.8		20.8	20.4
	Std. Dev. μ	8.7		7.2	15.8
VERTICAL TTV	Average μ	65.4		100.8	78.2
	Maximum μ	111.9		140.6	226.7
	Minimum μ	32.9		79.1	45.6
HORIZONTAL TTV	Average μ	18.6		26.4	17.5
	Maximum μ	38.3		35.7	46.8
	Minimum μ	6.2		18.1	7.0
VERTICAL BOW	Average μ	52.6		118.0	159.0
	Maximum μ	117.6		161.0	173.5
	Minimum μ	18.4		70.9	144.7
HORIZONTAL BOW	Average μ	63.9		41.7	30.7
	Maximum μ	86.2		64.2	50.9
	Minimum μ	24.0		26.7	12.6
VERTICAL CL BOW	Average μ	108.7		214.1	335.3
	Maximum μ	209.7		365.2	392.3
	Minimum μ	38.6		81.2	171.9
HORIZONTAL CL BOW	Average μ	139.4		70.1	43.3
	Maximum μ	195.2		107.6	65.4
	Minimum μ	40.2		20.5	27.8

TABLE 2
(continued)

WAFER THICKNESS CHARACTERIZATION SUMMARY

PARAMETER	TEST	2-3-10	2-4-04	2-4-05	2-5-03
SLICE	Diameter (mm)	100	100	100	100
	Area (cm ²)	78.5	78.5	78.5	78.5
THICKNESS	Average μ		322	332.6	341.1
	Std. Dev. μ		21.7	21.7	21.0
TOTAL VARIATION	Average μ		35.6	63.8	35.1
	Std. Dev. μ		23.3	19.7	14.9
STD. DEVIATION	Average μ		13.7	24.6	13.3
	Std. Dev. μ		10.2	7.8	6.3
VERTICAL TTV	Average μ		44.0	65.9	44.3
	Maximum μ		137.2	102.1	72.5
	Minimum μ		17.4	34.3	21.8
HORIZONTAL TTV	Average μ		9.0	15.3	11.5
	Maximum μ		17.7	34.3	18.5
	Minimum μ		1.9	6.6	4.3
VERTICAL BOW	Average μ		36.6	56.8	36.1
	Maximum μ		109.0	95.8	70.6
	Minimum μ		11.5	30.09	16.1
HORIZONTAL BOW	Average μ		15.7	53.4	24.1
	Maximum μ		30.8	101.0	35.7
	Minimum μ		6.5	8.7	5.5
VERTICAL CL BOW	Average μ		91.7	113.3	60.3
	Maximum μ		306.9	164.4	102.3
	Minimum μ		15.9	81.3	31.6
HORIZONTAL CL BOW	Average μ		29.2	109.7	48.7
	Maximum μ		55.3	203.8	74.3
	Minimum μ		8.6	19.4	14.9

TABLE 2
(continued)

WAFER THICKNESS CHARACTERIZATION SUMMARY

PARAMETER	TEST	2-5-04	2-5-06	2-6-01	2-6-02
SLICE	Diameter (mm)	100	100	100	100
	Area (cm ²)	78.5	78.5	78.5	78.5
THICKNESS	Average μ	330.1		287.4	299.7
	Std. Dev. μ	18.4		35.8	22.7
TOTAL VARIATION	Average μ	61.1		56.9	25.1
	Std. Dev. μ	13.9		23.7	17.8
STD. DEVIATION	Average μ	23.0		21.9	12.7
	Std. Dev. μ	5.2		9.5	7.6
VERTICAL TTV	Average μ	90.3		75.4	
	Maximum μ	122.7		162.5	
	Minimum μ	50.6		30.2	
HORIZONTAL TTV	Average μ	12.7		14.6	
	Maximum μ	22.9		36.3	
	Minimum μ	6.4		4.9	
VERTICAL BOW	Average μ	119.5		31.9	
	Maximum μ	142.3		68.0	
	Minimum μ	46.8		12.8	
HORIZONTAL BOW	Average μ	16.5		29.3	
	Maximum μ	24.1		42.4	
	Minimum μ	8.2		13.0	
VERTICAL CL BOW	Average μ	274.0		80.4	
	Maximum μ	344.1		129.0	
	Minimum μ	95.9		28.9	
HORIZONTAL CL BOW	Average μ	38.8		66.4	
	Maximum μ	68.1		84.3	
	Minimum μ	13.8		15.1	

TABLE 2
(continued)

WAFER THICKNESS CHARACTERIZATION SUMMARY

PARAMETER	TEST	2-6-03	2-6-04		
SLICE	Diameter (mm)	100	100		
	Area (cm ²)	78.5	78.5		
THICKNESS	Average μ	273.6	267		
	Std. Dev. μ	18.4	28.8		
TOTAL VARIATION	Average μ	45.9	61.8		
	Std. Dev. μ	22.5	21.1		
STD. DEVIATION	Average μ	16.8	24.2		
	Std. Dev. μ	9.1	9.5		
VERTICAL TTV	Average μ	60.1	78.6		
	Maximum μ	127.4	121.9		
	Minimum μ	32.0	34.9		
HORIZONTAL TTV	Average μ	7.8	13.6		
	Maximum μ	20.4	27.7		
	Minimum μ	2.2	4.0		
VERTICAL BOW	Average μ	51.5	85.1		
	Maximum μ	73.3	157.4		
	Minimum μ	26.6	19.4		
HORIZONTAL BOW	Average μ	18.4	21.0		
	Maximum μ	38.9	47.3		
	Minimum μ	7.2	2.5		
VERTICAL CL BOW	Average μ	117.0	172.2		
	Maximum μ	157.3	397.3		
	Minimum μ	45.7	64.9		
HORIZONTAL CL BOW	Average μ	40.7	40.9		
	Maximum μ	70.8	93.1		
	Minimum μ	19.6	7.0		

The results of this test were encouraging in terms of using potentially cheaper abrasive, but controlled cutting conditions were not achieved. Cause of the low yield must be established.

3.1.2 Light Mix Lubrizol: Test #2-3-06

Since Lubrizol 5985 oil had not performed well under the same conditions as the standard slurry oil, we decided to vary the abrasive mix. Feeling that Lubrizol may provide a higher effective mix at the cutting interface due to the higher suspension power and lower viscosity, we decided to reduce the amount of abrasive.

For this test, the mix was 0.24 kg/l (2 lb/gal) and conditions were standard (0.15 mm blades, 85 grams/blade loading). Efficiency, abrasion rate, and productivity were slightly low. Cutting time was longer than usual, and kerf loss was high. Yield was only 19%. Slice taper and bow were slightly high.

We felt that since a slight improvement over previous tests was noted in the early stages of this test, we were going in the right direction.

3.1.3 Mixed Abrasives: Test #2-3-07

Continuing the effort to lower the price of abrasive by using a broader spectrum of particle sizes, a slicing test was made using equal parts of #600, #800 and #1000 grits. Cutting force, cutting speed, ingot size, and suspension oil were standard. 0.15 mm x 6.35 mm blades with 0.40 mm spacers were used. An error was made in slurry mixing: only half the desired amount of abrasive was mixed, so the overall abrasive mix was 0.18 kg/l.

Cutting time was good, 23.2 hours. However, severe slice breakage occurred and the yield was only 3%. The blades, again, showed anomalous side wear, up to 1/3 the total thickness. The appearance of side wear may indicate that a wafer breakage is caused by a machine problem, although no measurements have supported this.

3.1.4 Mixed Abrasives: Test #2-3-08

In an attempt to reduce kerf loss and abrasive cost, a standard condition run was made using equal parts of #800, #1000 and #1200 grit abrasive.

Again, yield was very low (11%). Cutting time was long (about 44 hours) as before with #800 grit slurry. Kerf loss was slightly reduced: bow and taper were somewhat large. The mixture of #800 and smaller abrasives does not seem to offer any improvement over #800 alone.

3.1.5 Light Mix Lubrizol: Test #2-3-09

Continuing the trend of Test #2-3-06, a run was made at a mix of 0.12 kg/l (1 lb/gal). All other conditions were standard.

Kerf loss was reduced. Slice taper was increased slightly and slice bow increased significantly. All other measurements were comparable to Test #2-3-06. Yield was only 12%.

The low yield and high taper and bow were partly a result of blade breakage and wear. The blades were worn on the side by approximately 1/3 the thickness. The ratio of the number of blades worn on one side to the number worn on the other side was 10:1, indicated some asymmetry in the cutting process. This amount of wear

is unprecedented in cutting any material in any condition. We cannot yet give a good reason for this wear. However, the early stages of cutting appeared quite good. It is possible that the abrasive was limiting the slurry life at the end of the cut. However, it appears that light mix was the correct approach for standard Lubrizol.

3.1.6 Light Mix Lubrizol: Test #2-3-10

In order to find the point at which a Lubrizol slurry has too little abrasive, and to investigate the side wear problem, a test was run with a 0.06 kg/l ($\frac{1}{2}$ lb/gal) mix. Yield was so low (4%) that only cutting time could be measured. The cutting time increased significantly. This has always been a good indication that the total amount of abrasive was too little; thus, it seems that a heavier mix is necessary with Lubrizol.

The high side wear occurred again. Measurements were made during the cut with the following results. At $\frac{1}{4}$ of the cut depth, side wear could not be measured; at $\frac{1}{2}$ the cut depth, side wear was 0.05 times the blade thickness; at the end of the cut the side wear was $\frac{1}{3}$ of the blade thickness.

These results indicate that the side wear is due to some effect which changes during a cut, perhaps the geometric changes due to the round cross-section of the ingot or abrasive breakdown due to the small amount of abrasive used. Although Lubrizol with a light mix is economically attractive, we cannot use it until we resolve the side wear question. It still remained that the early cutting was better controlled and breakage occurred after $\frac{1}{3}$ of the ingot has been cut.

3.2 Cell Fabrication: Test #2-4-04

Three hundred 0.15 x 6.4 mm blades with .41 mm spacers were used to cut a 10 cm silicon ingot for surface preparation and cell fabrication studies. Cutting time was 28 hours, but yield was only 29%. Slice thickness was .322 mm and kerf loss was 0.237 mm. Slice breakage during the cutting process and poor yield with thin slices continues to plague this phase of the program.

3.3 Miscellaneous Slicing Techniques

3.3.1 Upside Down Cutting: Test #2-5-03

To determine the characteristics of slurry ingress to the blades during MS slicing, a special work holding fixture was installed on a standard Varian 686 MS saw to allow "upside-down" cutting of a 10 cm silicon ingot. 150 0.20 x 6.4 mm blades and 0.41 mm spacers were used with 113 grams of blade load. 0.48 kg/liter of #600 SiC was used as a slurry with "pulse-type" application to either side of the ingot.

Cutting time was 26.1 hours, yield was 100% and the bow and taper of the 10 cm slices was 36 and 44 microns respectively. Indeed the cutting process proceeded well in this mode and the slice accuracy was the best seen to date.

The work-holder tended to loosen and rock slightly at the end of each bladehead stroke due to the direction of loading in this cutting mode. For this reason a new test was scheduled to eliminate the rocking motion which may have cushioned the cutting shock to wafers and been responsible for the improvements noted.

3.3.2 Constant Pressure Cutting: Test #2-5-04

It was assumed that the cutting pressure at the blade/silicon interface was important to controlled abrasion and that variations in pressure due to ingot cross-section (at constant load) might cause some of the bow/taper variations seen in MS slices. Cutting force was varied to maintain constant pressure with the maximum load being 113 grams per blade. 136 0.15 mm blades and 0.41 mm spacers were used. In order to suppress wafer fracture, a thin coating of epoxy was used on the perimeter of the ingot. The epoxy slowed the cut so severely during the early and late portion of the test that the overall slicing time was 63 hours. Yield was 71% and the edge chipping seen in the past did not occur. The coating disturbs the cutting process so severely, however, that an alternate will be sought. Wafer accuracy in the vertical direction was degraded, but in the horizontal direction, it was greatly improved.

3.3.3 Upside Down Cutting: Test #2-5-06

A second upside down cut was run to isolate the effect of the upside down mode from that of the rocking work-holder experienced in test #2-5-03. A rigid work-piece mount was used and cutting went very well until half way through the ingot when the workpiece broke loose from the submount. This experience was sufficient to show that the reversal of gravity on the action of slurry was the useful improvement with this technique.

3.4 Alignment Device Tests

This series tests a device designed to improve the alignment of a set of multiple blades. The concept considers the possibility of blade misalignment being the limiting condition for thin wafer slicing and the use of thin blades in MS slicing.

3.4.1 Alignment Device: Test #2-6-01

The alignment device was installed onto a package with 150 0.15 mm blades and 0.35 mm spacers. The installation was facilitated by positioning the rack gears into engagement with the blades prior to tensioning. Both end blades were parallel within $2-3\mu$, a distinct improvement over normal blade packages. By adjusting rack gear positions, a vertical runout of ± 3 microns was obtained in the four measurable points at the corners of the blade package. Slurry was a standard mix of 0.36 kg/liter. Total cutting time was 23 hours faster than normal, however, the first half of the ingot was cut with a blade force of 127 grams, rather than 85 grams. Total wafer yield was 81% (120 of 149). Slice thickness averaged 287 microns with a kerf loss of 221 microns. Wafer accuracy was improved over the best cutting accuracy obtained with 0.15 mm blades. However, the difference was not significant to herald success of the alignment device at this point.

3.4.2 Alignment Device: Test #2-6-02

A second test of the alignment device was performed using a different installation technique. The blade package was first measured to assure that its width, after compression, could match the exact spacing of the rack gears. Opposing pairs of spacers were replaced with oversized spacers to

achieve this condition. The package was fully tensioned, and then the width was adjusted by modulating the side compression. The rack gears were easily engaged at this point. All preliminary alignment went as before except that vertical alignment of one side of the package was off vertical by 75-125 μ . This was averaged over that end of the package, but the variation was not correctable since one gear seemed to be longer than the other. The rest was run with 150 0.15 mm blades, 0.35 mm spacers and 85 grams of blade load with a slurry mix of 0.24 kg/liter.

Cutting appeared to go well, but the ingot broke loose from the submount after half of the ingot had been cut. Measurements of the broken wafer pieces indicated 200 microns of kerf loss and 300 micron thick slices. Bow and taper measurements were not meaningful, but the surface profiles were very impressive. Further testing, following this installation technique, will be pursued. Four new sets of gears are expected soon.

3.4.3 Alignment Device: Tests #2-6-03 and #2-6-04

Two cutting tests were performed using the multiple blade alignment device with identical conditions (0.15 x 6.4 mm blades, 0.36 mm spacers, 85 grams/blade loading, 0.36 kg/liter mix of #600 SiC abrasive).

In the first, a set of gears used many times was installed. Blade parallelism was within 3 microns, but vertical alignment was, as in test #2-6-02, out by 60 microns at one end of the pack. Cutting time was 28.3 hours and yield was 53% (10 cm slices). Taper and bow were 50-60 microns average in the vertical direction. Slice thickness was .273 mm with .235 mm kerf loss.

A new set of rack gears was installed for test #2-6-04. Vertical alignment was only within 20-30 microns, but improved over previous tests. Cutting time was 32.3 hours and 66% yield resulted with 10 cm slices. Slice thickness was .267 mm and kerf loss was .241 mm. Bow and taper were not improved (80 microns average).

Since only minor improvements in slice accuracy have resulted from tests with the alignment device, the next step in its test process will be to test it using 300 blades (150 have been used previously) and then with 0.10 mm blades which have suffered from fatigue induced breakage in the past.

4.0 DISCUSSION

4.1 Cell Fabrication

A set of 20 silicon wafers cut on the MS saw was sent to Solar Power Corp. for fabrication into solar cells in their standard commercial processing line. The slices were 10 cm diameter with a nominal thickness of 300 μ . Of the twenty wafers, only 1 survived the complete processing sequence. One was broken in shipment, 7 broke during the boron diffusion step and 11 others broke during other process steps. The remaining cell produced V_{oc} of 0.55V, I_{sc} of 1.68A, maximum power (P max) of 0.67W and a fill factor of 0.725 at 100 mw/cm² illumination and 28°C. This represents an efficiency based on full wafer area of 8.53%, (8.97% based on 9.75 cm diameter applied cell area). Since the potting compound acts as part of the AR coating system for Solar Power's cells, the performance cited above is expected to improve by 10% in a completed panel. Therefore, the efficiency of this cell may be characterized as 9.4% based on the 10 cm wafer or 9.9% based on the size of the active cell applied.

4.2 Lab Saw

Because of the complete change of design necessary in the laboratory saw, the fabrication of that unit will be delayed the next quarter. The small number of blades requires a new concept of feed mechanism to apply the small loads required. The blades will be adjustable from 10 inches to 22.5 inches in length, requiring a new, longer bladehead, a longer waybed and an adjustable position drive system. The bladehead has been completed during this reporting period. The waybed was ordered in September and delivery was slow. These two have been subcontracted for machine work, and grinding and expected delivery of mid-December was not met. Drawings for the lab saw are shown in Appendix I in the S-2000 series.

4.3 Prototype Large Capacity MS Saw

Basic mechanical design for the 1000 blade capacity multi-blade slurry wafering saw is complete and fabrication began during this quarter. The machine is designed to slice a 45 cm long silicon ingot with up to 1000 blades of 0.15 x 12.7 mm cross-section. The blade tensioning capacity is 270,000 kg (600,000 lb). The basic design concept is a modification of the underslung reciprocating workholder carriage described in the previous report. Gravity is utilized to protect sliding members from the abrasive slurry. Drawings for the prototype are shown in Appendix I in the S-1000 series.

The bladehead tensioning is accomplished with two clamping elements spread apart by a pair of closing scissors. Design for the system indicates that a torque of 35 kg-m (250 ft. lbs) must be applied to each of two scissor closing bolts in order to apply 270,000 kg of tensioning force. Final bladehead design will be completed soon after the first of the year.

4.4 Investigation of Suspension Media

We are investigating the possibilities of using various oil or water bases suspension media for slurry sawing. To date, most of the research has concentrated on oil based suspensions, since few water based suspensions are manufactured and we do not know the optimum characteristics of such media. (Manufacturers of water based media are being contacted.) We are currently working with our standard suspension oil (PC oil) and a new oil manufactured by the Lubrizol Corporation (Lubrizol 5985).

Attempts to use 5985 have been disappointing. The best results so far have been obtained using 1/3 the amount of abrasive normally used in PC oil (0.36 kg/l). A portion of the wafer breakage problems may be traced to machine problems (poor yield in standard cutting tests), but this condition is yet to be certainly corrected. It is possible that some wafer breakage was due to abrasive failure, abrasive settling, or some other mode of failure, all due to the small amount of abrasive in the system. When we are sure the machine faults have been corrected, we will retest 5985 with a low abrasive mix: this combination is attractive because the cost approaches the \$3.00/m² slurry cost goal.

In the meantime, we are carrying out a more structured investigation of the two suspension oils. The first steps have been consideration of important differences and characterization of the two oils.

4.4.1 Comparison of 5985 and PC

The major differences between 5985 and PC are:

1. Different suspension power (5985 holds abrasive in suspension longer).
2. Viscosity (5985 is less viscous).
3. Suspension method (5985 uses a dissolved polymer, PC uses colloidal clay platelets).

We feel that the suspension method does not affect the cutting process significantly (although it may affect reclamation).

It seems likely that the suspension power and/or viscosity affect the cutting process through abrasive transport. The cutting process is controlled not by the actual abrasive mix but rather by the "effective mix" (i.e., a measure of the number of active particles at the cutting interface). Greater suspension power and/or lower viscosity might well increase the effective mix by transporting particles to the cutting interface more efficiently.

The first step in our systematic investigation must be to identify the important variables. In order to demonstrate that viscosity and/or suspension power are the important variables, we intend to mix mineral oil with 5985 or the 5985 polymer additive to match PC as closely as possible. If this mixture behaves like PC, that will show that only viscosity and/or suspension power are important. Once we have identified the important variables, we can vary them systematically and independently to ascertain their effects and relative importance.

4.4.2 Characterization of Oils

The viscosities of both oils were measured using a Brookfield LVF viscometer with the #2 cylindrical spindle. The samples were 550 ml of the test fluid in a 600 ml Griffin low form beaker (K1max #14000). The spindle-beaker combination were calibrated with silicone oil viscosity standards (92 cps $\pm 1\%$ and 505 cps $\pm 1\%$). The temperature was $25^\circ \pm 1^\circ\text{C}$ in all tests. The results are presented in Figure 1 and discussed below.

Suspension power was measured by static settling tests. 50 g of PC, 5985, or 5985 cut with 130 cps mineral oil were mixed with 20.85 g of #600 SiC (corresponding to a standard PC mix: note that the specific gravity of all the oils ranges from 0.89 to 0.91). These mixtures were shaken and allowed to stand until significant settling took place.

PC oil is a thixotropic fluid: the viscosity depends on both strain rate and history. The viscosity decreases asymptotically with time at a given strain rate. This is not surprising, since the clay platelets probably line up as shearing proceeds. The viscosities in Figure 1 are asymptotic viscosities.

PC settles by loss of suspension power. Both the platelets and abrasive settle, so that a clear oil area forms at the top, with a homogeneous mixture of abrasive and platelets below.

Lubrizol 5985 is a psuedo-plastic fluid (on the time scale investigated): the viscosity depends only on strain rate. Only the abrasive settles out: larger abrasive particles settle faster, so a three-layer structure forms: a thin layer of oil and suspension agent above a region of oil, suspension agent, and fine abrasive particles above a cake of fully settled particles.

It is essentially impossible to match 5985 and PC by diluting 5085. Consideration of Figure 1 shows that the viscosities can be matched at all strain rates by diluting 5985 with carefully tailored psuedo-plastic fluid (a difficult job !)*. We do not know if the thixotropic nature of PC is important. However, it seems that a reasonable viscosity

* The strain rate in MS slicing varies during each stroke from 0 to approximately 10^5 sec^{-1} , with an average value of $5 \times 10^4 \text{ sec}^{-1}$.

FIGURE 1 VISCOSITY OF SUSPENSION OILS

match may be obtained by mixing 5985 with a mineral oil chosen to give a viscosity of around 250 cps at 12.5 sec^{-1} .

Matching suspension power is also difficult because 5985 forms a cake at the bottom and PC does not. On the basis of clear top area, it appears that a mixture of 40-45% 5985 matches PC best.

4.5 Slurry Reclamation

Earlier reports stated that the failure mechanism of slurry appears to be debris accumulation. We have been investigating the possibilities of several methods of separating the components of used slurry for reuse. In the last quarter, sufficiently encouraging replies have been received from manufacturers so that we feel able to discuss possible mechanisms of reclamation.

There are many problems which make the separation of slurry components difficult. The abrasive nature of the slurry could lead to excessive separating machine wear. The large solid volume could lead to clogging. The oil is designed to keep the solids in suspension.

We currently envision a two-stage separation process. In the first stage, the majority of the oil would be removed, leaving a Si/SiC sludge. If the oil were PC, the separated oil would probably have little or no suspension power since the clay platelets would be left in the sludge. If the oil were LZ 5985 or an equivalent, the separated oil would probably still contain dissolved polymer and the suspension characteristics would be at worst slightly degraded. With the suspension oil removed, separation of silicon and silicon carbide would be easily done in the second stage.

The most promising oil separation device is the Mott Inertial Filter, manufactured by Mott Metallurgical Corporation, Farmington, CT. The filtration element consists of a sintered stainless steel tube, sintered under little or no pressure so the tube is porous. The tube is open at both ends, and the liquid to be filtered is pumped around a closed loop which includes the tube. As the liquid passes through the tube, the cross-sectional pressure gradient and inertial effects concentrate the solids in the center of the tube, while the liquid passes through the walls. Filtrate flow ranges from 0.4 to 8 l/min depending on many factors. Particles down to 0.1 μ m are filtered out. The element does not clog, and wear is negligible or not present. The machine is relatively low cost (approx. \$3000 for the machine and \$500 for the filter element). We will test this system with both PC and 5985 based slurries.

Once the oil is removed, the Si/SiC separation step would be relatively easy. The SiC particles are about 10 times larger and 50% denser than the Si particles. Separation should thus be possible either by static settling (in a liquid in which Si floats and SiC sinks) or elutriation (in which an upward flowing stream of liquid lifts lighter and smaller particles from a liquid). Both systems will be tested with the sludge obtained from filter tests.

5.0 CONCLUSIONS AND RECOMMENDATIONS

1. Slice breakage from fracture resulting from the wafering process reduces yield in the case of fully propagated cracks and limits the production of solar cells from thin 10 cm silicon slices. This problem has not been resolved.
2. Mixtures of abrasive sizes and different slurry oils do not give suitable cutting performance with the current approach to MS slicing.
3. A scissor type blade tensioning system has the design potential to reduce operator setup time with a larger capacity MS wafering saw.

6.0 PLANS

Plans for the next quarter include:

- Complete lab saw
- Complete final design of large scale prototype.
- Fabricate low cost oil of characteristics similar to present oil. Test in MS slicing.
- Prepare SAMICS analysis of MS slicing.
- Test alignment device with 300 0.15 mm blades, and with 0.10 mm blades.
- Complete thorough etching studies with 10 cm and 2x2 cm MS silicon wafers. Begin cell fabrication.
- Test blade hardness variations.

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APPENDIX I

Engineering Drawings and Sketches

MATERIAL - STRUCTURAL STEEL TUBING EMPTY AS WELD
WELDED CONSTRUCTION

DO NOT SCALE DRAWING

DESCRIPTION OF CHANGE	DRAWN	DATE	APPROVED	DATE	CHECKED
	<i>RFB</i>	<i>10/4/77</i>			☒
	CHECKED	DATE	APPROVED	DATE	CLARK
	<i>FRAME - WELDMENTS & MACHINING</i>				
	<i>JPL PROTOTYPE SAW</i>				
WDM	NOT OTHERWISE SPECIFIED: <i>N/A</i>				SCALE <i>1/8" = 1"</i>
ECD		<i>DRW BY DEC 22-81 JLS/AG</i> <i>VAC LEX</i>		<i>DEC 22-81</i> <i>S-1001</i>	
QPT					
CHKD DATE

DESCRIPTION OF CHANGE		DRAWN <i>RPB</i>		DATE <i>10/17/77</i>		APPROVED		DATE		CODE ✓		
		CHECKED		DATE		APPROVED		DATE		CLASS		
		FLYWHEEL SHAFT JPL PROTOTYPE SAW										
NUM				NOT OTHERWISE SPEC: FRAC = $\frac{1}{4}$ ANG = $\frac{1}{2}$ "						SCALE		
EO				FIN. $\sqrt{\text{DEC } 3 \pm .1}$ $XX \pm .02$ $XXX \pm .005$						$\frac{1}{2}$		
DFT				VAC/LGX		C		S-1002				
CHK				DIVISION		SIZE		DRAWING NO.				REV
DATE				version								

DASH NO	TYPE OR MODEL	NEXT ASSEMBLY

REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

#9 (.196) DRILL 6 HOLES EQ. SP.
ON A 5.00 DIA B.C.)

MAT L - BRASS

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DESCRIPTION OF HANDLE	NAME	DRAWN BOB		DATE 10/7/77	APPROVED	DATE	CODE ✓
	QTY	CHECKED	DATE	APPROVED	DATE	CLASS	
	DATE	LOCKING RING JPL PROTOTYPE SAW					
	CER	NOT OTHERWISE SPEC: FRAC ± ANG ± SCALE FULL					
	DATE	FIN. ✓ DEC X ± .XX ± .XXX ±					
REV	VAC/LEX		B		S-1003		
	DIVISION		SIZE		DRAWING NO.		REV

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MAT'L - AISI - 1045 STEEL

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					CHECKED		DATE		APPROVED		DATE		CLASS	
					ECCENTRIC HUB FOR FLYWHEEL JPL PROTOTYPE SAW									
NUM					NOT OTHERWISE SPEC: FRAC ± ANG ± 1/4° SCALE									
EO					FIN. ☒ DEC. X ± .1 XX ± .02 XXX ± .005 <i>Full</i>									
DFT
CHK					VAC/LEX B <i>5-1004</i>									
DATE					DIVISION SIZE DRAWING NO. REV									
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DATE	BY	CHECKED	BY	APPROVED	BY
10/1/68	N/A				
LAYOUT - SIDE VIEW					
JPL PROPERTY SAW					
NOT FOR CONSTRUCTION					
JPL					
E S 1000

SIDE PANEL -
21" LONG
H.O.D. & I.D. STEEL TUBING 1/4" - 12
CENTRAL H.O.
1" LONG
H.O.D. & I.D. STEEL TUBING 1/4" - 12 THRO

NAME RFB	DATE 2/23/77	APPROVED	DATE	SCALE
DRAWN 02445	DATE	APPROVED	DATE	SCALE

LAYOUT - SECTION VIEW
J.P.L. PROTOTYPE SAW

SOFT STEEL/ALUMINUM BRASS	Part #	REV #	SCALE
	IN V. DET. S.S.	REV #	REV #	1/2 = 1
E 51007.			DATE	SCALE

REV	DATE	BY	CHKD	APP'D
1	10/1/77	JPL		
LAYOUT - TOP VIEW				
J.P.L. PROTOTYPING Saw				
SYMBOL	DATE	BY	CHKD	APP'D
1	10/1/77	JPL		
E 5 1000

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

A 5-1012
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13/32 HOLE THRU

13/32
1.25
+0.00
-0.001

MAT'L - BRASS

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	SHIM-STROKE ADJ. MECH. JPL PROTOTYPE SAW									
	NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/4°									
NUM	FIN. ✓ DEC .X ± .1		XX ± .02		XXX ± .005		SCALE FULL			
EO	VAC/LEX		A		S-1012					
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- 42 -

DESCRIPTION OF CHANGE	DRAWN					DATE					APPROVED					DATE					CODE									
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	BRACKET - HIGH SPEED MOTOR																													
	JPL PROTOTYPE SAW																													
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ED	FIN. $\sqrt{DEC} \pm .1$										XX $\pm .02$										XXX $\pm .005$					HALF				
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3/4-16 TNRD
(BOTH ENDS)
3/4 O.D. X 1/4 I.D. STEEL TUBING
(2 REQ'D)

1/16 X 45°
(BOTH ENDS)

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	CHECKED		DATE		APPROVED	DATE	CLASS
	SIDE RODS - CARRIAGE STROKE JPL PROTOTYPE SAW						
	NOT OTHERWISE SPEC: FRAC $\pm \frac{1}{64}$ ANG $\pm \frac{1}{4}^\circ$ SCALE FIN. $\checkmark$ DEC. $X \pm .1$ XX $\pm .02$ XXX $\pm .005$ FULL						
UM	VAR		VAC/LEX		A	S-1018	
IO	varian		DIVISION		SIZE	DRAWING NO.	
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DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

MAT'L - 1/4 O.D. X 3/8 I.D.
STEEL TUBING

1/16 X 45°
(BOTH ENDS)

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	CHK	MAIN DRIVE LINK				
DATE	JPL PROTOTYPE SAW					
REV	NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/4°					
	FIN. ✓ DEC .X ± .1 .XX ± .02 .XXX ± .005					
	VAC/LEX		A	51019		
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DASH NO	TYPE OF MODEL	TEST ASSEMBLY

QTY	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM
		SNAP RING # NS000-244	
		BEARING-MRC 7305

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DESCRIPTION OF CHANGE	DRAWN <i>RPA</i>		DATE 11/25/77		APPROVED		DATE		CODE	
	CHECKED		DATE		APPROVED		DATE		CLASS	
	BEARING MOUNT - BALL SCREW									
	J.P.L. PROTOTYPE SAW									
NUM	NOT OTHERWISE SPEC: FRAC ± 1/4		ANG ± 1/4°		SCALE					
EQ	FIN. ✓ DEC 2 ± .1		XX - .02		XXX ± .005		FULL			
DFT	VAC/LOX		C		S1020					
CHK	DIVISION		SIZE		DRAWING NO.		REV			
DATE										
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DESCRIPTION OF CHANGE	NUM	TO	DFT	CHK	DATE	REV	DRAWN 00063 CHECKED DATE APPROVED DATE CODE CLASS
	UPPER SLURRY SHIELD JPL PROTOTYPE SAW						NOT OTHERWISE SPEC: FRAC ± .005 FIN. √ DEC 3 ± .1 XX ± .02 XXX ± .005
	VAC/LOX						SCALE FULL
	C S 1024						DIVISION SIZE DRAWING NO.
	REV						REV

NO	PART NUMBER	DESCRIPTION OR MATERIAL	QTY

1

MAT'L - .032 THK SHEET STEEL

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PREPARATION OF CHANGE		DRAWN		DATE		APPROVED		DATE		CODE	
		0000		10/28/77							
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		LOWER SLURRY SHIELD JPL PROTOTYPE SAW									
NUM		NOT OTHERWISE SPEC: FRAC ±						ANG ±		SCALE	
EO		varian		FIN. ✓ DEC. 3 = 1		XX ± .02		XXX ± .005		HALF	
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			1		CLAMP TYPE COLLAR #15414 5/8	1

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	DFT	LVDT MOUNTING TUBE JPL PROTOTYPE SAW				
	CHK	NOT OTHERWISE SPEC: FRAC ± ANG ± SCALE				
DATE		FIN. ✓ DEC .X ± .1 XX ± .02 XXX ± .005			FULL	
REV		VAC/LEX		A	51026	
		DIVISION		SIZE	DRAWING NO.	REV

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

3/8 DRILL TO SPLIT
5/16-18 TAP THRU

1.19

1.499
1.500 D.I.A.

1/4-20
1/2\"/>

DO NOT SCALE THIS PRINT
UNLESS OTHERWISE SPECIFIED
BREAK ALL SHARP EDGES
DIMENSIONS ARE IN INCHES

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DESCRIPTION OF CHANGE	DRAWN	DATE	APPROVED	DATE	CODE
	CHECKED	DATE	APPROVED	DATE	CLASS
SLURRY SHIELD SUPPORT JPL PROTOTYPE SAW					
NUM	NOT OTHERWISE SPEC: FRAC ±		ANG ±		SCALE
EO	FIN. ✓ DEC .X ± .1		XX ± .02		XXX ± .005
DFT	VAC/LEY		A		51027
CHK	DIVISION		SIZE		DRAWING NO.
DATE					REV
REV					

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

DO NOT SCALE DRAWING

$\frac{1}{32} \times 45^\circ$
(BOTH ENDS)

SOLID 60 CASE HARDENED & GROUND
CLASS 5" SHAFTING

10 PCS REQ'D.

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DESCRIPTION OF CHANGE	DRAWN RQB		DATE 10/31/77	APPROVED	DATE	CODE ✓
	CHECKED		DATE	APPROVED	DATE	CLASS
	GUIDE PINS JPL PROTOTYPE SAW					
	NOT OTHERWISE SPEC: FRAC ± ANG ± SCALE FULL					
IUM			FIN. ✓ DEC .X ± .XX ± .XXX ±		A 51028	
EO			VAC/LEX		DIVISION	
DFT			SIZE		DRAWING NO.	
CHK			REV		REV	
DATE						
REV

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

DO NOT SCALE DRAWING

MAT'L - 1/2 x 2 M/S

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DESCRIPTION OF CHANGE	DRAWN	DATE	APPROVED	DATE	CODE
	CHECKED	DATE	APPROVED	DATE	CLASS
<p>PIVOT BLOCKS JPL PROTOTYPE</p>					
<p>NOT OTHERWISE SPEC: FRAC ± ANG ± SCALE</p>					
<p>FIN. ✓ DEC .X ± .XX ± .XXX ± FULL</p>					
<p>YAC/LEX A S 1032</p>					
<p>DIVISION SIZE DRAWING NO. REV</p>					

DASH. NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ.	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

1/2" D.I.A. DRILL ROD

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DESCRIPTION OF CHANGE	NUM	DRAWN <i>RR Bell</i> 10/12/77				DATE	APPROVED	DATE	CODE
	EO	CHECKED				DATE	APPROVED	DATE	CLASS
	DFT	ADJUSTING SCREW-STROKE ADJ. JPL PROTOTYPE SAW							
	CHK	NOT OTHERWISE SPEC: FRAC $\pm 1/4$ ANG $\pm 1^\circ$ SCALE							
	DATE	FIN. $\sqrt{\text{DEC } X \pm .1 \text{ XX} \pm .02 \text{ XXX} \pm .005} 1/2$							
REV	VAC/LEX		B		5-1034				
	DIVISION		SIZE		DRAWING NO.		REV

- 19 -

DO NOT SCALE DRAWING

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM
		DS-1001				

DO NOT SCALE DRAWING

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DESCRIPTION OF CHANGE	DRAWN	DATE	APPROVED	DATE	CODE
	CHECKED	DATE	APPROVED	DATE	CLASS
SHAFT SUPPORT MOUNTING PADS					
NUM	NOT OTHERWISE SPEC: FRAC $\pm 1/64$ ANG $\pm 1/4^\circ$				SCALE
EO	FIN. $\checkmark$ DEC. $\pm .1$.XX $\pm .02$.XXX $\pm .005$				FULL
DFT	VAC/LEX		A	S-1037	
CHK	DIVISION		SIZE	DRAWING NO.	
DATE				REV	
REV

441 6-6 APR 67
LITHO IN U S A

- 65 -

DRILL	A	B	C
NO.	270	270	270
QTY	100	100	100

DO NOT SCALE DRAWING

REVISIONS	DATE	1/11/77	DESIGNED	BY	DATE
	CHECKED	BY	APPROVED	BY	DATE
	END SUPPORTS - BLANK - PAD				
	JPL PRITYTYPE SAW				
MATERIAL	NOT OTHERWISE SPECIFIED				
	VAC/EX				
	D: 1000				
	D: 1000				

A horizontal number line with arrows at both ends. The line is marked with integers from 11 down to 1 on the left side, and from 4 down to 1 on the right side. An arrow points to the number 5.

2		1	
NO	PART NUMBER	DESCRIPTION OF MATERIAL	NO

[illegible]

2		1		1	
MO	PART NUMBER	DESCRIPTION OR MATERIAL			ITEM

1 REQ'D.

DRAWN <i>RRB</i>	DATE <i>12/1/77</i>	APPROVED	DATE	CODE
CHECKED	DATE	APPROVED	DATE	CLASS

SPEED SHIFT PARTS
JPL PROTOTYPE SAW

NOT OTHERWISE SPEC: FRAC = $\frac{1}{64}$ ANG = $\frac{1}{4}^\circ$			SCALE
	FIM. $\sqrt{\text{DEC. } \pm .1}$.XX $\pm .02$.XXX $\pm .005$			<i>FULL</i>
VAC/LEX	C	S1047		
DIVISION	SIZE	DRAWING NO.		REV

- NOTE- HEAT TREAT
FINAL COND. ROCKWELL C - 35/40
38 ✓ EXCEPT AS NOTED
REMOVE SHARP CORNERS EXCEPT AS NOTED

DO NOT SCALE DRAWING

REPRODUCTION OF DOCUMENT	COPIES <u>200</u> DATE <u>11/11/71</u> APPROVED <u>SLM</u> SIGN <u>SLM</u> CHECKED <u>SLM</u> APPROVED <u>SLM</u> SIGN <u>SLM</u>			
	BURNING MOVING CLAMP-BLADENHEAD JPL PROTOTYPE SAW			
	(not included) WELD Wt. = 75.00 Lbs. ± 5.0% SERIAL NO. <u>461</u>			
	DRAW <u>15</u> DES <u>15</u> APP <u>15</u> DATE <u>15</u> BY <u>15</u>	VAC <u>15</u> VAC <u>15</u> VAC <u>15</u> VAC <u>15</u>	<u>15</u> <u>15</u> <u>15</u> <u>15</u>	SERIAL NO. <u>15</u> SIGN <u>15</u>

NOTE: HEAT TREAT
FINAL COND. ROCKWELL C-35/40

³²✓ ALL OVER EXCEPT AS NOTED

REMOVE SHARP CORNERS EXCEPT AS NOTED

DO NOT SCALE DRAWING

[illegible]

NAME RPS	DATE 1/14/77	PROJECT BLADENHAW	SCALE 1/4" = 1"
DRAWN BY OWG/SL	CHECKED BY SL	DATE 1/14/77	SCALE 1/4" = 1"

BLADENHAW LAYOUT

JPL PROTOTYPE SAW

REV	DATE	BY	APP	SCALE
	1	1/14/77	SL	RPS	1/4" = 1"
VAL/LEX	E	5/10/51		

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL

$\frac{17}{32}$ DRILL THRU - $\frac{13}{16}$ C BORE
 $\frac{1}{2}$ " DEEP (2 HOLES) $\pm .008$

$\frac{1}{2}$ -13 TAP
 $\frac{3}{4}$ DEEP

$\pm .008$

DASH NO	A	B
001	5.00	2.50
002	6.38	3.88

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DESCRIPTION OF CHANGE	DRAWN <i>RPB</i>		DATE <i>11/17/77</i>		APPROVED	DATE	CODE
	CHECKED		DATE		APPROVED	DATE	CLASS
	GUSSETS - BLADE HEAD JPL PROTOTYPE SAW						
	NOT OTHERWISE SPEC: FRAC $\pm$ ANG $\pm$ SCALE FIN. $\checkmark$ DEC $\times \pm$.XX $\pm$.XXX $\pm$ FULL						
NUM	VAC/LEX		A		51052		
EO	DIVISION		SIZE		DRAWING NO.		
DFT	varian						
CHK							
DATE							
REV							

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

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MAT'L - 1/4" SAE 1020 KEY STOCK
(2 REQ'D)

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DESCRIPTION OF CHANGE	DRAWN	DATE	APPROVED	DATE	CODE
	CHECKED	DATE	APPROVED	DATE	CLASS
<p>NUM</p> <p>EO</p> <p>DFT</p> <p>CHK</p> <p>DATE</p> <p>REV</p>					
<p>SMALL BLADEHEAD KEY</p> <p>JPL PROTOTYPE SAW</p>					
<p>NOT OTHERWISE SPEC: FRAC $\pm 1/64$ ANG $\pm 1/4^\circ$ SCALE</p> <p>FIN. $\checkmark$ DEC .X $\pm .1$ XX $\pm .02$ XXX $\pm .005$ $\sim$</p>
<p>VAC/LEX</p> <p>DIVISION</p>		<p>A</p> <p>SIZE</p>	<p>51053</p> <p>DRAWING NO.</p>
					REV

5		4		3		2		1	
DASH NO	TYPE OR MODEL	NEXT ASSEMBLY		REQ	PART NUMBER	DESCRIPTION OR MATERIAL		ITEM

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DIMENSIONS ARE IN INCHES

MAT'L - 1/2" SAE 1020 KEYSTOCK

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DESCRIPTION OF CHANGE	NUM	DRAWN	DATE	APPROVED	DATE	CODE
	EO	ROB	12/16/77			
	DFT	CHECKED	DATE	APPROVED	DATE	CLASS
	CHK					
DATE		LARGE BLADEHEAD KEY				
REV		JPL PROTOTYPE SAW				
		NOT OTHERWISE SPEC: FRAC ± 1/4 ANG ± 1/4" SCALE				
		FIN. ✓ DEC. X ± .1 XX ± .02 XXX ± .005				
		VAC/LEX		B S 1054		
		DIVISION		SIZE		DRAWING NO. REV

5	4	3	2	1
DASH NO		TYPE OR MODEL		REPT ASSEMBLY
			REQ	PART NUMBER
			DESCRIPTION OR MATERIAL	
			ITEM	

NOT TO SCALE
DRAWING

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DESCRIPTION OF CHANGE						DRAWN	DATE	APPROVED	DATE	CODE
						K. Z.	10-10-77			
						CHECKED	DATE	APPROVED	DATE	CLASS
						PILLOW BLOCK SPACER LAB. SAW				
						NOT OTHERWISE SPEC: FRAC = 1/64 ANG ±				
NUM							FIN. ✓ DEC. X ±		SCALE FULL	
EO							XX ± .01		XXX ±	
DFT										
CHE										
DATE										
REV										

441-6-4 JUNE 66

LITHO IN U.S.A.

5

4

3

2

1

DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY

REQ.	PART NUMBER	DESCRIPTION OR MATERIAL	ITEM

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DESCRIPTION OF CHANGE	NUM		DRAWN	KZ.	DATE	10-11-77	APPROVED		DATE		CODE	
	EQ		CHECKED		DATE		APPROVED		DATE		CLASS	
	DIT		TAKE-UP SCREW LAB. SAW									
	CHN											
DATE		NOT OTHERWISE SPEC: FRAC $\pm \frac{1}{64}$, ANG $\pm \frac{1}{2}^\circ$ SCALE FIN. $\sqrt{63}$ DEC. X $\pm$.XX $\pm .01$ XXX $\pm .005$ FULL										
REV		varian B S 2036										
		DIVISION		SIZE		DRAWING NO.		REV

44) 6-4 JUNE66

5

LITHO IN U.S.A.

4

3

2

1

5			4			3			2			1		
DASH NO.	TYPE OR MODEL	NEXT ASSEMBLY	REQ						PART NUMBER		DESCRIPTION OR MATERIAL		ITEM

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DESCRIPTION OF CHANGE	NUM					DRAWN	DATE	APPROVED	DATE	CODE	
	EO					KZ.	10-18-77				
	DPT					CHECKED	DATE	APPROVED	DATE	CLASS	
	CHE					BOTTOM PLATE (W/1/2 HOLE)					
	DATE					NOT OTHERWISE SPEC: FRAC ± 1/100 ANG ± 1/4° SCALE FULL					
REV					FIN. ✓ DEC. X ± XX ± .01 XXX ± .005						
						DIVISION		SIZE		DRAWING NO.	REV

5			4			3			2			1																			
DASH NO.			TYPE OR MODEL			NEXT ASSEMBLY			REQ			PART NUMBER			DESCRIPTION OR MATERIAL			ITEM													
<div style="position: relative; width: 100%; height: 100%;"> <div style="position: absolute; top: 20%; left: 25%;"> </div> <div style="position: absolute; top: 30%; left: 55%;"> </div> </div>																															
<p>DO NOT SCALE THIS PRINT UNLESS OTHERWISE SPECIFIED BREAK ALL SHARP EDGES DIMENSIONS ARE IN INCHES</p>																															
<p>This document contains proprietary information of Varian Associates. Except as authorized by Varian in a separate writing, this document and its information shall not be copied, used or disclosed to others, and shall be returned to Varian upon request.</p>																															
<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="writing-mode: vertical-rl; transform: rotate(180deg);">DESCRIPTION OF CHANGE</th> </tr> </thead> <tbody> <tr><td>NUM</td></tr> <tr><td>EO</td></tr> <tr><td>DT</td></tr> <tr><td>CHK</td></tr> <tr><td>DATE</td></tr> <tr><td>REV</td></tr> </tbody> </table>									DESCRIPTION OF CHANGE	NUM	EO	DT	CHK	DATE	REV	<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td>DRAWN K. Z.</td> <td>DATE 10-15-77</td> <td>APPROVED</td> <td>DATE</td> <td>CODE</td> </tr> <tr> <td>CHECKED</td> <td>DATE</td> <td>APPROVED</td> <td>DATE</td> <td>CLASS</td> </tr> </table>			DRAWN K. Z.	DATE 10-15-77	APPROVED	DATE	CODE	CHECKED	DATE	APPROVED	DATE	CLASS	<p style="text-align: center; font-weight: bold;">CLAMP (WORK HOLDER) LAB. SAW</p>		
									DESCRIPTION OF CHANGE																						
									NUM																						
									EO																						
									DT																						
CHK																															
DATE																															
REV																															
DRAWN K. Z.	DATE 10-15-77	APPROVED	DATE	CODE																											
CHECKED	DATE	APPROVED	DATE	CLASS																											
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2">NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2°</td> <td colspan="2">SCALE</td> </tr> <tr> <td>FIN. ✓</td> <td>DEC. X ±</td> <td>XX ± .01</td> <td>XXX ± .001</td> </tr> </table>					NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2°		SCALE		FIN. ✓	DEC. X ±	XX ± .01	XXX ± .001																			
NOT OTHERWISE SPEC: FRAC ± 1/64 ANG ± 1/2°		SCALE																													
FIN. ✓	DEC. X ±	XX ± .01	XXX ± .001																												
		<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2">B S2041</td> </tr> <tr> <td>DIVISION</td> <td>SIZE</td> </tr> </table>			B S2041		DIVISION	SIZE																							
B S2041																															
DIVISION	SIZE																														
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td>DRAWING NO.</td> <td>REV</td> </tr> </table>		DRAWING NO.	REV																												
DRAWING NO.	REV

DESCRIPTION OF CHANGE OR REVISION DATE REV	DRAWN	DATE	APPROVED	DATE	CODE
	R. Z	10-12-77			
	CHECKED	DATE	APPROVED	DATE	CLASS
UPPER BRACKET LAB. SAW					
NOT OTHERWISE SPEC. FRAC ± 1/10 ANG ± 1/2°					
FIN. V DEC R ± .XX ± .01 XXX ± .005					
SCALE FULL					
C 52043					
DIVISION SIZE					
DRAWING NO. REV

- 97 -

HOLE	STROKE
A'	3 1/2
B'	3 1/4
C'	3
D'	2 3/4
E'	2 1/2
F'	2 1/4
G'	2
I	8 1/4
O	8 1/2
R	8 3/4
S	9
T	9 1/4
U	9 1/2
V	9 3/4
W	10
X	4 1/4
Y	4
Z	3 3/4

DC BOT SCALE DRAWING

[illegible]

Owner K. Z.	Room 4-4-2	Address 2000 10th	City Chicago	State Ill.
HORIZONTAL DRIVE BASE PLATE LAB. SAW				
How obtained this material Saw 1/2, Saw 1/2		Date 2049		Grade FULL
Saw 1/2, Saw 1/2		Date 2049		Grade FULL

NOTE: LOCATE THE DIA. HOLE AT
ASSEMBLY WITH REPOSED DIM. 231120

DATE	11/11/11
BY	11/11/11
CHKD	11/11/11
APPD	11/11/11
REV	11/11/11
QTY	11/11/11
UNIT	11/11/11
TOTAL	11/11/11
PRICE	11/11/11
TOTAL	11/11/11

DESCRIPTION OF CHANGE	DRAWN K.R.		DATE 10-5-77		APPROVED		DATE		CODE						
	CHECKED		DATE		APPROVED		DATE		CLASS						
	WORK HOLDER LAYOUT LAB. SAW														
	NOT OTHERWISE SPEC. FRAC ± ANG ± SCALE FIN. ✓ DEC 3 ± XX ± XXX ± FULL														
NUM										VIA VARIAN	C 52053	DIVISION	SIZE	DRAWING NO.	REV
EO															
DFT															
CHK															
DATE															
REV															

APPENDIX II

MAN-HOURS AND COSTS
PROGRAM PLAN (UPDATED)

MAN-HOURS AND COSTS (PHASE II)

During the reporting period of September 19, 1977 to December 17, 1977, total man-hours were 2768.2 hours and total costs were \$119,367. Previous expenditures were 2659.3 hours and \$136,242. As of December 17, 1977, total program man-hours were 5427.5 hours and total program costs were \$255,609.

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
Page 1 of 8

SCH 6/15/77
Updated 1/12/78

SLICING OF SILICON INTO SHEET MATERIAL

Varian Associates/Lexington Vacuum Division
JPL Contract 954374
Starting Date: 1/9/76 (I) 5/19/77 (I-)

Phase II
Program Plan
Page 2 of 8

SCH 6/15/77
Updated 1/12/78

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
Page 3 of 8

- 109 -

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
Page 4 of 8

SCH 6/15/77

Upda 1/12/78

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
Page 5 of 8

SCH 6/15/77

Updated 1/12/78

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
Page 6 of 8

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		▼						▼							▽											

SCH 6/15/77

Upda 1/12/78

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
Page 7 of 8

PROGRAM LABOR SUMMARY

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
Page 8 of 8

PROGRAM COST SUMMARY