I.D. WAFERING TECHNOLOGY

PETER AHARONYAN
SILICON TECHNOLOGY CORPORATION
OAKLAND, N.J. 07436

First developed in the late 1950's, I.D. wafering began to replace other wafering techniques such as the multi-blade slurry saw and the O.D. saw. By 1963 I.D. wafering had become the preferred production tool for wafering silicon and other semiconductor materials. During the past two decades, semiconductor wafer manufacturers have investigated a wide variety of slicing techniques, such as laser cutting, high pressure fluids, wire saws and band saws. Today, the I.D. saw still remains the most accurate and economical way of wafering semiconductor wafers.

The majority of wafers cut are usually three to four inches in diameter with five and six inch wafers beginning to be used on a limited basis. These dimensions compare with one-half inch and one inch crystal diameters in the 1960's. The machines have also increased in size from early saws that had six or eight inch blades to our experimental machine which supports a thirty-two inch blade, capable of slicing nine inch diameter wafers.

Production history of the I.D. saw is based on an estimated 2,500 saws being used worldwide. Majority of wafers are usually 20-30 mils thick with 10-14 mils of kerf loss. Estimated add-on costs are about $.29 per wafer for the semiconductor industry.

Although semiconductor manufacturers are concerned with wafering costs, raw materials represent only a small fraction of the cost of a finished device. Wafer quality, flatness and dimensional accuracy are very important. In photovoltaics the cost of a silicon wafer represents a substantial portion of the cost of a finished panel. To reduce raw material costs, research has been aimed at reducing the cost of silicon, reducing the amount of material per unit area of photovoltaics cells, and reducing the add-on cost for manufacturing silicon in sheet form suitable for solar cells. In terms of material usage and add-on cost, a variety of ingot wafering technologies and other technologies which do not require slicing such as silicon ribbons have been investigated both by government and private funding.

During the past few years, I.D. wafering has emerged as a viable alternative for slicing silicon ingots for solar cells. Unlike semiconductors, the main goals for wafering for photovoltaics are reduction in the amount of silicon used per unit area and a reduction in the add-on cost of wafering.

Based on a desired goal of producing photovoltaic power at $.70 per peak watt by 1986, and a projected cost for inexpensive silicon, wafering technology must be able to yield 25 wafers per cm from a 4 inch ingot and 18 wafers per cm from a 6 inch ingot. (The cost for producing ingots becomes less as ingot size is increased. It also becomes more difficult to handle very thin. large diameter ingots.) The add-on cost for wafering must be about $15 per square meter of wafers produced.

SLICING INFLUENCES

Some of the work we have been doing for the past two years indicates that the I.D. saw can reach these goals in the desired time frame.

As crystals are made larger, the blade size must also be increased, and in order to keep the blade from wandering axially in the cut, blades must be made thicker.

TABLE 1
BLADE SIZES

Max. Crystal size	Blade size	Av. Kerf loss
3-1/2 inch	16-5/8 inch	11 mils
5 inch	22 inch	13 mils
6 inch	27 inch	14 mils
9 inch	32 inch	16 mils

One of the primary causes for blade failure is due to blade wander during slicing and rubbing either the crystal or the wafer on the blade core. Cross sectional analysis of many blades that have been replaced after a few thousand cuts has shown that much of the original cutting edge diamonds still remain. A blade would have to slice more than 10,000 wafers before the diamonds on the cutting edge are completely worn.

One area of research is being aimed at finding suitable core materials which can be made thinner and yet provide adequate strength to minimize blade wander. We have begun to make experimental 22 inch blades using 4.8 mil cores as compared with our standard 6 mil cores. The 4.8 mil cores have yielded blades with 10.5 mil kerf loss. Using these blades, we have been able to slice some 4 inch material down to 5.5 mils thick which yields 25 wafers per centimeter. We have also sliced 6 inch diameter crystals at a thickness of 12 mils with 13 mils kerf loss which has yielded 16 wafers per centimeter. The 6 inch diameter crystal was sliced on our experimental 32 inch saw. We will be introducing a 27 inch saw for slicing 6 inch diameter crystals during June 1981. The 27 inch saw with the smaller blade should yield 18 wafers per centimeter for 6 inch diameter wafers. Add-on costs have been $42.50 for the 4 inch wafers and $25./6 for the 6 inch wafers. Add-on costs are calculated using the IPEG 2 equation as developed by the Jet Propulsion Laboratory. A version of the IPEG 2 equation which can be directly used for analyzing I.D. wafering costs is presented at the end of this paper. The equation assumes a three-shift operation. The second line of the equation adds the cost of silicon. A 1.2 factor has been applied to the cost of silicon. If only add-on costs are needed, the cost of silicon can be made zero. Blade cost is spearated as the third line of the equation. Blade life is represented as number of cuts per blade.

During our slicing experiments, we found that our results depend on the type of crystal we are slicing. Ordinarily, solar cells are sliced along the 1-0-0 crystal orientation because the wafers can be texture etched. Our tests indicate that the 1-1-1 orientation is much easier to slice, allowing thinner wafers at a lower add-on cost. Also, 1-1-1 wafers have much less chipping and breakage. We have also found a great deal of difference among the variety of cast polycrystalline ingots. We were able to slice one type of cast ingot at 5.5 mils thickness at one inch per minute. In one of the other samples, wafer thickness had to be increased to 8 to 10 mils to maintain the same slicing speed. Our yields with the second sample were very poor because the wafers were very weak and tended to break during cleaning. We think that the difference between the samples was due to stress and cracks in the poorer ingots. Annealing and etching the ingots may help theif performance.

ECONOMIC ANALYSIS

There is a definite inverse relationship between the length of time it takes to slice a wafer and wafer thickness. If ingot cost is included in the total cost of a wafer, there will be a trade-off between increased add-on cost, as wafer thickness is decreased, and increased material cost, as slicing speeds are increased. Figure 1 shows our estimates on wafer thickness and corresponding time to slice. Kerf loss and yield are kept constant. The calculated costs are shown in figure 2. The cost of silicon is varied from $20 to $200 per kilogram. The optimum speed and thickness appear to be relatively insensitive to ingot cost. For low cost silicon, wafer cost increases much more rapidly if the wafer is made thinner as opposed to increased costs due to an increase in wafer thickness. The curves we generated for wafer thickness and slicing speed were our estimates for our own slicing laboratory. Other slicing operations will usually have thicker wafers for the same speeds, however, the shape of the curves should be similar.

Fig. 1

TIME PER SLICE VERSUS WAFER THICKNESS

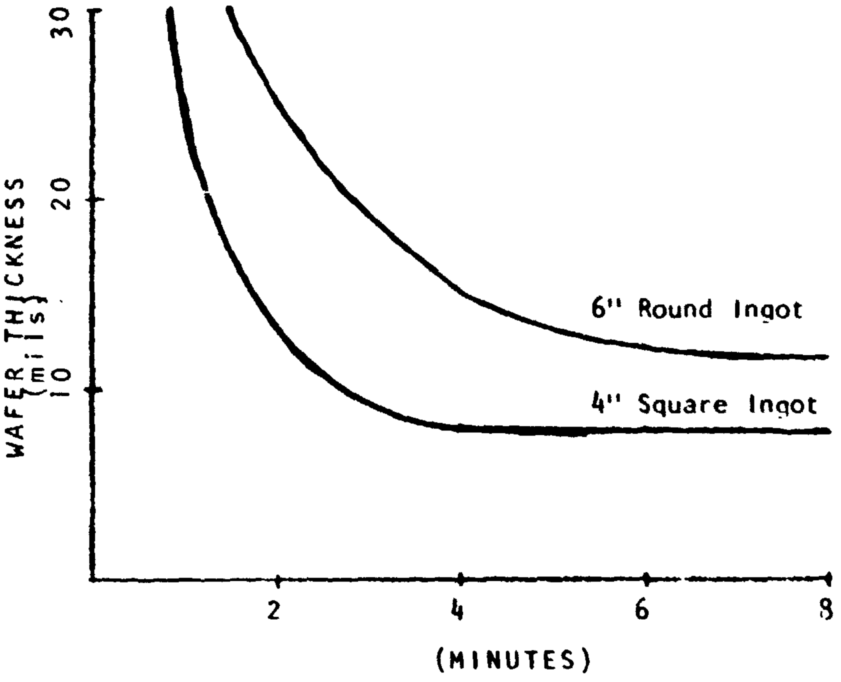


Fig. 2a

4 INCH SQUARE INGOTS

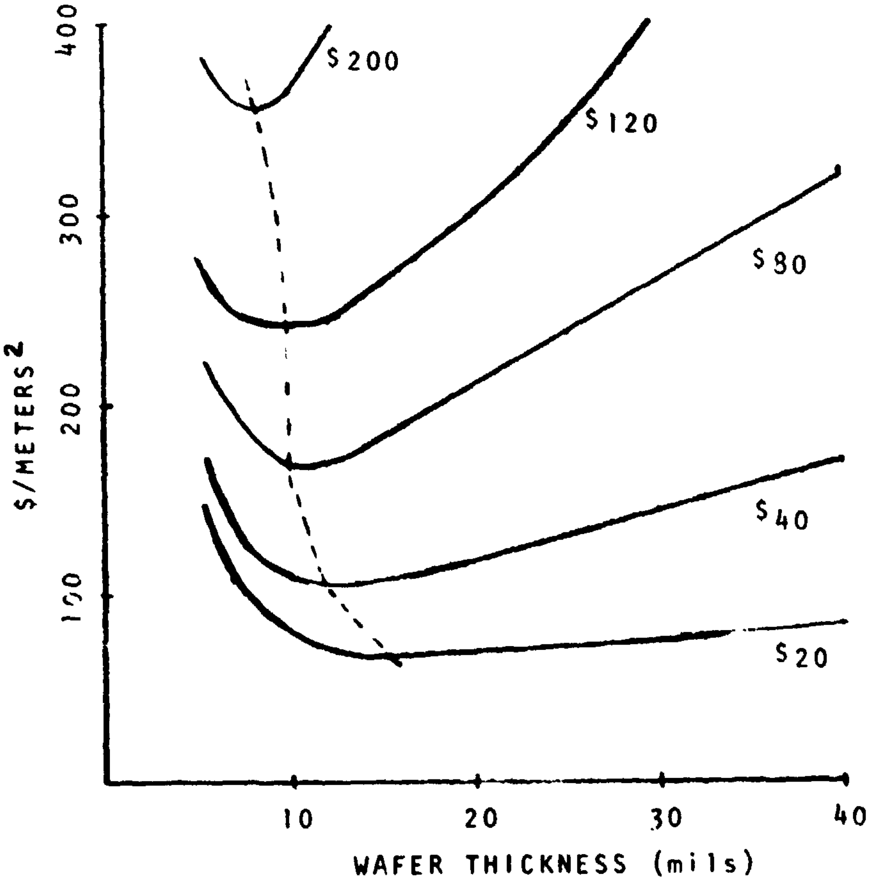
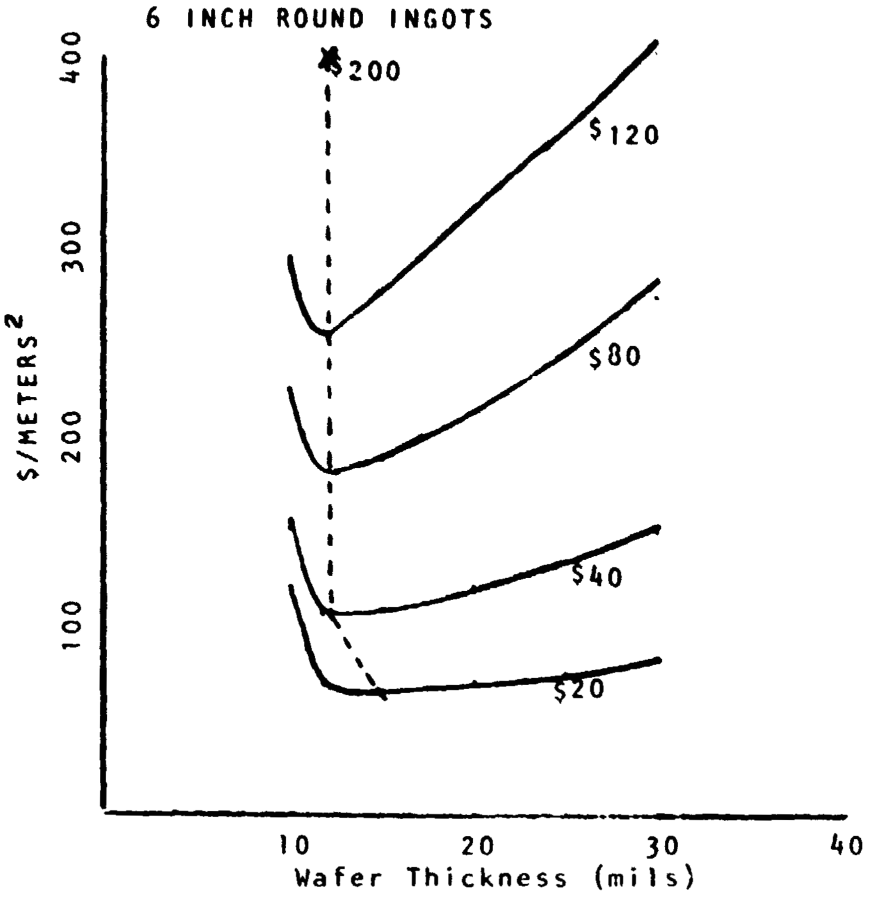


Fig. 2b



The dotted lines represent minimum cost.

Table 2 is an analysis of the relative importance of all the cost parameters, given one particular scenario for present day wafering capability. The third column is a dimensionless number which shows the percent change in total cost with percent change in the various parameters. Yield is by far the most important factor in controlling wafer cost. The calculated sensitivity values depend on the absolute value of the parameters; however, they give a good indication of the relative importance of each of the cost elements.

TABLE 2

COST SENSITIVITY ANALYSIS
on 10cm Square Ingots

COST PARAMETER	VALUE	$\dfrac{\Delta\,\text{TOTAL COST}\,/\,\text{TOTAL COST}}{\Delta\,\text{PARAMETER}\,/\,\text{PARAMETER}}$
Yield	.95	-.99
Ingot Cost	$40	.67
Ingot Size	10cm	-.37
Wafer Thickness	12mils	.34
Kerf	11.5mils	.33
Hours/day	20	-.29
Days/year	360	-.29
Slicing Speed	2 inches/min	-.28
Equipment Cost	$40,000.	.13
Labor Cost	$12,500.	.10
Floor Space	84 Sq. Ft.	.06
Blade Cost	$100.	.04
Blade Life	3000	.04
Utility Cost	$1,676.	.01

Total Cost = $105.17/Meter^2

DEVELOPMENT PROJECTS

Our work will be aimed at larger capacity machines, machine automation, and blade development. We have reduced blade core thickness by 1.2 mils for the 22 inch blades. We plan to investigate other material which may allow us to further decrease kerf loss. We will also investigate other matrixing material for bonding diamonds to the cutting edge.

Our next generation machines which will be introduced in June 1981 will have a 6 inch wafering capability. The machine will be fully automated in retrieving and cassette loading wafers. We have incorporated microprocessor controls which will allow future developments in communication with a centralized computer and feed back controls to further automate the machine.

Long-term development projects include 8 and 9 inch wafer capacity machines with centralized computer control and feed back loops to control feed rates and dressing. We also plan to introduce other equipment which will automate the line.

Based on D.O.E. requirements and our development pla the economic analysis for the future generation of saws is given in table 3 for 4 and 6 inch wafers, respectively.

TABLE 3

ECONOMIC ANALYSIS

4" SQUARE INGOT

T = 7 mils
K = 9 mils
S = 4 inches/min.
Equipment = $40,000
Floor Space = 84 square feet
Labor rate = $12,500/year, 4.7 shifts/year, 10 saws/operator
Utilities + Material = $1,676 /year
20 hours per day
360 days per year
Blade cost = $50.00
Blade Life = 4,000 wafers
Add-on Cost = $16.33
25 wafers/cm

6" ROUND CRYSTAL

T = 12 mils
K = 10 mils
S = 3 inches/min.
Equipment = $40,000
Floor Space = 84 square feet
Labor rate = $12,500/year, 4.7 shifts/year, 10 saws/operator
Utilities + Materials = $1,676/year
20 hours per day
360 days per year
Blade Cost = $80.00
Blade Life = 4,000 wafers
Add-on Cost = $15.83
18 wafers/cm

WAFERING COST MODEL BASED
ON THE IPEG 2 EQUATION

$$\text{Cost}/M^2 = \left[\frac{10{,}000\ (.52 \times E + 109 \times FT^2 + 2.8 \times L + 1.2 \times U)}{\frac{60rsD}{(r+s)} \times \frac{\pi}{4} \times (\text{hrs/day}) \times (\text{Days/Year})^{*}} \right.$$

$$+ \quad 2.33 \times 1.2 \times (T+K) \times (\text{Ingot Price})$$

$$\left. + \quad \frac{1.2 \times 10{,}000}{\frac{\pi}{4} \times D^{2**}} \times \frac{(\text{Blade Cost})}{(\text{Blade Life})} \right] \times \frac{1}{\text{Yield}}$$

*Substitute $\frac{60rs\ L \times W}{(r+s) \times L1} \times (\text{hrs/day}) \times (\text{Days/year})$

for Square or rectangular ingots

**Substitute $\frac{1.2 \times 10{,}000}{L \times W}$

for square or rectangular ingots.

Where:

E = Equipment Cost
Ft^2 = Equipment Area in Square Feet
L = Direct Labor Cost/machines per operator
U = Utility cost plus supplies
S = Slicing Speed (cm/min)
r = Return speed of blade (cm/min)
D = Diameter of round ingot (cm)
L&W = Lenth & Width of rectangular ingot
L1 = Cutting stroke length on square or rectangular ingot
T = Wafer thickness (mm)
K = Kerf (mm)
Life = Number of slices/blade

DISCUSSION:

WERNER: You mentioned new methods or ideas to put the diamond on the blades. Can you be a little more specific about that?

AHARONYAN: All blades are plated using nickel today. We have thought about using different plating materials and perhaps getting away from plating and using some sort of an epoxy bond for the diamonds or maybe a sinter bond.

In our lab, we have vibration analyzers on our machine. The main reasons the machines go out of balance is that some dirt is thrown up into the cutting head while it is spinning at fairly high rpm--1500 or 1600 rpm--and this causes a vibration. The head has to be kept clean, so we are looking at new ways of doing it, but besides warning that the thing is out of balance there is really not too much we can do. We have looked at putting automatic balancing into some of these machines and we may experiment with that. But the best way to do it is to keep the machine clean.

DYER: Are these heads twice as massive?

AHARONYAN: They are at least twice as massive, but the spindles themselves are larger and stiffer so that we actually wind up with less deflection on the bigger heads than we did with the small ones.

QUESTION: You mentioned that you got some yield improvement by heat-treating the crystal before cutting it.

AHARONYAN: We have heard of that. We haven't done it ourselves. We know some people that do and there seems to be an indication that there is some yield improvement.

FUERST: We are interested in the possibilities of heat-treating ingots before slicing too. Looking at it offhand, you cannot really heat-treat silicon like you would steel where you actually have to recrystallize the structure of the steel. You wouldn't be able to do this with the silicon.

SCHWUTTKE: First of all if you heat-treat a crystal to improve your yield, this indicates that the crystal has a lot of strain. Now the source of strain most of the time is too fast a cooling rate and to get rid of the strain you follow it up by an annealing period. I would suggest, particularly to the polycrystalline people, changing the cooling rate in the first place and they wouldn't have that much strain in the crystal and wouldn't use up time in heat-treating. Same as ribbon material; if you cool too fast, you have a lot of strain.

LANE: You showed a graph earlier that said that if you increase the time of slicing you can get the slice thinner; later, in your cost calculation, you seemed to indicate that the only way we can get the cost down is to slice faster; finally, you showed 25 slices per centimeter in that cost calculation. Do you see that what you are saying raises a critical problem?

AHARONYAN: The reason I did that was because that is a goal that has been set. In the curves I showed, the cost didn't go up steeply at all as we increased the thickness because we were able to cut faster. It may be more advantageous to cut a little bit thicker and reduce some of the other costs, which include the cost of the machine and the factory cost.

LANE: Do you see any routes to going faster in the cut and still getting a thin wafer? Do you have any approaches to that?

AHARONYAN: We are looking at programmed feed and controlling the blade. We have some feedback devices that we are working on now that may allow us to cut faster. Right now the maximum cutting speed is just at the weakest point of that wafer. In other words, right now, if the wafer breaks at the exit edge at a particular speed we go below that speed all the way through. But you may be able to cut faster elsewhere in the wafer. Therefore, programmed cutting may improve speeds somewhat.

YERKES: Is all of your testing done with water?

AHARONYAN: We normally use water with our own coolant. We have cut 4-inch material at an inch a minute. We have cut 5 1/2-mil wafers at an inch a minute but I think that is really pushing the process, and that was not the point of the graph.

YERKES: Now did you cut 100 slices that way, or two or three?

AHARONYAN: We cut maybe a few dozen; we didn't cut many because silicon is expensive and we didn't have that much of the particular crystal that we were cutting. As I said before, the type of crystal made a difference and this crystal happened to be very easy to slice, compared with some of the other crystals.

YERKES: Was that a Cz crystal?

AHARONYAN: It was a casting. This material happened to be, for some reason, a little easier to cut than Cz.

YERKES: Even if the Cz was reoriented to the (111)?

AHARONYAN: (111) may be able to cut at that thinness. We have got a lot of experience with 3-inch cutting with relatively thin dimensions and at fairly good rates. We can cut (111) at 3 1/2 or 4 inches a minute fairly consistently. It just cuts a lot easier than the (100) orientation.

YERKES: When do you plan to have this programmable saw that can saw faster at one point and then slow down at the end?

AHARONYAN: The machine that is going to be introduced this month will have that feature, the 27-inch machine.

SCHMID: Have you noticed any effect that small grain sizes cut easier or better than large grain sizes?

AHARONYAN: It is hard to say. We had three types of cast ingots that we experimented with. The smallest grain size seemed to cut the easiest. I don't know if you can say that it is grain size contributing or it is the method of growing the crystal that was really the important factor.