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OVERVIEW OF A NEW SLICING METHOD-- FIXED ABRASIVE SLICING TECHNIQUE (FAST)*

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ABSTRACT

FAST is a new slicing technique that has been developed to slice silicon ingots more effectively. It has been demonstrated that 25 wafers/cm can be sliced from 10 cm diameter and 19 wafers/cm from 15 cm diameter ingots. This has been achieved with a combination of machine development and wire-blade development programs. Correlation has been established between cutting effectiveness and high surface speeds. A high speed slicer has been designed and fabricated for FAST slicing. Wirepack life of slicing three 10 cm diameter ingots has been established. Electroforming techniques have been developed to control widths and prolong life of wire-blades. Economic analysis indicates that the projected add-on price of FAST slicing is compatible with the DOE price allocation to meet the 1986 cost goals.

INTRODUCTION

Silicon crystals have been sliced into wafers for the semiconductor industry by the Internal Diameter (ID) and Multiple Blade Slurry (MBS) techniques. While these processes were developed for semiconductor applications, they cannot be utilized, as they exist today, for photovoltaic applications. Unlike semiconductor devices where silicon material constitutes sometimes less than one per cent of the cost, the cost of silicon wafers comprises about half the cost of a solar panel. The wafering technique to produce silicon wafers from ingot is one of the important steps towards reducing costs for terrestrial photovoltaic applications. The slicing process must be low cost and must combine minimum kerf plus slice thickness to achieve high material utilization. With improved material utilization alone, the contribution of the cost of polysilicon and crystal growth for photovoltaic power generation, dollars per peak watt, is significantly reduced. Therefore, material utilization is critical for reducing costs to make photovoltaics a reality for terrestrial applications.

Besides being most developed and commercially available, the advantages of an ingot process towards making sheet are high throughput, purification of meltstock during growth, consistent quality, simple instrumentation and control; however, material utilization and kerf in slicing limits the low-cost potential. In fact, the justification for silicon ribbon processes is based on the premise that slicing cannot be cost effective. As the cost of polysilicon meltstock is reduced to the goal of $14/kg kerf losses in slicing become less significant but material utilization is still critical. The combination of an effective slicing process with an ingot process, such as the Heat Exchanger Method (HEM), allows the economical production of square shaped high conversion efficiency material to produce high power density modules at low cost.

SLICING TECHNIQUES

The essential parameters for a slicing technique for photovoltaic applications are (i) low-cost process, (ii) low expendable costs, (iii) high material utilization and (iv) produce high quality product. There are three commercially used wafering processes, *viz.*, ID, MBS and Multiple Wire Slurry (MWS) techniques. A comparison of the parameters for these wafering methods is shown in Table I. It can be seen that the advantages are low expendable material costs in ID, low equipment and labor costs in MBS, and high material utilization in MWS; however, tne ID is limited by material utilization, and MBS and MWS by their high expendable materials costs. A new slicing technique under development, the Fixed Abrasive Slicing Technique (FAST), combines the low expendable material advantage of ID, low equipment and labor costs of MBS and high material utilization of MWS.

TABLE I. A Comparison of the Essential Parameters of Wafering for Different Slicing Techniques

Parameter	ID	MBS	MWS	FAST
Equipment costs	High	Low	High	Low
Labor supervision	Medium	Low	High	Low
Throughput	Medium	Medium	Low	High
Expendable costs	Low	High	Very high	Low
Material utilization	Low	Medium	High	High
Surface damage	High	Medium	Medium	Low

In the FAST process (1) a multiple-wire bladepack is stretched in a frame and reciprocated on rails. Diamond is fixed onto the wires and used as an abrasive for slicing silicon. Diamond has been demonstrated to be an effective abrasive for silicon via the ID process and, therefore, the expendable materials costs are kept low. The simplified equipment concept of reciprocating bladehead keeps the FAST slicer costs low and this has been proven by the MBS. The best material utilization of wire slicing (2) is also incorporated in FAST. This feature is possible with wire because once the wire cuts through it no longer contacts the workpiece, hence less clearance is necessary. This reduces kerf and also make it possible to slice thinner wafers. In the MWS the silicon being sliced is completely lost when a wire breaks. For the FAST approach, a broken wire results in loss of two wafers it is contacting. In addition to the above advantages to FAST the surface damage of the sliced wafers is lower (3) than that reported for other slicing technologies (4).

FAST is a new slicing technique that has been developed to slice ingots more effectively. Work has been carried out in three areas, *viz.*, machine development, blade development and testing.

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FIXED ABRASIVE SLICING TECHNIQUE (FAST)

Machine Development

Initially a MBS slicer was used for evaluation of FAST slicing. Prior work reported in literature showed very limited success with slicing using diamond plated flat blades and wires. In the development of FAST it was found that the slicing is heavily dependent on pressure at the diamond tips during slicing. Effective slicing was not achieved with diamond plated wires used in a conventional MBS setup because of insufficient pressure at the cutting edge. Significant improvement was achieved when the crystal was rocked. Under this condition the kerf length or contact between the wire and the workpiece was minimized thereby maximizing the pressure at the diamond tips used in slicing. The MBS slicer was further modified by changing the feed system; the feed forces required for wire slicing were considerably lower than used in MBS slicing, hence a more sensitive and reproducible feed mechanism was incorporated. Grooved guide rollers were also installed on either side of the workpiece so that the feed force could be increased as well as to improve the slicing accuracy. With all the modifications to MBS equipment the workpiece size was limited to 4 cm x 4 cm cross-section. The concept of FAST was proven by demonstrating (i) slicing 25 wafers/cm at high yields, (ii) slicing wafers to a thickness as low as 100 μm, (iii) reducing kerf width to as low as 160 μm, (iv) absence of any edge chipping in sliced wafers and (v) surface damage depth of 3-5 μm (3).

Experience with the modified MBS slicer showed some essential parameters which could not be incorporated. A new high speed slicer was designed and fabricated. The essential features of this machine were lightweight bladehead, longer stroke, sensitive feed mechanism, crystal rocking assembly, variable guide roller position and vibration isolation of the drive unit. A schematic of the bladehead is shown in Figure 1. This unit is designed to accommodate up to 30 cm long and 15 cm diameter workpiece. The lighter bladehead and longer stroke allowed faster reciprocation and, consequently higher surface speeds; 130 meter/min has been achieved with this unit as compared to 30 meters/min with the modified MBS unit. A more rigid support system minimized vibrations at these high speeds.

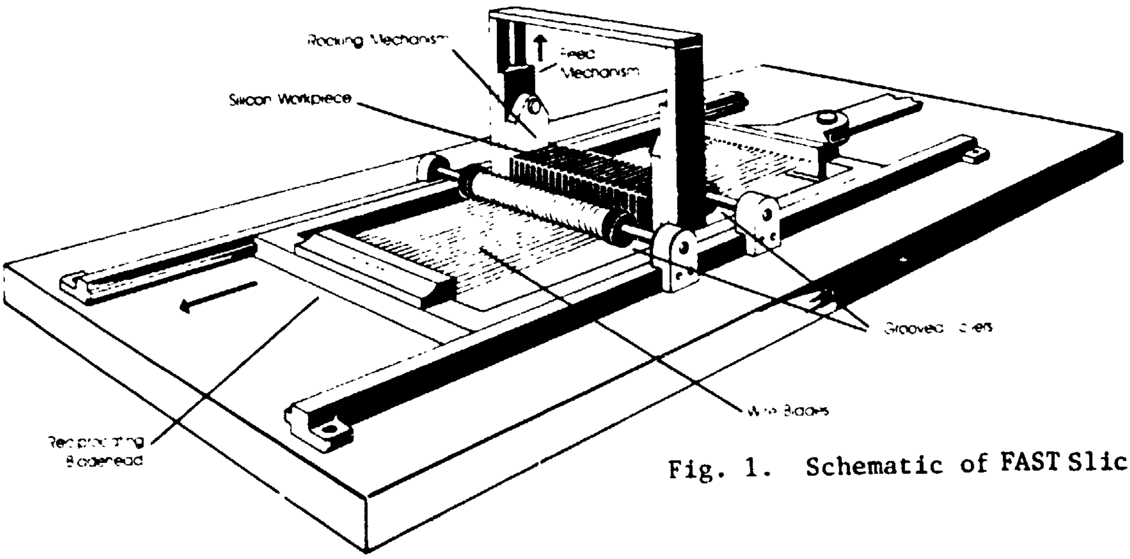

Fig. 1. Schematic of FAST Slicer

The prototype slicer designed is a two-bladehead unit linked to a single drive unit. The two bladeheads will be reciprocated 180° out of phase so that the acceleration forces will be counterbalanced equal and opposite, thereby cancelling each other. This will allow even higher speeds, less vibration and more effective slicing.

Blade Development

In order to slice effectively it is imperative to have a good blade; for FAST slicing it is important to develop effective wire blades. More detailed information on this aspect is discussed in another paper of this conference (5). In the initial stages of FAST development the only fixed abrasive wires available were diamond impregnated wires (6). Testing with these wires showed that they suffered diamond pull-out. Nickel plating of commercially available wires prolonged their life.

A wire-blade development program was, therefore, initiated to produce fixed-abrasive wires for FAST slicing. Two types of approaches were pursued, viz., impregnated blades and electroplated blades. In the former case diamonds were pushed into a soft copper sheath on a high strength core; this wire was then nickel-plated to prevent diamond pull-out. Techniques were developed to impregnate diamonds in the cutting edge only--the bottom half-circumference of the wire. Significant advances were made but this approach needs much more development.

Prior to this program there was no source of electroplated wires. Even though plating of ID blades is carried out in the industry the large surface area-to-volume ratio in the case of wires presented problems. Electroplated wire-blade development has involved optimization of type and size of wire core; coatings on the wire substrate; nature, type and size of diamonds; plating baths, etc. (5). Techniques have also been developed to electroform the diamond plating to reduce kerf and achieve long life of the wirepacks (5).

Testing

The present work is a report on slicing of 10 cm diameter, 10 cm x 10 cm cross-section and 15 cm diameter silicon workpieces at 19 wafers/cm. With 10 cm diameter even 25 wafers/cm have been demonstrated.

One of the first variables studied by FAST was the surface speed. Figure 2 shows slicing tests of 10 cm diameter as a function of surface speed. A comparison of data from Tests A and C shows that by doubling the surface speed the average slicing rate increased from 59 µm/min to 145 µm/min, a factor of 2.45. Test B was carried out using the same wirepack as Test A for a second slicing life test. The average slicing rate for Test B was 122 µm/min, a slight decrease showing deterioration of cutting effectiveness. The data in Figure 3 is for slicing tests using a mixture of 15, 30 and 45 µm diamond size electroplated wirepack spaced at 19 wires/cm and shows a life of three 10 cm diameter ingots at an average cutting rate of 127, 82 and 75 µm/min. The surface speed during this experiment was 120 meters per minute.

Figure 4 shows the slicing test carried out using the same electr ed wirepack. The diamond size used was 30 µm and the surface speed of t . S1

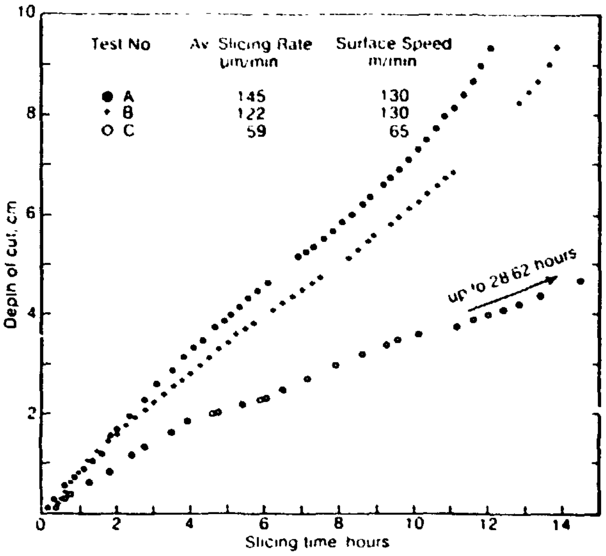

Fig. 2. Slicing performance showing the effect of surface speed

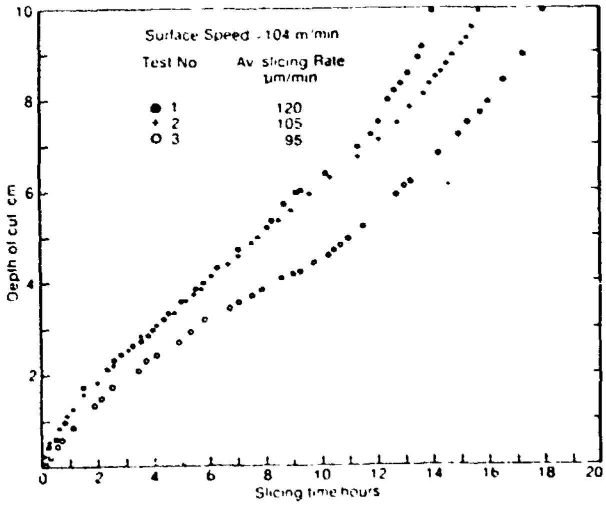

Fig. 4. Slicing performance from the same wirepack using 30 µm diamonds

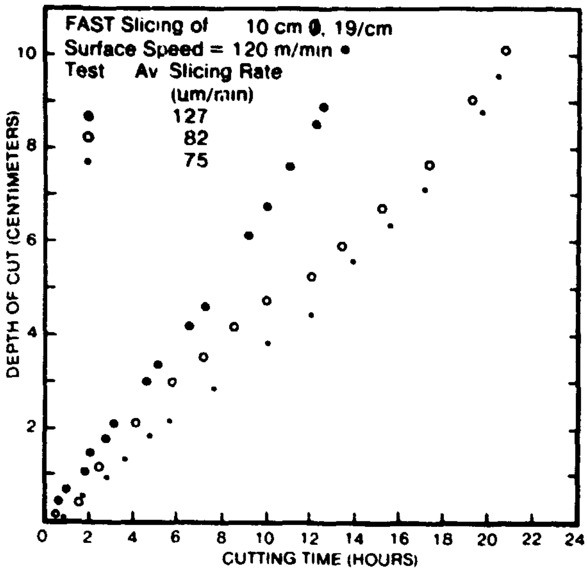

Fig. 3. Slicing of three 10 cm Ø ingots using same electroplated wirepack

slicer was 104 meters per minute. The average slicing rate for tests 1, 2 and 3 were 120, 105 and 95 µm/min respectively.

A similar test with wires impregnated with 45 µm diamonds showed an average slicing rate of 72 µm/min on a 10 cm diameter workpiece. These wires could not be used for a second slicing test; in fact toward the end of the first test wafer breakage was observed which was attributed to loss of cutting effectiveness.

In order to reduce the kerf width for slicing 25 wafers/cm a 30 µm diamond electroplated wirepack was used. During the first test a 99.1% yield (222 out of 224, 10 cm diameter wafers) was achieved with an average slicing rate of 77 µm/min. In this test low feed forces of only 24.4 gms/wire were used. Very good surface quality of wafers was achieved and the average wafer thickness of 0.195 mm with a kerf of 0.205 mm. During the second slicing test the average slicing rate dropped to 45 µm/min and the yield was only 36.2%. The average wafer thickness increased to 0.249 mm with kerf of 0.151 mm. The data shows that during the first slicing test considerable diamonds from the sides of the wires were pulled out, thereby reducing kerf, increasing wafer thickness and decreasing the average slicing rate. The plot of the depth of cut with time is shown in Figure 5.

Slicing tests with 15 cm diameter silicon workpiece were also carried out. For the larger kerf length 60 µm natural diamonds were electroformed into a

V-shape so that the diamonds were fixed only in the cutting edge of the wires. The average slicing rate was 74 µm/min. This is considerably higher wafering rate especially in view of the larger kerf length. During the test some wire wander was observed because the diamonds on the top surface of the wires could not be completely eliminated. The non-uniform nature of the top surface caused perturbation and, therefore, the wires did not seat well in the guide rollers. The data for this run is shown in Figure 6.

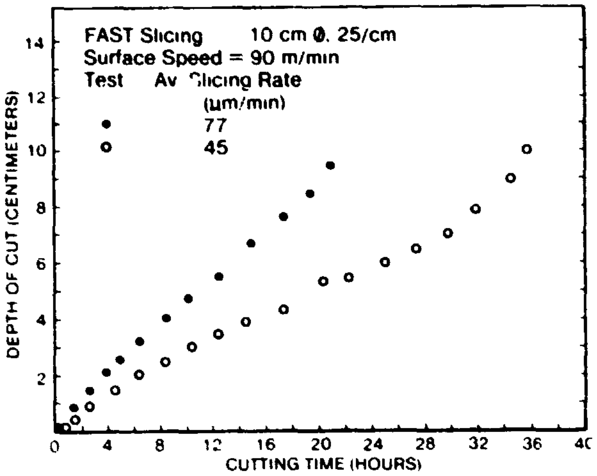

Fig. 5. Slicing results of 10 cm Ø ingots at 25 wafers/cm

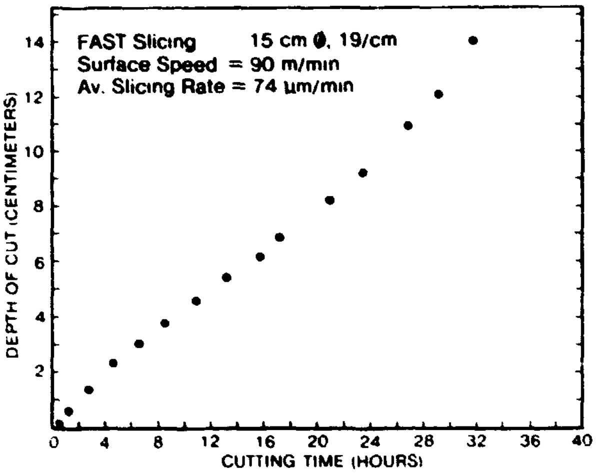

Fig. 6. Slicing performance of 15 cm Ø ingot

ECONOMIC ANALYSIS

The economic analysis has been carried out to estimate the projected add-on price of FAST slicing using IPEG methodology (7). It is intended to use a FAST slicer with two bladeheads reciprocating 180° out of phase. Each bladehead will slice a 10 cm x 10 cm x 30 cm bar to produce wafers of 10 cm x 10 cm cross-section. Two types of scenarios were developed, a conservative and an optimistic case, to estimate the projected price. The assumptions and the final add-on price are shown in Table II. Even in the conservative case the final value is less than half of the price allocation (8) for ingot technologies to meet DOE price goal of $0.70/peak watt in 1986.

CONCLUSION

The Fixed Abrasive Slicing Technique (FAST) combines the low expendable materials advantage of ID, low equipment and labor costs of MBS and high material utilization of MWS. Besides FAST produces a wafer which shows no edge chipping and with a surface damage of only 3-5 µm. This new slicing technique was initially developed by modifying a MBS slicer. After establishing the proof of concept a high speed slicer was designed and fabricated.

Techniques were developed to produce wirepack with equal spacing and tension. The wire-blade development program has involved impregnation and electroplating techniques. It has been shown that diamonds can be fixed only in cutting edges of wires. With electroforming it has been possible to control the shape and size of the plating.

Slicing effectiveness has been demonstrated on 10 cm and 15 cm diameter ingots. It has been possible to slice 25 wafers/cm on 10 cm diameter ingots and 19 wafers/cm on 15 cm diameter ingots. A blade life of slicing three 10 cm diameter ingots has been demonstrated.

Projected economic analysis has shown that the FAST technique will be able to slice silicon ingots effectively to meet the DOE price allocation for 1986 goal of $0.70 per peak watt.

TABLE II. IPEG ANALYSIS FOR VALUE ADDED COSTS OF FAST SLICING USING CONSERVATIVE AND OPTIMISTIC PROJECTIONS OF TECHNOLOGY

	Estimate	
	Conservative	Optimistic
Equipment cost, $	30,000	30,000
Floor space, sq.ft.	80	80
Labor, units/operator	5	10
Duty cycle, %	90	95
Set-up time, hrs	1.5	1.0
Slicing rate, mm/min	0.1	0.14
Slices/cm	22	25
Yield	90	95
Expendables/run, $	28	14
Motor power, h.p.	5	3
Conversion ratio, m^2/kg	0.85	1.0
Add-on Price, $/$m^2$	13.13	5.9

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DISCUSSION:

JACKSEN: Could you give us some taper and wafer-to-wafer dimensional variations, especially when you were cutting 4-mil wafers?

SCHMID: In the initial work with the 686, to cut 25 per centimeter you have to be slicing with reasonably good accuracy. Those tests were performed with much larger kerf. Basically we were looking at 10 mils. So we actually were slicing wafers around 5 mils thick and were seeing taper of maybe a thousandth of an inch. On the new machine we are seeing less than that at the higher speed. As your cutting rates go up your accuracy tends to get better.

JACKSEN: You mentioned this reciprocating machine. Has that machine been built or do you anticipate it being built?

SCHMID: The machine that we have is an R&D prototype and we feel that that machine is very similar to the prototype machine that would be used as the production prototype. There isn't that much change.

JACKSEN: The main reason I am asking is to understand what increase you can expect from your productivity figures from that reciprocating machine. Obviously you are running at a higher rate of meters per minute and I was wondering what you projected your meters per minute of slicing rate would be with a reciprocating machine.

SCHMID: We now are running between 350 and 400 feet per minute for most of these tests. We have gone through all of the calculations and we think by balancing it out you save horsepower, you take out vibration and you can go to higher speeds which does help you in your slicing performance. That is why we would expect to be able to exceed the actual cutting rate that we have set here as a goal.

DYER: You were mentioning that you had facilities for accurate alignment. If you are going to put something into production for an industry that has to produce slices cheaply then it has to be something that an operator can do easily and without a great deal of training. What I envision in that is perhaps something where you have the alignment fixture on a cart and push it up against the machine and clamp, pull something towards them and lock it in. You shouldn't have to expect them to read a dial indicator or anything like that.

SCHMID: This is the R&D machine in which we had to make sure that we did have the accuracy. Once the machine is set up there is no reason to have to realign it. It is nice to be able to have a serviceman come in and check to be sure that it is lined up properly, and that really is the goal. As for the tensioning, the way we tension these wires is by elongation and that is where you do have to read a micrometer.

DYER: Doesn't the saw blade have to be lined up every time you put a new pack on?

SCHMID: With this technique it is possible to circumvent that. We now are checking it optically to see that the wires are running true.