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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. Third Quarterly Report, September 20, 1976—December 19, 1976

S. C. Holden

December 27, 1976

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

Lexington Vacuum Division
Varian Associates
Lexington, Massachusetts

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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

THIRD QUARTERLY REPORT

By

S. C. Holden

December 27, 1976

Reporting Period September 20, 1976 to December 19, 1976

JPL Contract No. 954374

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1.0 SUMMARY

The stability of tensioned blades used in multiblade sawing does not seem to be the limitation in cutting with thin blades. So far, 0.010 cm thick blades have been totally unsuccessful. Recently, 0.015 cm blades have proven successful in wafering, offering an 0.005 cm reduction in the silicon used per slice.

The failure of thin blades is characterized as a possible result of blade misalignment or from the inherent uncontrollability of the loose abrasive multiblade process. Corrective procedures will be employed in the assembly of packages to eliminate one type of blade misalignment.

0.015 cm thick blades produced impressive cutting rates, 70% of the blade wear ratio as 0.020 cm blades and among the highest wafer accuracy recorded to date. Boron carbide abrasive reduced the standard time to cut a 10 cm silicon ingot from 20 hours to 15 hours. Higher kerf loss indicates that this may be a result of larger effective particle size than with the same grade of silicon carbide abrasive.

Slow machine speed reduced the cutting rate of a 10 cm ingot by an expected factor of two due to machine speed and a factor of 1.5, assumed to be due to reduced slurry ingress to the blades. Wafer accuracy was very good in this case.

Two ingots were sliced with the same batch of standard silicon carbide abrasive slurry to determine the useful lifetime of this expendable material. After 250 slices, the cutting efficiency had not degraded. Further tests will be continued to establish the maximum lifetime of both silicon carbide and boron carbide abrasive. Electron microscopy will be employed to evaluate the wear of abrasive particles in the failure of abrasive slurry.

The surface damage of silicon wafers has been characterized by JPL as predominantly subsurface fracture. Damage with #600 SiC is between 10 and 15 microns into the wafer surface. This agrees well with previous investigations of damage from silicon carbide abrasive papers.

2.0 INTRODUCTION

As reported in earlier reports, the multiblade slurry process can presently slice 10 cm silicon ingots into 230 slices in 20 hours. The resulting wafers are 0.025 cm thick and a total of 0.05 lineal centimeters of silicon is used in the production of each slice.

A cost analysis of the process has shown that the major elements of the process costs are the expendable materials used to produce each slice. For this reason, tests have been initiated to determine the useful lifetimes of the abrasive slurry. Also, different abrasives are being tested to allow either longer useful lifetimes or less costly materials.

No keys have been identified in the reduction of blade wear. This impacts the cost of a significant expendable, but blade wear, at the present, is only a by-product of the loose abrasive cutting process.

Thin blades are also being explored for two reasons. First, the reduction of silicon kerf loss due to blade thickness reduction will impact the conversion of silicon ingot into sheet in terms of area produced per ingot weight. The second effect is the lower utilization of slurry with the reduced kerf removal requirement.

Wafer thickness will also be reduced to explore the process limitations. However, handling and devise thickness requirements may not allow wafers thinner than 0.025 cm.

3.0 SLICING TESTS

3.1 General

The tests over the last quarter were aimed at clearing up some of the questions involving blades and slurry in multiblade sawing. In most cases, 10 cm diameter silicon was sliced. In tests involving abrasive effects, standard 0.020 cm thick by 0.635 cm high blades were used with a cutting force of 113 grams. Thin blades are being tested in order to reduce the silicon material loss in producing a slice. Table 1 is a summary of the slicing tests described below. Tables 2 and 3 are records of the wafer characterizations and blade wear from the tests.

3.2 Large Slurry Volume: #2-004 and #2-005

A 38 liter volume of slurry was used in two simultaneous tests. The slurry was mixed with the standard 0.48 kg/liter of #600 SiC abrasive. The same blade package was used to cut through two 10 cm ingots. The large volume of slurry was meant to reduce the effects of viscosity increase of the standard 7.6 liter slurry volume as the silicon debris is accumulated.

Cutting time for the first ingot was 21.5 hours with otherwise standard conditions of cutting. The kerf loss with 0.020 cm blades was 0.0255 cm, similar to other tests. There was a reduction of average slice taper to 0.007 cm, but this is the same as the first "improved" 10 cm ingot slicing test, #2-001.

The second ingot took 26.5 hours to slice, due to the necessary reduction of bladehead stroke to compensate for the worn blades. The blades began to break after 60% of the ingot was sliced. The height of the worn blades was about 0.254 cm (60% worn) at this point. More than 80% of the blades survived to the end of the cut where the height of the worn blades was 0.150 cm. Slice taper in this ingot was 0.0015 cm, typical for the worst cases of 10 cm wafering.

No improvement in slice taper resulted from the large slurry volume, and it was found that 60% height loss may be a practical limit to blade wear. In both tests, slice thickness was 0.025 cm.

TABLE 1

SUMMARY OF MULTIBLADE SLICING

PARAMETER	TEST	2-004	2-005	2-006A	2-006B
MATERIAL		Si {111}	Si {111}	Si {100}	Si {100}
LOAD (gram/blade)		113.4	113.4	113.4	113.4
SLIDING SPEED (cm/sec)		62.4	56.7	57.8	59.1
NUMBER OF BLADES CUTTING		142	144	125	125
ABRASIVE (grit size)		#600 SiC	#600 SiC	#600 SiC	#600 SiC
OIL VOLUME (liters)		37.9	(37.9)	7.6	(7.6)
MIX (kg/liter)		0.48	0.48	0.48	0.48
KERF LENGTH (cm)		10.0 max	10.0 max	10.0 max	10.0 max
INGOT HEIGHT (cm)		8.62	8.62	8.62	8.62
BLADE THICKNESS (cm)		0.02	0.02	0.02	0.02
KERF WIDTH (cm)		0.0255	0.0247	0.0255	0.0238
ABRASIVE KERF LOSS (cm)		0.0055	0.0047	0.0055	0.0038
AREA/SLICE (cm^2)		73.8	73.8	73.8	73.8
CUTTING TIME (total hours)		21:35	26:30	27:00	26:15
EFFICIENCY	(full test)	1.24	1.08	1.07	1.01
	(typical)	1.74	1.50	1.19	1.12
	(maximum)	2.11	1.86	1.88	1.70
ABRASION RATE	(full test)	0.0872	0.0709	0.0696	0.0669
(cm^3/hr/blade)	(typical)	0.1223	0.0958	0.0777	0.0748
	(maximum)	0.148	0.1187	0.1228	0.1135
PRODUCTIVITY	(full test)	3.42	2.78	2.73	2.81
(cm^2/hr/blade)	(typical)	4.79	3.88	3.05	3.14
	(maximum)	5.81	4.81	4.82	4.77
SLICE TAPER (cm)		+.0007	+.0015	+.0016	+.0016
ABRASIVE UTILIZATION (cm^3/kg)		14.7	(29.1)	64.5	(124.7)
OIL UTILIZATION (cm^3/liter)		7.05	(13.98)	30.9	(59.9)

TABLE 1
(cont.)
SUMMARY OF MULTIBLADE SLICING

PARAMETER	TEST	2-021	2-041	3-021	3-031
MATERIAL		Si {111}	Si {100}	Si {111}	Si {111}
LOAD (gram/blade)		113	113	57	85
SLIDING SPEED (cm/sec)		35.5	67.1	65.8	62.7
NUMBER OF BLADES CUTTING		150	118	145	136
ABRASIVE (grit size)		#600 SiC	#600 B_4C	#600 SiC	#600 SiC
OIL VOLUME (liters)		7.6	7.6	7.6	7.6
MIX (kg/liter)		0.48	0.48	0.48	0.48
KERF LENGTH (cm)		10.0 max	10.0 max	7.62	7.62
INGOT HEIGHT (cm)		6.83	8.3 cm	5.40	5.31
BLADE THICKNESS (cm)		0.02	0.02	0.010	0.015
KERF WIDTH (cm)		0.0262	0.0284	(0.015)	0.023
ABRASIVE KERF LOSS (cm)		0.0062	0.0084	(0.005)	0.008
AREA/SLICE (cm^2)		61.6	72.1	41.1	40.5
CUTTING TIME (total hours)		54:35	14:50	23:10	17:00
EFFICIENCY	(full test)	.74	1.83	0.71	1.03
	(typical)	.96	2.07	0.86	1.15
	(maximum)	1.14	3.18	1.61	1.65
ABRASION RATE	(full test)	0.0296	0.1380	0.0266	0.0547
(cm^3/hr/blade)	(typical)	0.0384	0.1564	0.0335	0.0611
	(maximum)	0.0456	0.2403	0.0626	0.0876
PRODUCTIVITY	(full test)	1.13	4.86	1.77	2.38
(cm^2/hr/blade)	(typical)	1.46	5.51	2.23	2.66
	(maximum)	1.74	8.46	4.18	3.81
SLICE TAPER (cm)		+.0004	+.0009	+0.012	-0.0003
ABRASIVE UTILIZATION (cm^3/kg)		66.36	66.23	22.9	34.6
OIL UTILIZATION (cm^3/liter)		31.85	31.79	10.9	16.6

TABLE 2

SUMMARY OF WAFER CHARACTERIZATION

TEST		2-004	2-005	2-006A	2-006B
THICKNESS (AVE)	cm	.0253	0261	0253	0270
STD. DEVIATION	cm	.0037	0015	0022	0029
TOTAL VARIATION (AVE)	cm	0643	0043	0040	0057
STD. DEVIATION	cm	0020	0018	0015	0024
STD. DEVIATION (AVE)	cm	0024	0016	0015	0022
STD. DEVIATION	cm	0009	0007	0006	0009
VARIATION (AVE WAFER)	cm	0020	0015	0016	0017
TAPER (AVE WAFER)	cm	0007	0015	0016	0017
BOW (AVE)	μm	40	--	--	--
TAPER (AVE)	μm	--	--	30	--
WAVINESS (p-p) (10^{-2}m)	μm	24	51	23	48
ROUGHNESS (p-p) (10^{-4}m)	μm	2.4	2.0	2.3	2.3
ROUGHNESS (RMS)	μinch	18-20	18-22	15-17	14-16
STEPS	μm	--			8.5
DAMAGE DEPTH (>10^4/cm^2)	μm				

TABLE 2
(cont.)
SUMMARY OF WAFER CHARACTERIZATION

TEST		2-021	2-041	3-021	3-031
THICKNESS (AVE)	cm	0246	0326	0394	0331
STD. DEVIATION	cm	0013	0016	0047	0020
TOTAL VARIATION (AVE)	cm	0021	0042	0171	0027
STD. DEVIATION	cm	0009	0018	0111	0011
STD. DEVIATION (AVE)	cm	0007	0015	0067	0010
STD. DEVIATION	cm	0003	0006	0044	0005
VARIATION (AVE WAFER)	cm	0004	0009	0122	0003
TAPER (AVE WAFER)	cm	0004	0009	0122	0003
BOW (AVE)	µm	9	--	--	--
TAPER (AVE)	µm	10	--	27	--
WAVINESS (p-p) (10^{-2}m)	µm	16	38	62	13
ROUGHNESS (p-p) (10^{-4}m)	µm	1.9	2.6	2.3	2.2
ROUGHNESS (RMS)	µinch	15-18	17-19	22-24	17-22
STEPS	µm	28	41	62	2
DAMAGE DEPTH (>10^4/cm^2)	µm				

TABLE 3

RECORD OF BLADE WEAR IN MULTIBLADE SLICING

TEST	THICKNESS (cm)	ORIGINAL HEIGHT (cm)	FINAL HEIGHT (cm)	WEAR RATIO (r)
2-004	.020	0.635	0.424	0.046
2-005	.020	0.424	0.150	0.052
2-006A	.020	0.635	0.406	0.047
2-006B	.020	0.635	0.386	0.056
2-021	.020	0.635	0.447	0.047
2-041	.020	0.635	0.429	0.042
3-021	.010	0.475	0.290	0.082
3-031	.015	0.635	0.554	0.027

3.3 Slurry Lifetime: #2-006A and #2-006B

A 7.6 liter batch of slurry (0.48 kg/liter of #600 SiC) is being used to slice a series of 10 cm silicon ingots. For each ingot, a new blade package is installed. Two ingots have been fully sliced, and the test will be continued until the "lifetime" of the slurry is determined. At various points, samples of the slurry have been collected. These will be analyzed to indicate the mechanism of slurry failure.

In #2-006A, kerf loss was 0.0255 cm and slicing time was 27 hours. The reduction of cutting rate is not explained, since the conditions were identical to #2-003 (18.2 hours). Wafer accuracy was normal and slice taper was 0.0016 cm, similar to previous tests. The cutting time for #2-006B was 26.25 hours and taper was identical to #2-006A. In this case, kerf loss was only 0.0238 cm, less than in #2-006A.

In both cases, wafers were 0.025 cm thick, and 125 slices were produced in each. The cutting did not seem to degrade during these two runs. The remaining tests will continue until some form of slurry degradation can be determined.

3.4 Slow Speed: #2-021

A 10 cm ingot was sliced with a bladehead speed of 35.5 cm/sec, half of that normally used. Total cutting time was 54.5 hours. Even though the cutting time was long, the efficiency (0.96) was similar to the efficiency of early cuts and of tests with square workpieces. As speculated in previous reports, the shape of the workpiece promotes bounce of the vertical feed. This motion may increase flow of abrasive into the cutting region under the blades. With square workpieces, this bounce is limited. The slow machine speed also limited the vertical feed bounce even with the round workpiece, resulting in the lower cutting efficiency. The cutting time was expected to be at least 40 hours due to the slow bladehead speed, and using the high cutting efficiency of round workpieces with improved slurry mixture.

The wafers produced at this slow speed were the most accurate to date. The kerf loss was higher than normally seen in 10 cm diameter ingots, but this may be due to the longer time available for material removal beside the blades under the reduced cutting efficiency.

3.5 Boron Carbide Abrasive: #2-041

A standard 10 cm ingot was sliced with a 7.6 liter volume of slurry made with an 0.48 kg/liter mix of #600 B_4C abrasive. This abrasive is harder than SiC and is expected to give a longer lifetime to the abrasive grains. Total cutting time was 14.8 hours, a reduction of 25% compared with SiC. However, the abrasive kerf loss was 0.0084 cm, an increase of 70% over the typical abrasive kerf loss with #600 SiC abrasive. This is an increase of 14% in total kerf loss using the 0.020 cm thick blades.

Wafer accuracy in general was degraded compared to #600 SiC abrasive slicing. However, slice taper was improved compared with typical 10 cm slices, except for the lower taper seen in Test #2-004 (38 liter slurry volume).

3.6 0.010 cm Thick Blades: #3-021

A package of 0.010 cm thick blades was used to cut a rectangular block of silicon with 7.62 cm kerf length. Blades were 0.476 cm high, as opposed to the 0.635 cm high blades used in previous cutting tests with thin (0.010 cm) blades. A cutting force of 57 grams per blade was used, and cutting efficiency of approximately 1.0 resulted, indicating a proper cutting mechanism. The slurry consisted of 7.6 liters of PC oil with 0.48 kg/liter of #600 SiC abrasive.

The blade breakage that had plagued the earlier tests in the thin blade series did not occur until nearly the end of the cut. The blades had been elongated to 0.254 cm, the elongation used successfully with thicker (0.02 cm) blades, and corresponding to 80% of the yield strength of the blade steel.

However, severe blade wandering occurred from the beginning of the cut. Throughout the test, blades would distort so severely that wafers regularly broke out of the workpiece. The blades all assumed a "tipped" or buckled cutting configuration, and the direction of overturning could be determined by the worn appearance of the blades. The blades are made of a blued steel, and under the action of the abrasive, the bluing is worn away.

Typically, a blade wears only near its lower edge. The tipped blades showed a lack of bluing on the "downward" side of the blade. Associated with that wearing was a loss of blade thickness to 0.0075 cm. In a normal cut, thickness loss is negligible and blades wear away only on the botton edge.

In a given area of the blade package, blades overturned in the same direction. Across the package, the overturning direction would gradually change from one side to the other. The lack of random overturning indicates that the buckling of blades is governed by improper vertical blade alignment determined by the blade package assembly or tensioning impact on the overall blade alignment.

The steel used in this cut was of a different tensile strength than previous thin blade cuts (205 kg/mm^2 compared to 215 kg/mm^2), but was identical to the steel used in 0.020 cm thick blades. The harder material of the previous thin blade cuts might have contributed to the higher breakage, but the mechanism is not obvious.

The only wafers remaining from the cut were ones that were excessively thick, due to divergent blade wandering, and thus strong enough to survive the cut.

3.7 0.015 cm Thick Blades: #3-031

A cut using 0.015 cm thick blades, 0.635 cm high, was made in another rectangular workpiece with a kerf length of 7.62 cm. The standard slurry volume (7.6 liters) and mix (0.48 kg/liter of #600 SiC) were used with 85 grams of cutting force per blade.

The cut was surprisingly successful, with the wafer accuracy among the best recorded in this program. The cutting efficiency was very impressive, especially considering the lower efficiency normally experienced with rectangular workpieces.

The blade wear was even more impressive, with a resulting wear ratio of 0.027, 68% of the previous lowest wear ratio with 0.020 cm thick blades.

The wafers had a noticable difference in shape compared to other cuts. The normal wafer surfaces are slightly convex, with the appearance of reduced kerf loss as the slurry path from the ingot exterior is increased. However, in Test #3-031 the wafers are slightly concave.

4.0 DISCUSSION

4.1 Blade Stability

The blades used in slicing by the multi-blade technique exhibit a very low tolerance for cutting forces above 200 grams per blade. Thin blades have not even been able to cut loads of 50 grams per blade without wandering severely from their ideal cutting path. In order to determine the source of blade instability, the following is a series of analyses based on the mechanical deformation of a tensioned steel blade.

Consider a steel blade of length ℓ_B, thickness t_B and height h_B. The blade is tensioned to a uniform stress, σ_o, and the end-points are fixed (see Figure 1). For blades of the size and tensioning level used in the Varian 686 saw, the predominant effect in deflection of a blade is the taught string effect. This is shown in Figure 2, with a load F applied to the center of a string with tensioning force F and total length ℓ_B. The force required to apply a displacement x is

$$F = 2T \sin \left(\tan^{-1} \frac{2x}{\ell_B}\right) \qquad (1)$$

For small angular deflections, Equation (1) reduces to

$$F = \frac{4Tx}{\ell_B} \qquad (2)$$

There are three modes of blade stiffness of interest at the center of a blade, and these are shown in Figure 3. Under a vertical force, F_v, the displacement, z_o, of the center of the blade is

$$\frac{z_o}{F_v} = \frac{\ell_B}{4T} = \frac{\ell_B}{4\sigma_o h_B t_B} \qquad (3)$$

Since the string effect dominates, this case is identical to the blade deflection under a side load, F_s. The horizontal deflection of the

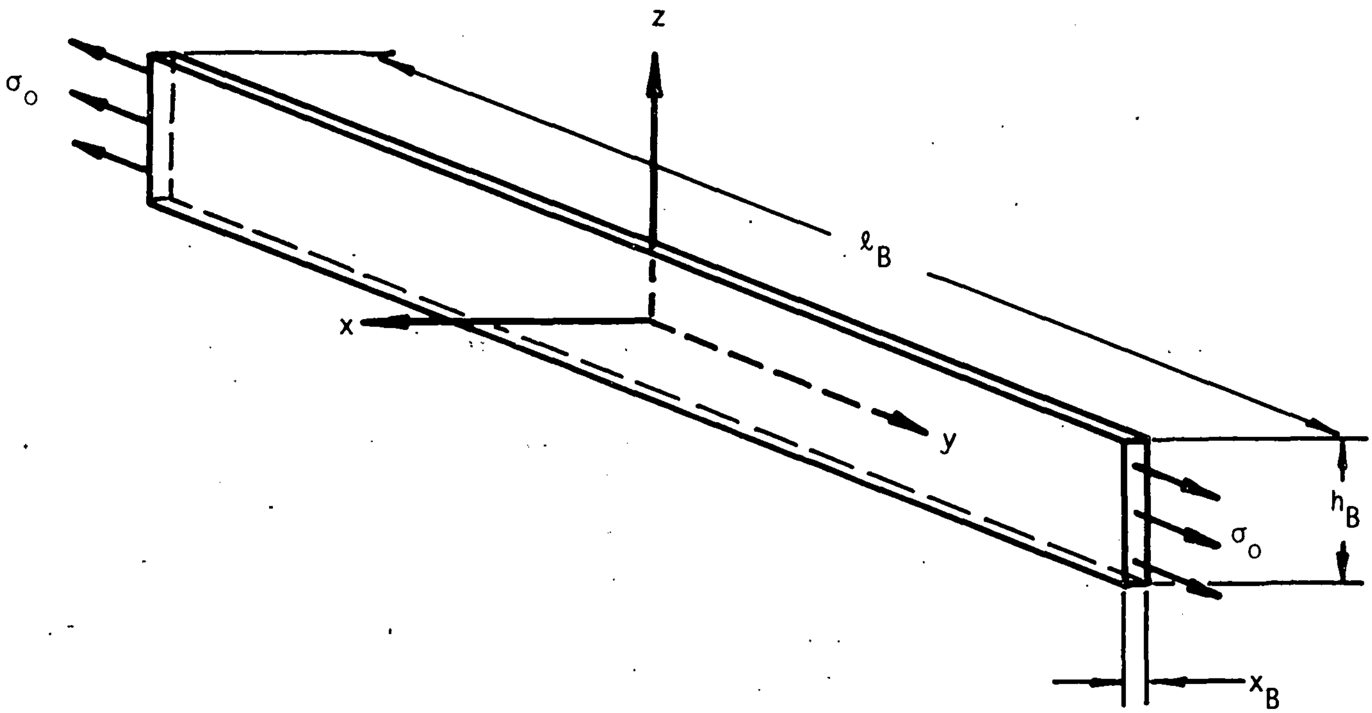

FIGURE 1

GEOMETRY OF A TENSIONED BLADE

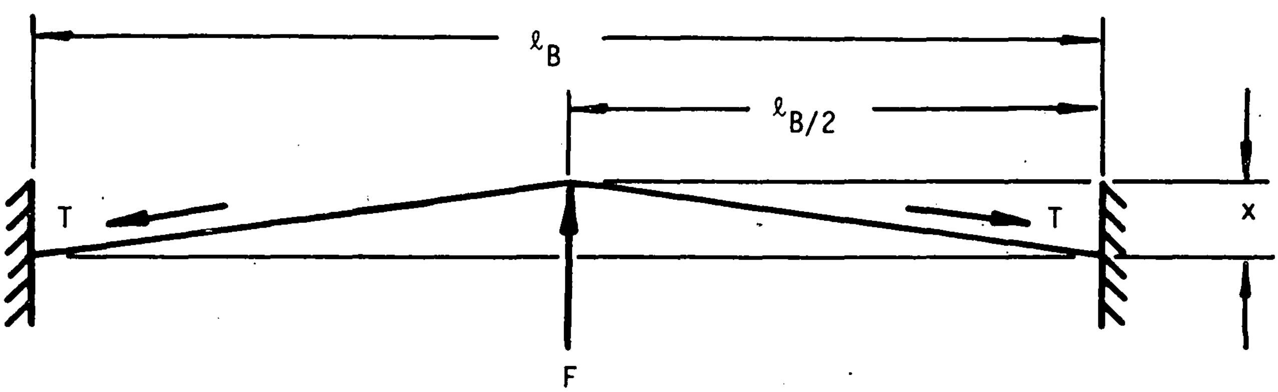

FIGURE 2

DEFLECTION OF A TENSIONED STRING

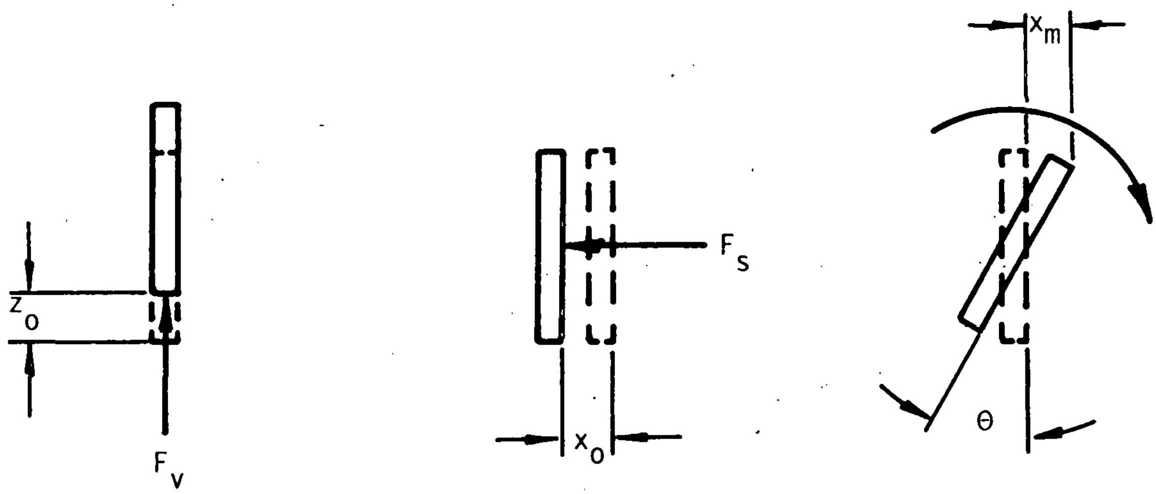

FIGURE 3

MODES OF BLADE DEFLECTION

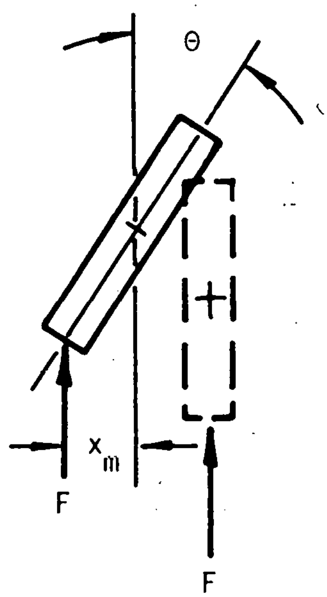

FIGURE 4

GEOMETRY FOR BUCKLING UNDER VERTICAL CUTTING FORCE center of the blade is

$$\frac{x_o}{F_s} = \frac{\ell_B}{4\sigma_o h_B t_B} \qquad (4)$$

For a tensioning force of 1.406 x 10^7 g/cm^2 (200,000 psi), a blade of 0.020 cm thickness 0.635 cm height and 38.1 cm length (standard blade), the stiffness of the blade center is

$$\frac{x_o}{F_s} = \frac{z_o}{F_v} = 5.3 \times 10^{-5} \text{ cm/g} \qquad (5)$$

At a standard cutting force of 113 grams per blade, this corresponds to a vertical displacement of 60 microns.

The application of a bending moment, M , will result in rigid body rotation of the center of the blade, Θ .

$$M = \frac{\sigma_o t_B h_B^3}{3\ell_B} \quad \Theta = \frac{2\sigma_o t_B h_B^2}{3\ell_B} \quad x_m \qquad (6)$$

4.2 Simple Buckling Under a Vertical Load

Under a vertical cutting force, F , applied at the center of the blade (Figure 4), the simplest buckling mode occurs when a small rotational perturbation Θ causes the applied moment M_A to exceed the restoring moment from Equation (6).

$$M_A = F\, x_m \geq \frac{2\sigma_o t_B h_B^2}{3\ell_B} \quad x_m \qquad (7)$$

The critical buckling load for this simple case, F_c° , is equal to

$$F_c^\circ = \frac{2\sigma_o t_B h_B^2}{3\ell_B} \qquad (8)$$

The buckling of a blade should occur at a load proportional to the blade thickness, tensioning stress and the square of blade height, and inversely proportional to the blade length. For the standard blade described above, the critical buckling force is 2013 grams, an order of magnitude greater than the highest applied cutting force. Figure 5 shows the magnitude of the buckling load for various blade heights and thicknesses.

The vertical deflection, z_o, of the blade center at the buckling load

$$z_o = \frac{1}{6} h_B \qquad (9)$$

For an 0.635 cm high blade to reach the buckling load, it would protrude out of the blade package by 0.106 cm.

4.3 Blade Deflection with Offset Load

Figure 6 shows a blade loaded by an angular offset cutting force. Under this loading, the blade will merely achieve a tipped configuration. The moment applied to the blade in the new tipped configuration will be in equilibrium with the restoring moment from Equation (6).

$$F (\Theta + \Theta_o) \frac{h_B}{2} = \frac{\sigma_o t_B h_B{}^3}{3 \ell_B} \Theta \qquad (10)$$

Simplifying this using Equation (8)

$$F \left(1 + \frac{\Theta_o}{\Theta}\right) = F_c^\circ \qquad (11)$$

At loads much lower than the critical buckling load, the change of attitude of an already tipped blade is very slight. Therefore, the initial offset of the blades may be more of a factor in governing blade wandering than deflection under normal cutting forces.

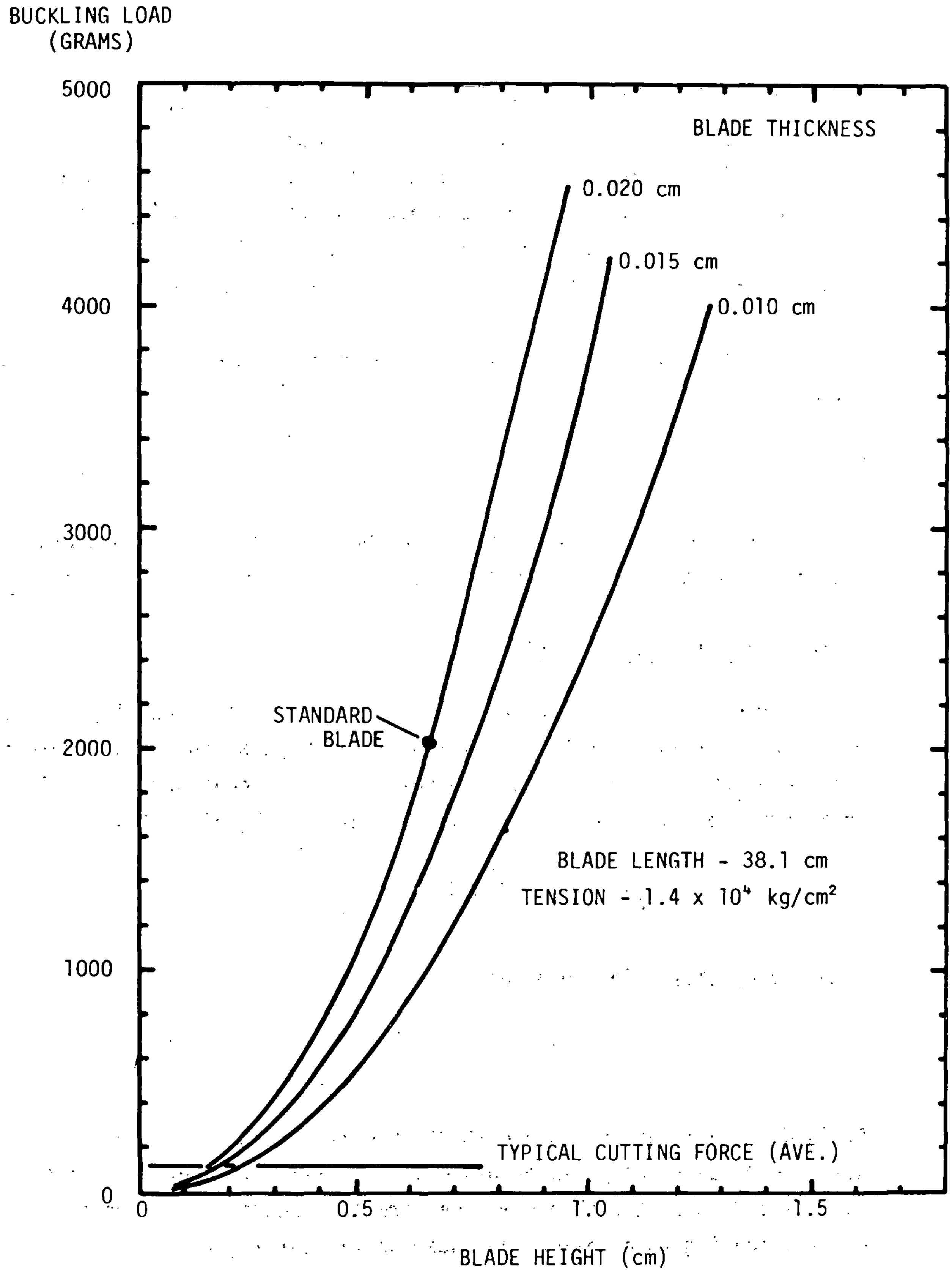

FIGURE 5

BUCKLING LOAD AS A FUNCTION OF BLADE HEIGHT AND THICKNESS

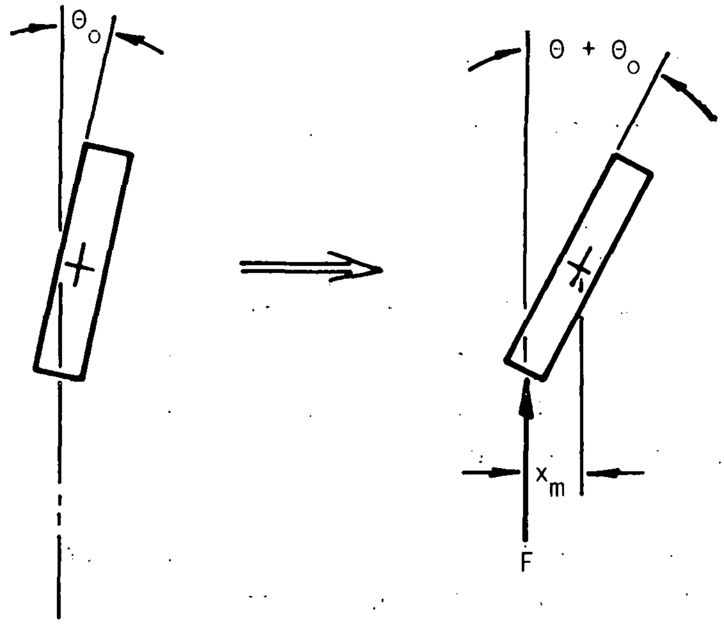

FIGURE 6

GEOMETRY FOR OFFSET BLADE LOADING

4.4 Boron Carbide

It was shown in the "First Annual Report"[1] that cutting efficiency was decreased as abrasive particle size was reduced from #600 to #1200 SiC. From this trend, the cutting efficiency with B_4C abrasive in Test #2-041 would correspond to an abrasive grain size of 18 to 20 microns (average size of #600 SiC is 16 microns). The higher kerf loss resulting with the #600 B_4C also indicates a particle diameter in this range.

It is logical, from local fracture considerations, that the cutting rate of larger particles is high. From the results shown previously it is reasonable to assume that the major improvement in cutting rate seen with B_4C is due to an effectively larger particle diameter (despite the similar grit size).

Due to its higher material hardness, boron carbide should last longer as an effective abrasive particle than silicon carbide. However, the mechanism of slurry failure must be determined first before this effect is considered too heavily. Also the order of magnitude higher cost for boron carbide will severely offset the increase in cutting efficiency, as well as even a large improvement in slurry "lifetime".

5.0 SURFACE CHARACTERIZATION

5.1 Wafer Accuracy

Results of wafer thickness and surface profile testing were recorded in Table 2 of Section 3.0. The accuracy of wafers cut with 0.020 cm thick blades is consistent, with few significant variations encountered.

0.010 cm thick blades have failed totally. In the one test where a few wafers survived, #3-021, the accuracy is very poor. The wafers survived only because the two blades producing those wafers diverged in their paths. The wafers were actually thicker than the spacers used to form the blade package.

The remarkable result is the cutting of 0.015 cm thick blades. Here wafer accuracy is better than with typical 0.020 cm blades. This does indicate the potential for success with 0.015 cm blades.

5.2 Surface Damage

Previous work with dislocation etch techniques showed a damage in silicon wafers that was assumed to consist of dislocations. However, angle lapping and etch studies performed by JPL has indicated that the damage consists mostly of subsurface fracture.

Due to the nature of damage and the equipment required for testing, JPL will now perform the surface damage characterization on wafers produced under this contract.

Preliminary results indicate that #600 SiC abrasive produces 10 to 15 microns of subsurface fracture, with dislocation damage confined to the near surface. Stickler and Booker[2] found damage of a similar nature in abrasion with both loose diamond powder and SiC abrasive papers.

Their results can be used to support the abrasion process of multiblade slurry sawing, and to gauge the performance of other abrasives. They found that loose abrasive powders produced a factor of two to three lower surface damage (4.5 microns) than did the SiC abrasive paper (11 microns) even though the abrasive particle sizes were identical. First, the damage from the #600 SiC paper is in the same range as the preliminary damage results from JPL for #600 SiC abrasive. Second, the damage indicates that the multiblade slurry process is indeed a "fixed abrasive" cutting technique when operating properly. The fact that damage does not correlate with Stickler and Booker's loose diamond powder abrasion supports the concept that has been shown in these reports from cutting efficiency and blade wear viewpoints.

A second possibility for using the cited work on surface damage is in characterizing the performance of other abrasives. It was speculated in Section 4.4 that #600 B_4C produced a higher cutting efficiency and higher kerf loss because its particle size was larger than that of #600 SiC abrasive. If this is the case, it should exhibit another micron of two deeper surface damage than does #600 SiC. In Stickler and Booker's work, the surface damage from #600 SiC paper is 9 to 12 microns, and from #400 SiC paper it is 13 to 18 microns.

6.0 CONCLUSIONS AND RECOMMENDATIONS

A major concern in multiblade slurry sawing is the ability to slice accurately using thin blades and thin slices. For this reason, the analysis of blade stability was given in Section 4.0. Two types of limitation seem to exist.

The average blade loading now used in slurry sawing is a factor of ten lower than the theoretical buckling load of a tensioned blade. Even under an offset load, the additional misalignment of the blade under load is minimal, and loads near the buckling load must be experienced in order to provide significant overturning.

Assuming that initial blade positioning is a critical factor in cutting, then the construction and set-up of the blade package must be investigated. The package is a stacked assembly of some 400 individual components. The thickness tolerance of these blades and spacers are near the highest available, yet can still accumulate additively to provide misalignments. Any misalignments in assembly, as apparently seen in Test #3-021 may be eliminated by well designed assembly and usage techniques. It is unlikely that the component tolerance errors can be eliminated without costly materials (lapped blades and spacers), or smaller numbers of components per blade package. In the light of a larger productivity from a slicing machine, a new concept of blade alignment must be attempted.

The second mode of blade failure may be a result of the uncertainty of the abrasion mechanism relied upon. The blades are all fixed to move together, and a variation of one blade's ability to cut could provide the buckling loads required. This cutting ability may undergo cycles as fresh abrasive makes its way to a blade and then is restricted. The uncontrollability would not be noticed with the numbers of blades used presently. The only means of isolating and curing this problem is extended testing of slurry types and application methods with a saw of small (1 to 10 blades) capacity and sensitive instrumentation.

Thin blades have been unsuccessful until the performance of 0.015 cm thick blades in Test #3-031. An identical blade package will be used in slicing a 10 cm ingot. Corrective procedures will be employed to provide maximum initial blade alignment from assembly and installation of 0.010 cm thick blades.

Slurry lifetime has been shown to be at least 33 wafers per liter of standard slurry. Cutting efficiency has not been reduced through the two tests run (#2-006A and #2-006B), and further testing will indicate the current limit to utilization. It will also indicate the nature of the failure and samples collected from the tests may show the deterioration of the abrasive in this process.

Boron carbide has shown 30% shorter cutting time in a 10 cm ingot, but larger particle size may be the major reason, since kerf loss was also higher than with the same grading (#600) of silicon carbide. Lifetime testing will be performed to indicate the possibility of longer slurry lifetime with the harder boron carbide.

7.0 PLANS

Plans for the next three months include:

- Complete testing of lifetime of SiC abrasive slurry.
- View samples of slurry taken at various stages of usefulness with electron microscopy.
- Cut with 0.015 cm thick blades.
- Cut with a 10 cm ingot with 0.020 cm blades and 0.020 cm spacers to result in wafers nearly 0.013 cm thick.
- Cut with 0.020 cm thick blades and over 200 grams of blade load.
- Use corrective procedures to eliminate assembly and set-up error from 0.010 cm thick blade packages. Continue cutting with these thin blades.

REFERENCES

1 S. C. Holden, SLICING OF SILICON INTO SHEET MATERIAL, FIRST ANNUAL REPORT, Varian Associates, ERDA/JPL - 954374 - 76/3, September 27, 1976.

2 R. Stickler and G. R. Booker, SURFACE DAMAGE IN ABRADED SILICON SPECIMENS, Phil. Mag., 8, 859 (1963)

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APPENDIX

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

MAN-HOURS AND COSTS

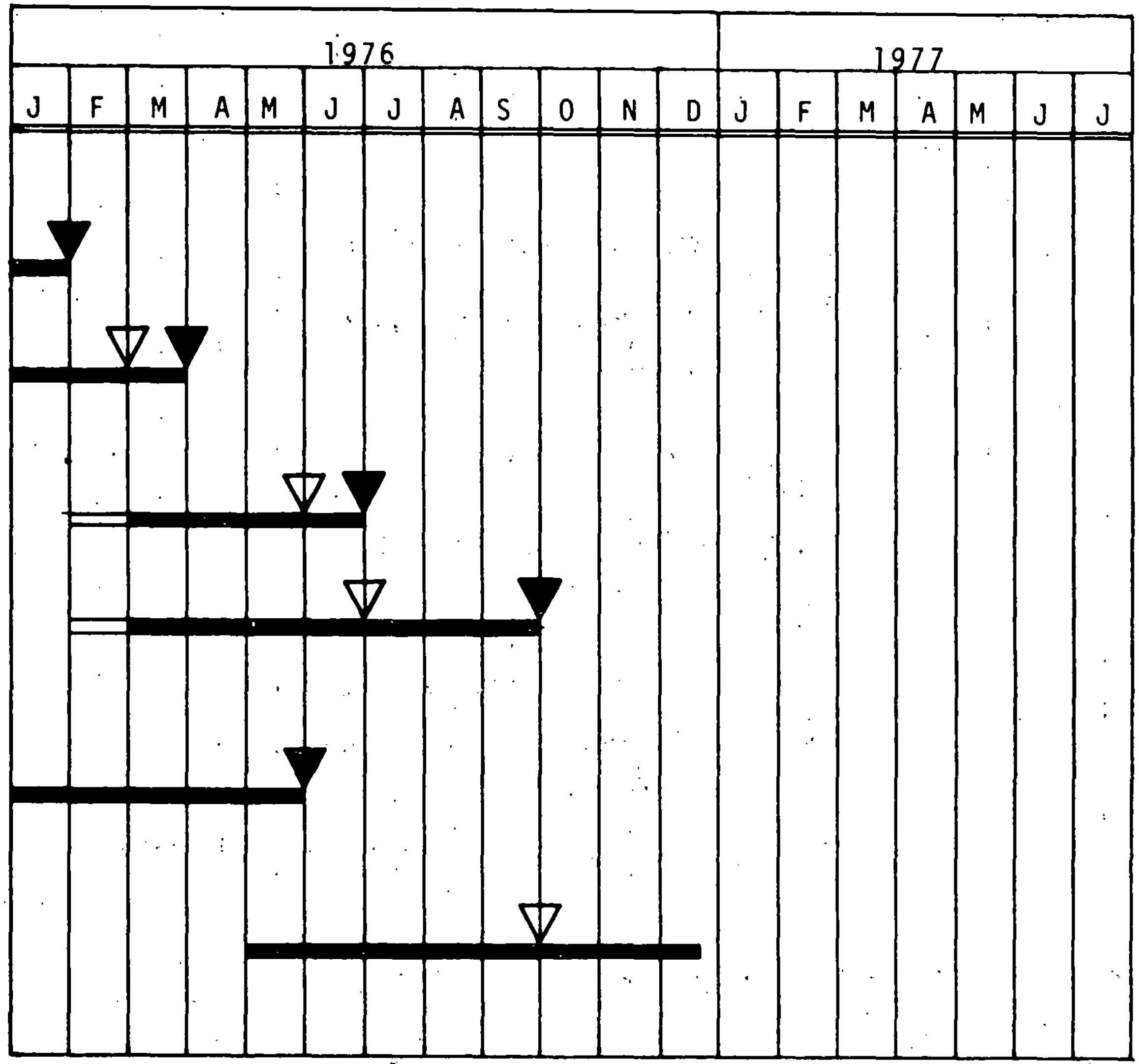
During the reporting period of September 20, 1976 to December 19, 1976, total man-hours were 937.0 hours and total costs were $26,520. Previous expenditures were 2175.4 hours and $75,431. As of December 19, 1976, total program man-hours were 3,112.4 hours, and total program costs were $101,951.

SLICING OF SILICON INTO SHEET MATERIALS

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

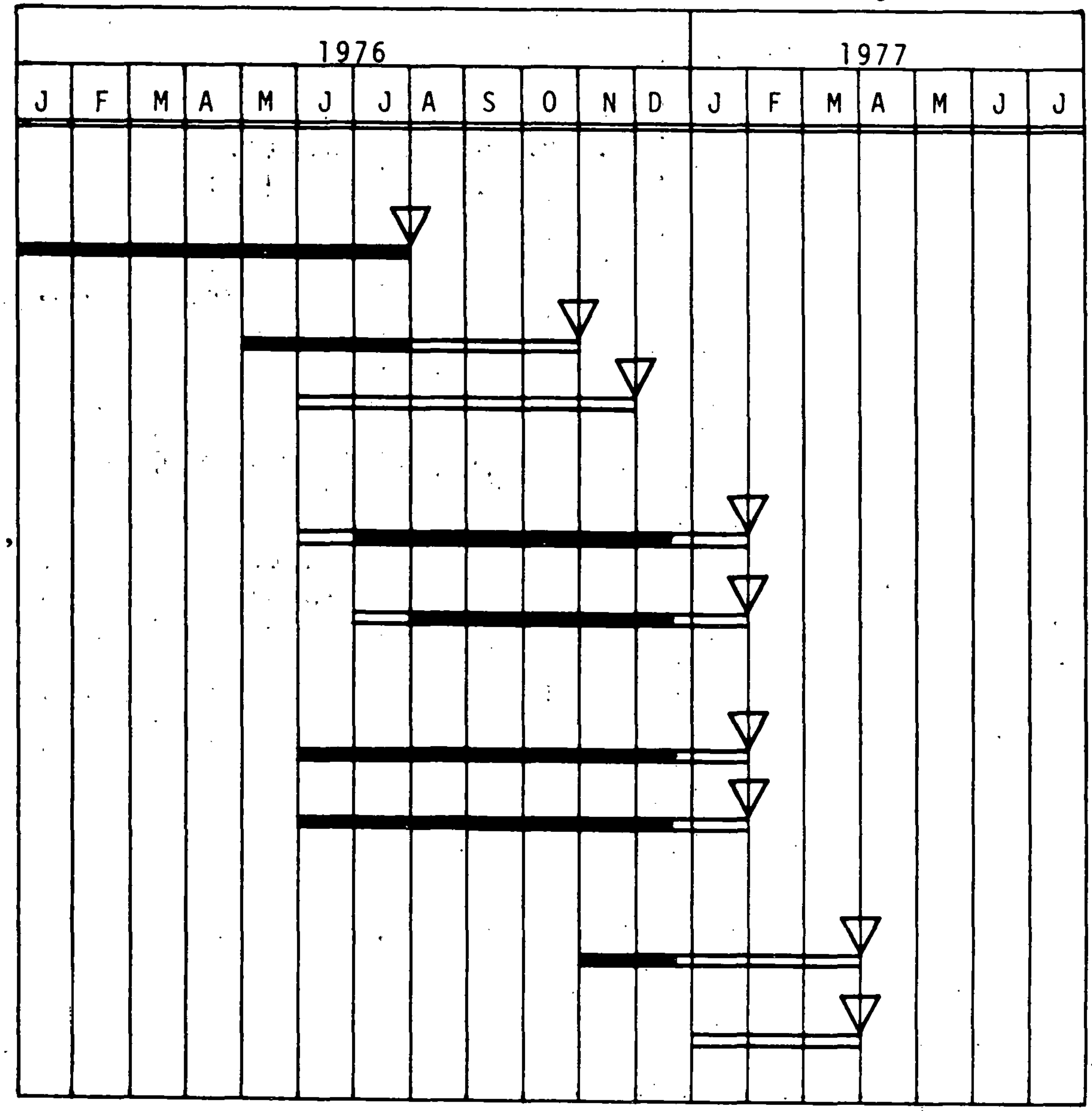
1. Background Parameter Study
   1.1. Establish standardized cutting format and data collection technique
   1.2. Modify saw, measure accuracy, build dynamometer
   1.3. Slicing tests - effects of load, speed, slurry, work configuration on rate, wear, wafer accuracy, etc.
   1.4. Wafer characterization

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 12/27/76

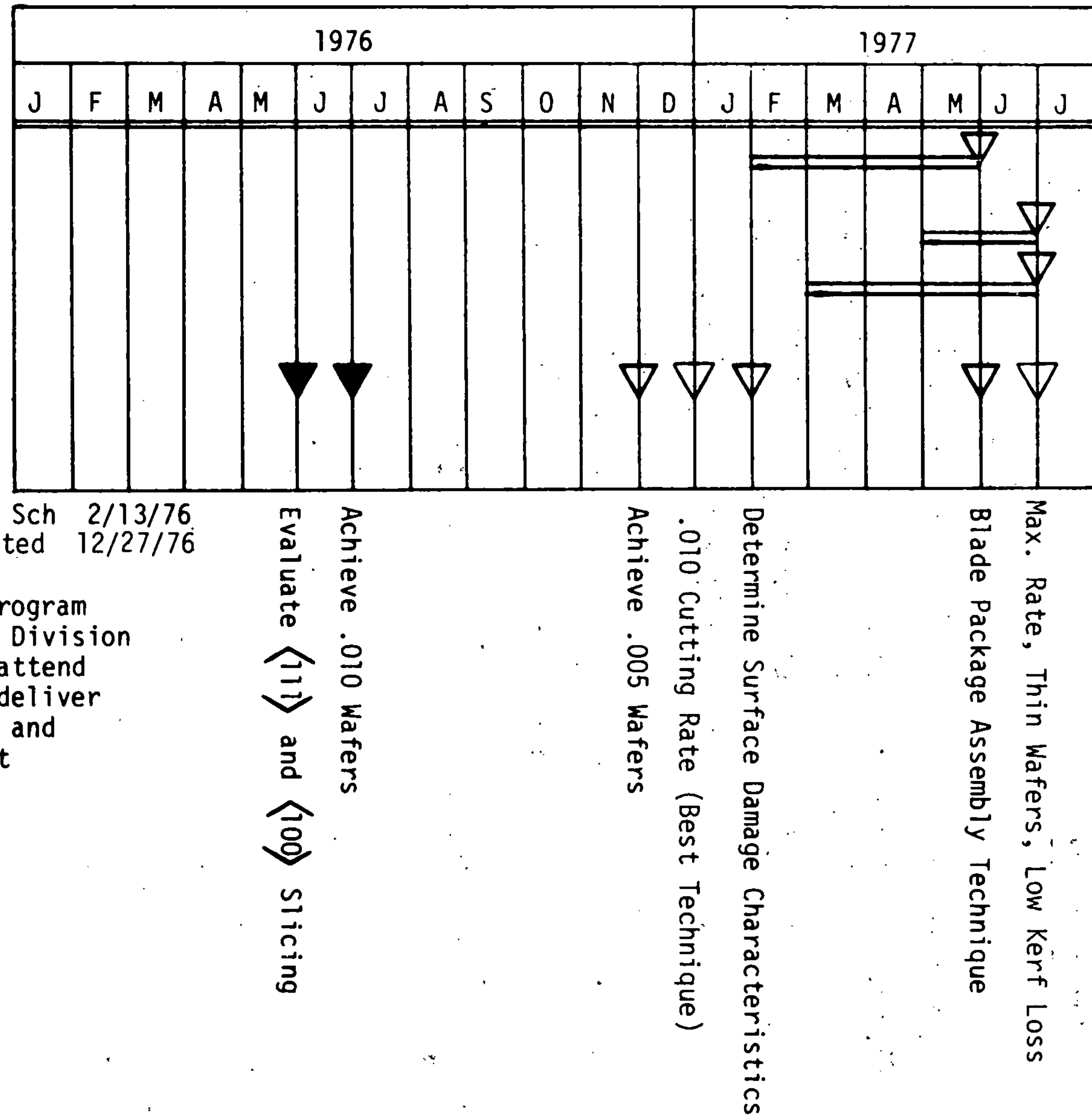
3. Load Balancing
   - 3.1. Build feedback control system - rate and force interaction
   - 3.2. Cutting performance vs. results of 1.3.
   - 3.3. Wafer characterization
4. Blade Materials
   - 4.1. Cutting tests - optimum blade material, thickness, etc. for silicon
   - 4.2. Wafer characterization
5. Abrasives
   - 5.1. Cutting tests - optimum size, slurry mix, application technique
   - 5.2. Wafer characterization
6. Prototype Production Technique
   - 6.1. Optimize previous results within guidelines of wafer specifications
   - 6.2. Modify equipment



Sch 1/22/76
Updated 12/27/76

7. Evaluation
   - 7.1. Cutting tests with final system
   - 7.2. Economic evaluation, scale-up potential
   - 7.3. Wafer characterization

8. Milestones

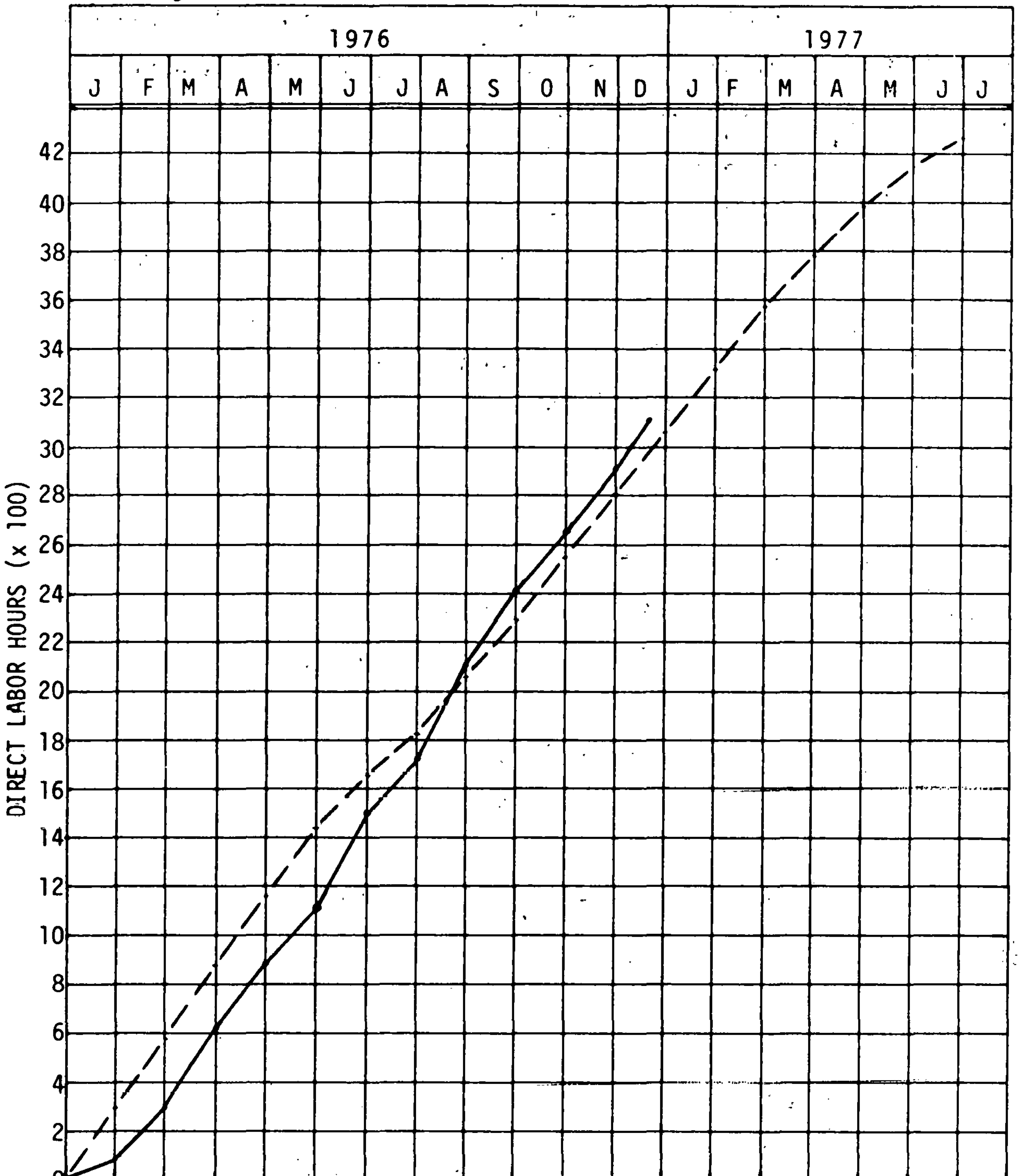


Sch 2/13/76
Updated 12/27/76

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

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



Sch 1/22/76
Updated 12/27/76

TOTAL HOURS: 4,260 PLANNED HOURS — — —
HOURS TO DATE: 3,112.4 INCURRED HOURS ———

PROGRAM LABOR SUMMARY

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

Program Plan
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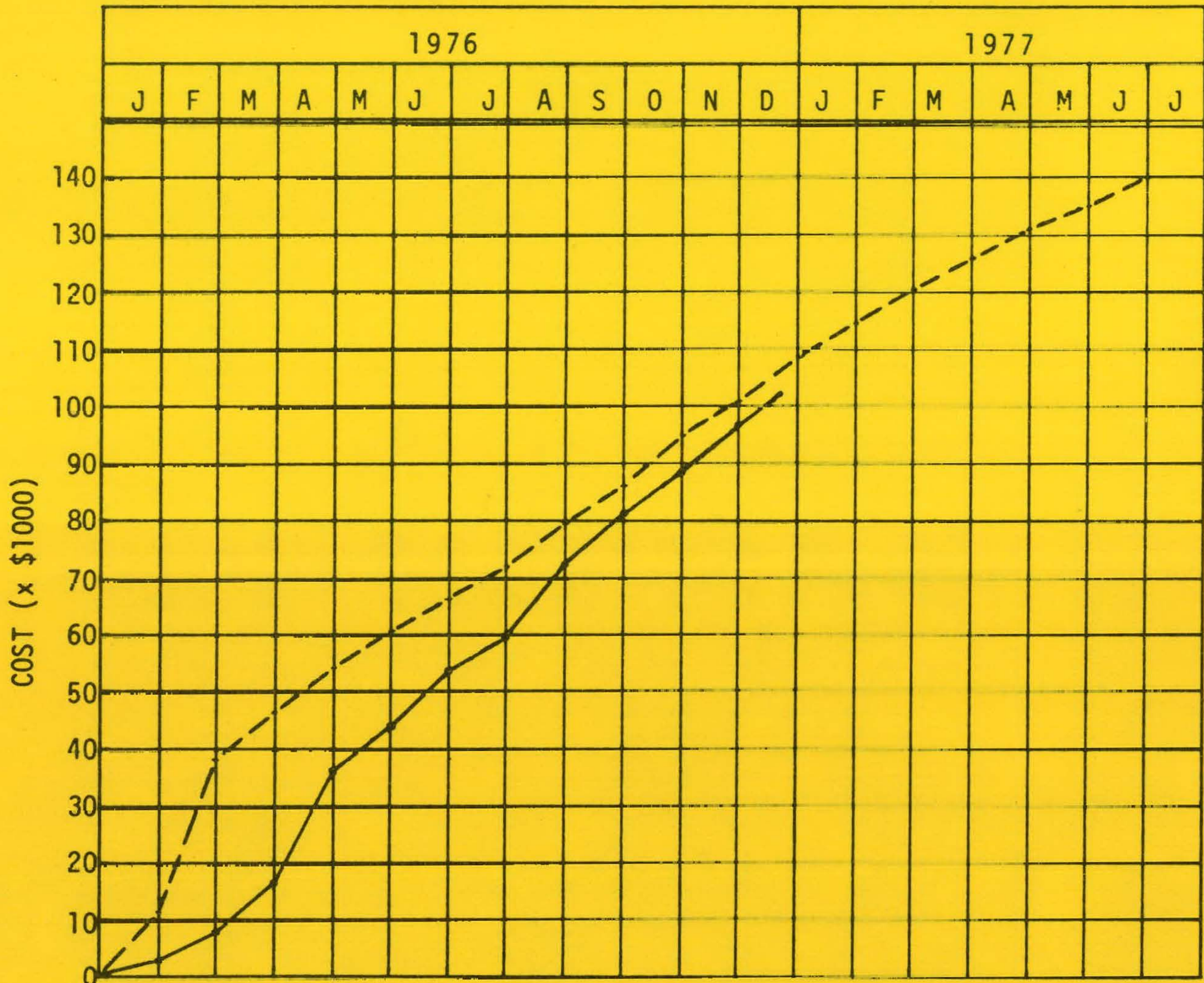

Sch 1/22/76
Updated 12/27/76

TOTAL COST: $140,000
COST TO DATE: $101,951

PLANNED COST — — —
INCURRED COST ———

PROGRAM COST SUMMARY