WAFERING ECONOMIES FOR INDUSTRIALIZATION FROM A WAFER MANUFACTURER'S VIEWPOINT

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Introduction

In assessing the potential of slicing techniques for the photovoltaic sheet industry, a basic issue arises concerning the ability of the wafering equipment industry to meet future needs:

Given the current state-of-the-art in wafering technology, can the technology be further developed to meet and surpass the national goal of $0.70/Wp?

This paper addresses the key technical limitations which inhibit the lowering of value-added costs for these state-of-the-art wafering techniques. From the best experimental results to date a projection has been made to identify those parts of each system which need to be developed in order to meet or improve upon the value-added cost reduction necessary for $0.70/Wp photovoltaics modules.

The major portion of the silicon wafer material used for solar cells today is sliced on the Internal Diameter (ID) and Multi-Blade Slurry (MBS) saws. Although a Multi-Wire Slurry (MWS) saw capable of slicing 10 cm x 10 cm square materials is not commercially available, this saw has been added for comparison and is considered as slicing 10 cm round material. A brief description of the three saw types follow:

1. MBS – The machine under study represents a standard multi-blade slurry system such as the Varian model 7176. The ingot is forced up into the multiple blade assembly, which is reciprocating at a low frequency (80-120 cycles/min.). The material is abraded away from beneath each blade by abrasive particles in a continuously recirculating slurry. The total cutting time for an ingot is long (>15 hours), but the large number of simultaneous cuts provide a wafer area throughput roughly equal to the other two techniques. Expendable materials costs for blades, oil, and abrasive are much greater than with the ID saw, but less than with the MWS. Wafer thickness and taper are also much more difficult to control than with the ID saw. The initial capital investment, however, is two to three times lower than either the ID or MWS saws.

2. ID – The ID saw slices one wafer at a time, but does so at a high output. The rigidity of the annular diamond plated blade edge, combined with high blade speed and diamond abrasive, allows high feed rates to be used. The wafered area throughput is usually higher than for the MBS or MWS saws. The blade is the only consumable used and its cost per wafer is low. In addition, the ID saw has good potential for automation, and cleaning costs after wafering can be reduced significantly. The initial capital investment, however, is higher than for the MBS saw.

3. MWS - A wire saw of the type made by the Yasunaga Engineering Company of Japan is considered here. This saw uses an abrasive lapping process like the MBS saw. Instead of strip steel blades though, a single strand of wire is wound in multiple loops on grooved rollers. Fine wires and abrasive particles allow wafers to be cut at the lowest center to center spacing of any of the techniques. But wire cost is high; consumables costs are higher for this process than for either of the others. Machine wear, especially on the grooved rollers, is a problem. Thus, maintenance is high and reliability low. Capital cost is comparable to the ID saw.

Another type of wire saw which uses a fixed abrasive, such as the FAST saw now under development, has the potential for competing with these other techniques. This saw has not been included here because: (1) it is not commercially available and it is not clear when a production tool will be available; (2) major technical problems are yet to be resolved; and (3), we lack sufficient data on it to make a good comparison.

ECONOMIC MODEL

The flow chart in Figure 1 illustrates how the various cost factors combine to contribute to the final wafer price. Because this cost analysis is concerned only with the wafering aspect of this problem it begins with an assumed ingot cost after sizing. Then, using various wafering assumptions (which are explained in the next section), a final wafer cost is computed for each ingot cost and wafering technique. An explanation of this computational method follows.[1]

We start with the silicon material cost.

A - Ingot Cost ($/kilogram)

In this analysis A is given

B - Material Yield (meters^2/kilogram)

(E1)

$$B = \frac{a}{2.33b}$$

Where a = yield including breakage in decimal fraction
b = center to center spacing of wafers in mm.

C - Silicon Material Cost ($/meter^2)

(E2)

$$C = \frac{A}{B}$$

The next four factors are all machine running costs in $/hour.

(E3)

D - Machine Capital Cost ($/hour)

$$D = \frac{c}{d} \left(\frac{1+f}{e} \quad \frac{2}{2} \right)$$

Where: c = capital investment per machine ($)
d = running hours per year
e = period of depreciation (years)
f = interest rate per year in decimal fraction

E - Labor Cost Per Machine ($/hour)

(E4)

$$E = \frac{g}{h}$$ Where: g = operator cost including overhead ($/hour)
h = number of machines per operator

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F - <u>Power Cost</u> ($/hour)

(E5)

$$F = i \cdot j$$

Where: i = power per machine (kilowatt)

j = energy cost ($/kilowatt-hour)

G - <u>Floor Space</u> ($/hour)

(E6)

$$G = \frac{k \cdot l \cdot m}{d}$$

Where: k = $/foot^2/year

l = area required per saw (ft^2)

m = excess space required (ft^2)

An output figure per machine in meters^2/hour is needed to convert D, E, F and G into wafering add-on costs in $/meter^2.

H - <u>Output</u> (meter^2/hour)

(E7)

For MBS and MWS saws

$$H = \frac{60 \cdot n \cdot a \cdot s}{(1+p) \cdot (q+r)}$$

For ID saws

$$H = \frac{60 \cdot n \cdot a \cdot s}{(n \cdot (1+p) \cdot q) + r}$$

Where: n = number of wafers cut per blade, bladepack, or wire length

p = machine downtime for maintenance over total running time

q = cycle or run time (min.)

r = total time spent on blade installation, work piece change, and dressing for blade or bladepack (min.)

s = area per wafer (meters^2)

Other wafering add-on costs are blades and consumables.

I - <u>Blades</u> ($/meter^2)

(E8)

$$I = \frac{t}{u \cdot a}$$

Where: t = tool cost ($/blade, bladepack, wire length)

u = tool life (meters^2)

For the ID saw, the cost of consumables is negligible. For slurry saws:

J - <u>Consumables</u> ($/meter^2)

(E9)

$$J = \frac{(v \cdot w) + (y \cdot z)}{a}$$

Where: v = oil cost ($/gallon)

w = oil use (gal/meter^2)

y = abrasive cost ($/lb)

z = abrasive use (lb/meter^2)

Wafer cleaning costs are not directly included. Analysis shows that direct materials add less than 1% to the wafer cost, and labor is included in the labor costs per saw.

The total wafering add-on price can now be calculated.

K - <u>Wafering Add-On</u> ($/meter^2)

(E10)

$$K = \frac{D+E+F+G}{H} + I + J$$

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And the final wafer cost is the sum of the silicon material cost and the wafering add-on.

(E11)

$$\text{Total Wafer Cost } (\$/\text{meter}^2) = C + K$$

TECHNOLOGY DISCUSSION

This analysis attempts to answer two questions. First, how do state-of-the-art results for each of the three wafering techniques compare over a range of ingot prices from 100 to 300 $/kg? Secondly, a 1986 scenario is shown. The ingot price is assumed to drop to 25 $/kg, which corresponds to 14 $/kg feedstock and 11 $/kg ingot value added.[2] At this cost, what developments in each saw type would allow production at less than 37 $/Wp for wafers or 56 $/m² at 15% cell efficiency. All costs are in 1980 dollars and correspond to the national goals, as allocated by the Jet Propulsion Laboratory.[3]

State of the Art Comparison

The set of assumptions for the state-of-the-art comparison are listed in Table 1 under heading I for each saw type. The numbers for the ID and MBS saws are based on the best experimental results to date in work done at Semix. The numbers used for the MWS are based on a JPL report, and some limited work done at Solarex.[4] A further explanation of some of the assumptions is also given below.

The ID saw uses a standard 22 inch blade. The wafers are 10 cm square and are cut at .023 in (0.58 mm) center-to-center spacing with .012 in (0.30 mm) of kerf loss. This results in .011 in (0.28 mm) thick wafers. The variable r at 120 minutes is the sum of 45 minutes for blade change, 60 minutes for dressing during the life of the blade, and 15 minutes for workpiece changes.

The MBS saw has two cases, a and b. In case a, 10 cm square wafers are cut at .024 in (0.61 mm) center to center spacing. The blades are .006 in (0.15 mm) thick with .018 in (0.46 mm) spacers. A #400 grit is used in a concentration of 4 lbs to a gallon of oil, resulting in a 24 hour run time. In case b, 10 cm by 15 cm rectangular wafers are cut at .026 in (0.66 mm) spacing. The blades are .008 in (0.20 mm) thick with .018 in (0.46 mm) spacers. With the .008 in blades, a higher abrasive concentration (6 lbs/gallon) and a higher feed pressure can be used, resulting in a 14 hour run time.

The MWS saw studied here can cut a maximum of 79 cm² in the form of 10 cm round wafers. The .018 in (0.46 mm) spacing produces .012 in (0.30 mm) thick wafers with .005 in (0.13 mm) wire and 10 micron SIC abrasive. Wire use is approximately 100 meters per wafer. The abrasive concentration is 12 lbs to a gallon.

Table 2 lists the results of the cost analysis. Looking at the Best To Date portion the following conclusions can be drawn.

- At all ingot prices the ID sawing technique demonstrates a lower wafer cost. This results from the high material yield and low consumable and blade costs.

- The MWS is competitive only at the highest ingot cost, and then only marginally. This is because this technique has very high blade and consumable costs and only at high ingot prices does the MWS's superior material yield make up for the high wafering add-on costs. The large wire and consumable costs for the MWS saw are illustrated in Figure 2.

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o Development of automated wafer retrieval, loading and transport through cleaning to reduce labor costs

o Lower capital costs

o Machine development to allow slicing of .008 to .010 inch thick wafers with a cycle time of less than ,nree minutes.

For MBS sawing the following improvements must be made:

o Reduce cutting time through high reciprocating speed

o Lower center-to-center spacing

o Decrease blade pack costs

o Better human engineering or automation for easier blade pack tensioning, loading, and unloading

o Reduced vibration, closer machine tolerances and better blade alignment accuracy in order to cut thin wafers.

These technologies can be developed to the point necessary to improve the national photovoltaic cost goal only through commitments by the wafering equipment manufacturers and continued support by DOE and JPL to pursue these areas of critical technology develppment.

ACKNOWLEDGEMENTS

REFERENCES

1   Several of the equations used were derived from equations presented in the pamphlet "Cost Comparisons for the Slicing of Semiconductor Materials with !D and Slurry Saws,"Meyer & Burger AG, 3613 Steffisburg-Station, Switzerland, June, 1980.

2   Based on a JPL SAMICS projection for the Semix process of .09 $/WP ingot value added with .021 inch spacing.

3   Aster, R.W., Price Allocation Guidelines January 1980, JPL Publication 80-51, January 15, 1980.

4   Chen, C.P., Multi-Wire Slurry Wafering Demonstrations, LSSA Project Task Report 5101, February 22, 1978.

5   Development of A High Efficiency Thin Silicon Solar Cell, JPL Contract 954883, Final Report, December 1980, Solarex Corporation.

6   Storti G., etal High Efficiency Ultrathin Coplauar Back Contact Cells, Fourteenth IEEE Photovoltaic Specialists Conference - 1980.

INGOT COST

FEEDSTOCK ($/KG)
CASTING VALUE ADDED ($/KG)
SIZING ($/KG)

A   INGOT COST ($/KG)

B   MATERIAL YIELD (M^2/KG)

C   SILICON MATERIAL ($/M^2$)

WAFERING COST

D   MACHINE CAPITAL COST
E   LABOR
F   POWER
G   SPACE
($/HR)
H   OUTPUT (M^2/HR)
I   BLADES ($/M^2$)
J   CONSUMABLES ($/M^2$)
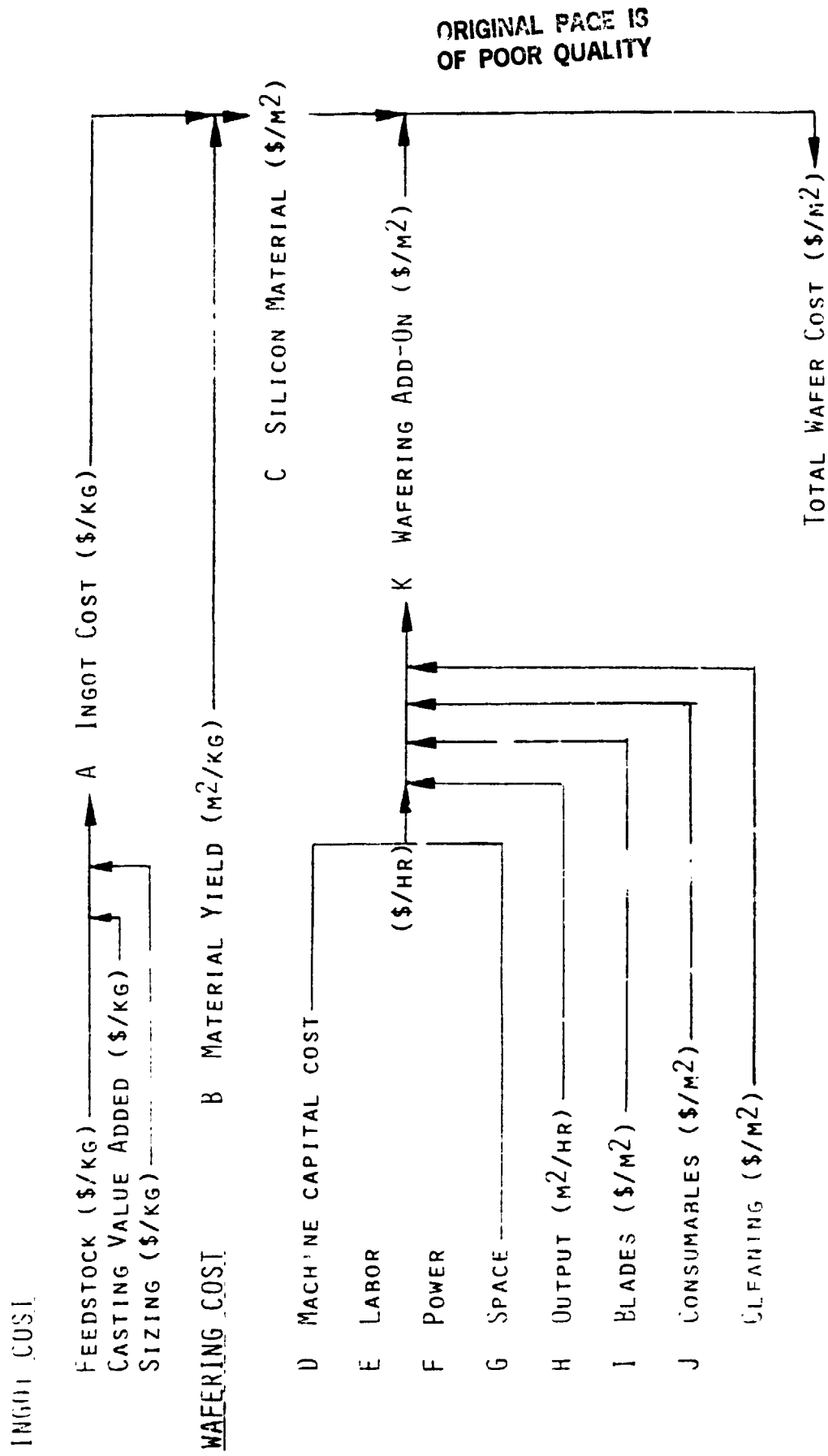CLEANING ($/M^2$)

K   WAFERING ADD-ON ($/M^2$)

TOTAL WAFER COST ($/M^2$)

FIGURE 1   WAFERING COST ANALYSIS FLOW CHART

ID Saw

2.3% Capital Cost 13%
2.8% Labor 10%
1.9% Blades 9%
Silicon 93%
Other
Silicon 64%

460 $/M^2

42 $/M^2

MBS Saw

.6% Capital Cost 4.4%
2.8% Labor 5.5%
1.9% Blades 8%
2.7% Consumables 23%
Silicon 93%
Silicon 57%

530 $/M^2

46 $/M^2

MWS Saw

2% Capital Cost
6% Labor
14% Wire
14% Consumables
Silicon 64%

530 $/M^2

300 $/Kg. Ingot
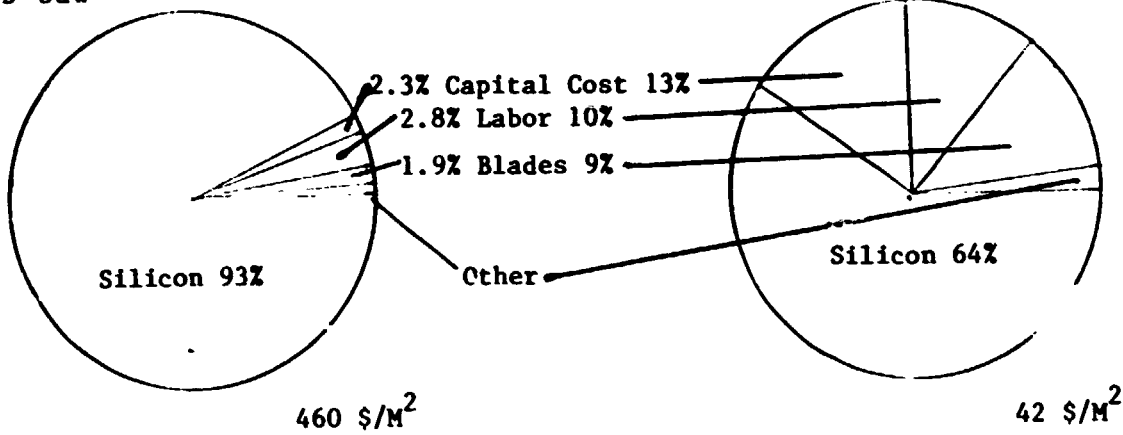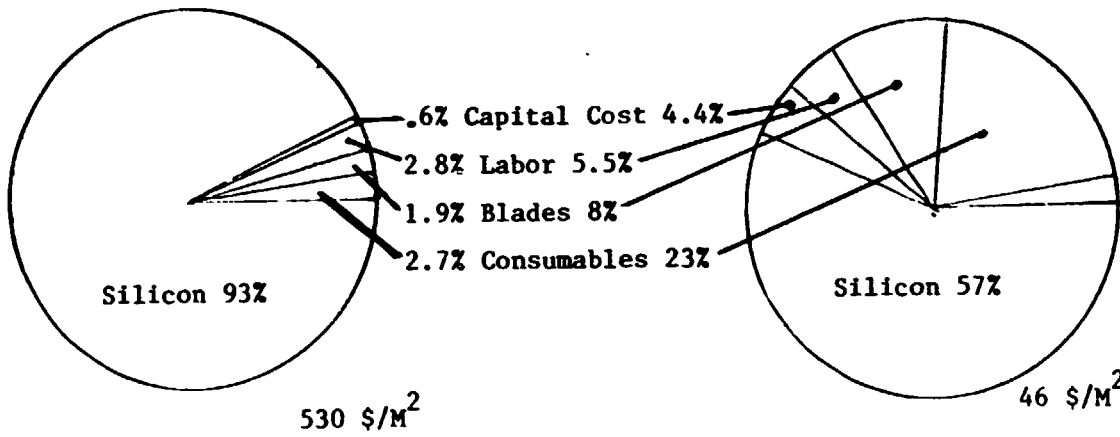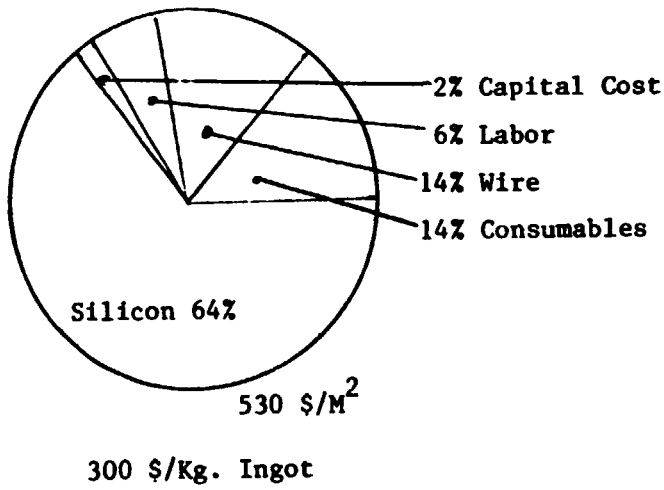
25 $/Kg. Ingot

Figure 2. Wafer Cost Contributions at 300 and 25 $/Kg. Ingot Cost.

TABLE 1
ASSUMPTIONS

	ID I	ID II	MBS I	MBS II	MWS I
a yield	.95	.98	.95	.98	.95
b center to center spacing, mm (in)	.584 (.023)	.457 (.018)	a .610 (.024) b .660 (.026)	.457 (.018)	.457 (.018)
c capital cost, $	60,000	50,000	22,000	60,000	50,000
d running hours per year	6,000	6,000	6,000		6,000
e depreciation, yrs	7	7	7		7
f interest rate	.12	.12	.12		.12
g operator cost, $	15	15	15		15
h machines per operator	6	12	a 6 b 4	6	3
i power use, kW	2	3	1.5	5	1
j energy cost $/kWhr	.07	.07	.07		.07
k space, $/ft²/yr	4.5	4.5	4.5		4.5
l space required, ft²	75	75	45	90	50
m excess space	1.2	1.2	1.2		1.2
n # of wafers per blade, bladepack, or wire length	1,500	1,800	a 312 b 288	458	222
p machine stand still	.05	.05	.05		.05
q cycle or run time, min	2.75	2.75	a 1,380 b 840	360	480
r other non slicing time, min	120	120	90	30	120
s wafer area, m²	.01	.015	a .01 b .015	.015	.0079
t tool cost, $	125	100	40	25	.0057
u tool life, m²	15	27	a 3.12 b 4.32	6.89	8.1×10^{-5}
v oil, $/gal	--	--	5.00		5.00
w oil use, gal/m²	--	--	.727	.242	.727
y abrasive, $/lb	--	--	2.25	3.5	7.5
z abrasive use, lbs/m²	--	--	a 2.9 b 4.4	2.5	8.7

TABLE 2

RESULTS

	BEST TO DATE				1986 SCENARIO	
	ID	MBS a	b	MWS	ID	MBS
Material Yield, m^2/kg	.698	.668	.617	.892	.920	.920
Silicon Material Cost, $/m^2$	143	150	162	112	27.1	27.1
	286	299	324	224		
	430	449	486	336		
Output, m^2/hr	.192	.115	.252	.158	.299	.987
Machine Running Cost, $/m^2$	10.6	6.43	2.94	10.7	5.65	2.06
Labor, $/m^2$	13.0	21.7	14.9	31.6	4.18	2.53
Power, $/m^2$	.73	.96	.44	.44	.70	.35
Floor Space, $/m^2$	.36	.35	.16	.32	.23	.08
Blades, $/m^2$	8.77	13.5	9.75	74.0	3.78	3.70
Consumables, $/m^2$	---	10.7	14.2	72.5	---	10.5
Wafering Add-On, $/m^2$	33.5	53.6	42.4	190	14.5	19.2
Total Wafer Cost, $/m^2$	180	200	200	300	42	46
	320	350	370	410		
	460	500	530	530		
Total Wafer Cost, $/Wp	1.50	1.70	1.70	2.50	.28	.31
	2.70	2.90	3.10	3.40		
	3.80	4.20	4.40	4.40		

Cell efficiencies used for total $/Wp are:

12% in Best to Date Section

15% in 1986 Scenario

Silicon Ingot Cost : in Best to Date section are 100, 200, and 300 $/kg

: in 1986 Scenario is 25 $/kg

DISCUSSION:

SCHMID: Frank, you've acknowledged that the FAST technique has many advantages, but have made an assumption that it would not be available to you. Why have you made that assumption?

FUERST: I made the assumption because it is not available to us now. We still are not convinced of its technical readiness. I did not want to project into '86 with a machine that is not working to our satisfaction now, whereas both the other techniques are. I feel more confident with our projections with a machine that is proven at the present time.

SCHMID: I think one of the major projections that you're making and one of the greatest difficulties that you have in projecting is on the kerf plus thickness to achieve--and nowhere have you assumed getting--25 wafers per cm, or 64 wafers per inch, which is something that has been achieved on the FAST machine, so I think one of the major hurdles has already been demonstrated with the FAST machine.

FUERST: We are eagerly awaiting further developments on that machine and as soon as one is available, we'll be happy to buy one or many of them.

WOLF: Also, 25 wafers per cm has been demonstrated on the ID machines, it seems to me.

FUERST: Yes, the numbers I used correspond approximately to 22 wafers per cm. 25 wafers per cm have been demonstrated on the ID saw, but not in the wafer size that we've assumed here.

GLYMAN: Your second last chart showed 28¢ for the ID and 31¢ for the MBS. Now are these cost, or price? You said you didn't use IPEG. I don't think vou plugged in any overhead costs into your numbers.

FUERST: They are included in terms of machine costs, investment over life of machine, interest paid on the investment cost of the machine, overhead on labor. We assume $6 per hour labor cost, which is high in 1980 dollars at 150% overhead.

SUREK: Frank, I missed something. Were these best-to-date results demonstrated for the semicrystalline material?

FUERST: For both the MBS and the ID saw, yes. The wire saw, no. As I said, those are all taken from a report.

SUREK: What sort of yields were obtained?

FUERST: Typically, over 95%. We've had some that were much better than that. That was the main criterion in picking those assumptions: yield. It had to be above 95%. We have in fact achieved closer spacings, but not at good yields.

DYER: The question of the surface of the multiblade and the wire saw slices I
haven't heard addressed much in this conference. I'd like to hear from a
multiblade champion and a multiwire champion, and then somebody who makes
solar cells. I'd like to find out what sort of a wavy surface that thing
gives, and then I'd like to hear if the solar-cell manufacturer can stand
it. We've done wafering of cells before at TI, and sometimes the surface
just didn't come out so well, and you wondered whether they could accept
any sort of metallization. On the ID saw you can generally produce a slice
that's smooth enough to make a solar cell, but is that true for the multi-
blade and the multiwire? I think that's a challenge.

FUERST: First of all, the solar-cell specifications are much looser than those
you would use in the semiconductor industry. Taper specs on the MBS can
be as high as 2 to 4 mils over a 4-inch length, and that is not a problem
in processing. Waviness can be a problem. It has not been a problem in
production with the MBS saws, but it can be if you don't use them prop-
erly. It's always been said that the ID saw produces greater surface
damage on the wafer. We're only beginning to work with that problem, and
I couldn't really speculate on it.

KOLIWAD: In general, the waviness has not been a problem, unless the whole
wafer ends up like a potato chip. But, if there are undulations on the
surface itself, that's really not much of a problem. Secondly, the ques-
tion about the damage depth effect on the solar cell. We presented a very
extensive paper in 1978, in the Photovoltaic Specialists Conference. We
did extensive studies of the damage depth on ID and multiblade and we also
looked at the effects of those things on solar cell efficiencies. And we
came to conclusions for ID wafering that were exactly what Dr. Schwuttke
observed, as far as the depth of damage was concerned. In the case of
multiblade, the damage depth was 10 microns compared to 25 to 50 microns
for ID wafering, which is consistent with what the semiconductor industry
people have seen. In the case of multiblade, the damage of 10 microns was
considered to be not extensive—as a matter of fact, so much so, that you
don't even have to remove it, if you're going to texturize the surface.
The paper contains all this data about efficiencies, and we measured the
efficiency by incrementally moving the damage also just to check to see if
a certain amount of damage is acceptable or not.

     I would like to solicit some comments from the wafer manufacturers
and from the machine manufacturers, particularly on the number of machines
per operator. In the analysis you have to assume something. You start
with one machine per operator, whatever is accepted level for today's
machines and so on. As you know, it is extremely hard to get data di-
rectly from the manufacturers. By the way, Martin Wolf has done extremely
good effort in the last four or five years continuously updating the prac-
ticed technology, which includes a lot of things like coffee breaks, peo-
ple sleeping on the machines, etc., and Martin has done several reports,
which are available. But when you do the sensitivity analysis, the
sensitivity analysis basically tells you the relative variations with re-
spect to any given parameter. It does not give you any absolute number.
So you can take those curves, and look at them, and secretly put your data
point wherever you think you are. My question to the wafer manufacturers
is: how many machines per operator do they realistically think are
practically possible, not just today but four or five years from now?

KACHAJIAN: In response to Kris's question regarding the number of machines
    that can be run by an operator, we have currently one customer running 10
    machines with one operator, and I think we'll learn later this evening
    that four or five years from now, we may have 50 to 100 machines run by
    one operator.

WOLF: I had opened this session with a comment with respect to the multiblade
    saw which was that we had a tremendous value on the machine, and it's
    important to want to keep the yield up, to have more people watching. I
    think the answer to the problem is that we have to learn to develop better
    sensing systems that will indicate readily if something starts to go wrong
    on the machine so that we don't need an operator there listening as some
    of the sound is changing, and so that one learns how to detect these oncom-
    ing changes early enough before too many wafers are ruined, and either the
    machine shuts itself off or sets off an alarm, and so on.

KACHAJIAN: We have that now, Martin. If there's a coolant fault, the machine
    will finish the cut, come back up, no alarms or bells, but a red light
    will go on distinguishing that machine from any other. So in the din of
    the noise, it's not as bad as you paint it. They can look down the line
    and see a machine with a fault of some sort, which we detect at this point.

WOLF: 1 was told on the MBS that there are things you don't see that start to
    go wrong and then very suddenly lead to catastrophic faults. Wafer break-
    age and so on, so that something seems to indicate something going wrong
    just as sounds, and they even told me that they tried to put on sound
    detectors, and at that time, they couldn't tell whether the operator's ear
    was more sensitive then the mechanical detectors they could put on. Now,
    I think that is again a state-of-the-art question with time, when they
    learn what frequencies to listen to, or what type of changes to listen to,
    and it will be just as good as or better than what an operator can do. So
    I think that these are technology questions where proper development can
    be done and should be successful.

DYER: We don't make solar-cell slices, but we slice, and I want to bring up
    some production problems. Now maybe half the people in this room don't
    really know what the problem is with regard to production of slices. Let
    me just take that example he made: The red light goes off. Now remember,
    we've made this so that there's just one man per 15 saws; that means
    there's no maintenance man back there. This man would have to not pay
    attention to the 14 other saws and go fix that thing. Now let me tell you
    what actually happens. If it's a bell, the bell bothers him, he'll go
    disconnect the bell. If it's a light, turn off the light. Let the yield
    go down, let anything happen, but fix the machine. Because that guy is
    just running back and forth between 15 machines. It's bad enough when we
    run back and forth in our smaller number of machines, now. I can give you
    horror stories as to what we've done to your saws in our place because
    this problem hasn't been addressed.

KACHAJIAN: I recognize the problem, and I guess the only answer is one of educa-
    tion. We've set up a seminar in our plant where we set aside a room for
    training people on a show-and-tell basis. Right next door, we have three
    machines allocated for test, for education, for operating by these customers
    of ours.

WOLF: I suspect the answer, to some degree, is not just that bells go off or lights flash, but that the machine shuts itself down in the proper manner, and doesn't keep running in a faulty way. And so then just your machine down time gets longer, if the man doesn't go there early enough, but at least your yield is reasonably maintained, and nothing really major can go wrong in the meantime. Now, I think Larry (Dyer) referred to the question of the maintenance people, and this is something I also had on my mind when I looked through these economic analyses, I see a machine availability of 90% listed, then I say I have to put in a maintenance man for something like one to two times this amount of time that the machine is down. At least there will be one man working most of the time that the machine is down, and in addition, he may have to repair a part after the machine is running again, or he spends time making sure parts get reordered, and so on. So I think it's more than a 1:1 ratio, normally. And so in economic analyses I think we ought to put something in for the upkeep of the machines and it is a higher priced labor than the operator labor.

KACHAJIAN: In the semiconductor business, you've got to look at that business as a competitive marketplace, and down time is critical. We've developed our equipment with that parameter in mind. As an illustration, I can say that one of our customers with over 100 machines, during a period of time extending about 15 months when demand exceeded supply, had 99% up time running seven days a week, 24 hours per day. What is also critical is that it's still a batch-wise process, and we have to get away from that.

WOLF: Yes. Whatever the down time of the individual machine is, that's what has to be accounted for, and this is one of the major considerations in the economic analysis. What is the reliability of the machine, how much is its availability, what are the costs of repairs?

ILES: Listening to all these fabulous projections, I think again that the problem of ganging ID wheels, even two of them, seems to be much simpler than perhaps 99% uptime, and complete automation for 50 machines. Perhaps we need the push that somebody mentioned, e.g., that the multiwire saw has to come on before the ID people are going to try and at least give us a conclusive experiment that proves that it's very difficult and maybe impossible to gang ID.

The work damage in general depends on the particle size and the rate of cutting. I think you have to be very cautious. At the moment, the ID saw certainly has around 25 microns work damage, because they run very quickly. Most multiwire saws are running 10 to 15 and thereabouts. But if the multiwire saws start running 6-hour cycles and 9-mil slices, you may find that you have to remove 1 or 2 mils of that 9-mil slice to get rid of the work damage, and then have to process a 7-mil slice down the line which might have some impact on the yield. I think you may find not always running the saw as fast as you can is necessarily the way to go.

SCHMID: As you increase the throughput through the machine, number of machines per operator will naturally go down. That's something that you really have to take into serious consideration. You would not be able to handle 10 machines per operator at speeds that would be greater than 4 mils per minute.

WOLF: In analyzing the labor content, it's always good to separate into
     machine loading and unloading time, into bladepack preparation time, and
     just machine watching time. For the machine watching time, you can easily
     keep a large number of machines per operator, but the unload-load time is
     constant per machine, per run. You can improve on this and learn how _o
     speed this up with proper tooling and so on, but there's always a limit.
     There's always more or less a constant in the whole calculation.

         Now, to this other question. How good are our assumptions?
     Regarding MBS, what can we do to oscillate at much higher rates, or with
     longer strokes? Can we get the tangential tool speed considerably up
     above what it is now?

LYNAH: The stroke rate that we presently are limited to is 250 strokes per
     minute. We have a capability to go above that, but the machine's hopping
     around too much. We have sawed at 150 strokes per min, and it's quite
     smooth. Unfortunately, we haven't noticed the straight-line relationship
     between the stroke speed and the sawing rate. And I have to again get
     back to what I feel is our basic problem, the feed. And I feel that possi-
     bly we're not getting a true picture of the stroke rate and sawing rate.
     But 150 means that we should get the cutting rate of our saw up about 50%
     over the present sawing.

FUERST: I was hoping Fred Schmid would talk a little bit about his solution
     to increasing cutting speed. There is an obvious solution and I have in
     fact worked with a machine designed for 1000 cycles per minute. We've cut
     at 800 cycles per minute. I wouldn't try to oscillate the workpiece at
     that speed. I think that would be asking for a lot of trouble. The
     stroke is shorter than that which you would find on the Varian MBS. The
     total tangential velocity increases about an order of magnitude.

SCHMID: The problem in going to high speeds is the acceleration forces at
     the end of the stroke. Obviously you'd want to reduce the mass of the
     bladehead as much as possible. With wire, you can do that because the ten-
     sion on the wire is about 5 pounds, and so you can use a much lighter frame.
     The other thing that we're looking at is balancing off those forces so it's
     180° out of phase, and making sure that the forces are all center-lined,
     so everything is balanced out. Using isolation and vibration mounts, you
     prevent the transmission of vibration from the drive unit to the bladehead
     itself. Those things can considerably increase the speeds. We've run
     speeds up to 500 feet per minute. Typically, we run around 400 feet per
     minute. I think 250 strokes is around 370 feet per minute. That 400 that
     we run routinely is with a single-head machine.

WOLF: With respect to the question of speeding up oscillatory motions, I think
     Mr. Lynah's approach that he discussed this morning about storing the
     energy in springs sounds to me like a very good approach. Just get a
     resonant system and don't try to dissipate all that energy in the outside
     machine frame, but rather store it and reuse it. But the oscillatory
     motion has its own problems with the particular type of blade wear and the
     question of having to abrade your workpiece at the end of the stroke with
     zero velocity. It seems that nobody has been able to work out a system
     where with rotary motion we can have multiple blades, and multiple cutting
     action at the same time.

ILES: Perhaps the multi-blade people could consider the analog of a rotating ingot and have an out-of-phase moving workpiece and tool. I wonder if perhaps you could take some of this problem at the end of the stroke out of it by having the two moving out of phase. Have the workpiece and the work tool working in opposition, so that the relative speed is increased by something like a factor of 50%.

LIU: I'd like to point out something else that's been overlooked in the discussion with the multiblade and multiwires. We heard a lot yesterday from the lubricant people with regard to the ID technology. I don't really think we've really examined that to the detail that we've done with the ID saws. So maybe that's another area to look at to increase the cutting speed.

WOLF: This is certainly an area which needs more exploration. It seems, from what we have been hearing, that it might be a factor-of-2 affair, rather than an order of magnitude affair, but even a factor of 2 at this point is very worthwhile exploring. Maybe if some miracles happen, it will turn out to be more than a factor of 2. The whole question of cutting action that is taking place as we have been seeing at this meeting is very unclear still. And so some considerable progress might be made once one really understands what is happening.

LIU: I think one advantage that we have with the multiblades and multiwire saws is that you can actually increase the throughput of the machines by just multiplying the number of wires or blades that the machine uses. You really don't have to increase the actual cutting speed of the physical wire or blade through the ingots, all this as opposed to a single-slice cutting technique like the ID saw.

FUERST: One comment that was significant that was made earlier was the one made by Fred Schmid in the discussion with Professor Werner: you don't maintain the point contact if you have a diamond-coated blade such as on the MBS saw. He didn't think you can maintain the pressure per particle that is necessary or that is achieved in slurry slicing where you actually have a point or a very short line contact. Is there anybody here from TI, who worked on the project that they had, slicing with diamond-coated blades?

DYER: I observed that project from a distance. I remember that it cut very fast at one time, and then it ran into some problem or something. It was dropped. It looked like at least an idea that could go on, i.e., combining the idea of the rotating crystal with the multi-blade saw, and it looked like it was worthy of at least somebody grabbing hold of it. Of course, when you get to the end of it, you're left with this little neck in the middle, and you have to cut that, and you have to do something to the thing so that it doesn't fall apart. So I think they just put some epoxy on the top. That may not be the best thing, maybe you'd want to put a series of spacers in or something. I really believe that it still a viable concept.

Has anybody considered or used or tried the idea of using a really cheap material for these blades, like some say as rigid as possible and as cheap as possible and as high-temperature as possible, e.g., a plastic?

FUERST: In the work done at TI, the blades were coated on the MBS saw, and they attempted to make slices using the normal mode of reciprocating motion with an ingot mounted beneath. The results were very poor, slicing times weren't good, slicing ability of the blade dropped off after the first cut. Then they went to the rotating crystal. They rotated the crystal at the same time they were reciprocating the bladehead. The results were very good, then they got very high cutting rates. Of course, they had the problem of 200 wafers all bound together by the tiny nipple running down the center of them. It was very difficult to demount.

WOLF: I was thinking of a blade by GE, diamond-coated uniformly along the cutting edge, make a very hard smooth cutting edge, and still have a free abrasive rolling underneath. This is not the fixed-abrasive-type system, but just a very hard tool, a counterpart of where the movable abrasive pushes against, but does not wear off the tool. The tool is harder than the workpiece, and the tool does not get abraded this way. We have to somehow look for ways of decreasing tool wear--that's one of our big costs--labor costs in mounting the tool of the bladepack, and cost of the blades, so if you could get to 100 runs per bladepack, we may have an economical system there.

SCHMID: By using a loose abrasive in combination with a fixed abrasive you tend to break down the bond, in fact you destroy the tool very quickly, because the loose abrasive is working on the nickel to release the diamond and you lose it.

WOLF: I'm not talking about embedded diamond. I'm talking about a uniformly coated grown crystal, a single crystal of diamond all along the cutting edge.

SUREK: Would you necessarily want to use any of these cutting techniques and approaches if you were to cut cheap silicon, maybe metallurgical-grade silicon, or would you want to maybe use that plastic blade which you can throw away after five cuts, or use a completely different approach where you're not worried about kerf and wafer thickness any more?

KOLIWAD: What happens in case we are to cut, not semiconductor-grade silicon, but metallurgical-grade silicon where we have silicon-carbide particles? What will be the blade life? Can we assume our projections to hold true there? Eventually, I think, we may go in that direction to further reduce the cost. So now we are at a point where we have those kinds of things to consider also.

Still, we have to have some estimation of the cost. So how cheap is the cheap plastic? Is there any state of the art we can establish?

WOLF: Also, I think that we ought to recognize that steel is one of the cheapest materials we have around, and practically all plastics cost a lot more than steel.

KOUNDAKJIAN: We manufacture ID blades. In the history of the ID blades you can see, 1960 to 1965, they were single-layer diamond. Because of the friction of certain points, it was getting real hot, and taking all the

diamonds. We should start thinking about multilayer plating and some kind of cooling channels on the diamond section. When you have a multilayered diamond, you shouldn't have any difficulty when you're slicing. I think you should look into that point, 10 to 12 mils diamond depth on the wire.

MORRISON: To respond to Martin's suggestion of a hard blade for free-abrasive wafering: right now, what we have is a soft blade and a hard workpiece. The process works because the hard workpiece fractures. A hard-blade material would have to be so hard it would not frac_ure as easily as the silicon. In that case, the one thing to worry about, I'm afraid, is the shadowing effect that Werner talked about this morning. One hard free-abrasive particle that's larger than the others will lift that blade away from all the other abrasive particles and only one will cut at a time.

WOLF: On the other hand, if you have a long cutting length, there will be a number that are cutting. Certainly, I agree there will be probably an order of magnitude fewer grains cutting at a time, but still it may be worth while if we can extend the tool life significantly.

AHARONYAN: Re ID cutting with low kerf loss: we've seen some small reductions in kerf over the past two or three years. One of the biggest stumbling blocks is the core of that blade, the stainless sheet metal that has to be used to support the cutting edge. The blade saws that we're looking at for 10- to 15-cm ingots are generally 22 inches in diameter or 27 inches in diameter. Normally, they would need a 6-mil core as a minimum to get a good stiffness. We have found that we can make blades with a 4.8-mil core which is going to reduce our kerf by 1.2 mils and still maintain a good stiffness, get good slicing action. So I think one of the biggest things we can do in terms of blade development is find material that's going to give us the stiffness of a 6-mil stainless steel sheet yet have thickness of 3 or 4 mils. That will bring us down into the 9-mil kerf-loss range for these blades. That's one of the biggest steps we can do. We have to have some clearance between the diamonds. If we plate 9 mils of diamonds, we have to have a little bit of spar^ between the diamond particles and the surface of the blade. You can make a very thin blade, but it's not going to cut well, unless you have this clearance. The core material seems to be a big area for improvement. Right now, the material is just plain old stainless steel sheets that are work-hardened to a very high tensile strength.

DAUD: Question to Peter (Aharonyan): if he could comment on etching the core and then making the blade--will it work or not?

AHARONYAN: We've done some etching, and we've seen some small differences. We've also done some heat treating and also seen some differences. But they're not dramatic. I think what has to be done is just a plain old percentage increase in the tensile strength of the material. Right now, we're working with material on the order of 250,00 to 300,000 psi. If we can increase tensile strength by 30% or 40%, we can reduce the thickness by 30% to 40%, in the core. The stainless steels we're using now are about as strong as they can be made.

DYER: I'd like to make a comment on the ID saw, I'm not necessarily in favor of it for the solar cells. But, it is the thing to be used, I think that the machine has to be developed more than the blade. I think that the

manufacturers may be up against a material-strength limit in the material they use for the blade core. I think we have to pay more attention to what the blade is doing and design some things into the machine to make it help the blade do that without fracturing the slice. The things that come to mind include: in order to decrease the contact stresses, as you're plunging through this material, you need to have the blade so that it's in contact all the time, rather than just part of the cycle. This means you have to have a concentric head which at the present time, means that you have to use a slightly more time-consuming setup of the mechanically tensioned head. If someone could develop one that could be done quickly with a hydraulic ring, but tensioning equally all around, then that's fine.

Other things include taking care of the out-of-plane vibrations spoken of by Dr. Kuan. Lubricants with a damping quality could help that. The idea in the Siltec contract of using air-bearing slippers on either side of the crystal to squeeze it down to where it's running as close to the center of a theoretical plane as possible, that's another that ought to be included.

The in-plane vibrations are made worse by any imbalances in the system. And they're also made worse by having this big heavy head come down on the thing. So maybe if you could lighten up the head as much as possible, and have some automatic way to wash the sludge and perhaps broken slices out of the machine, make this all built into the design of the thing. And then one that I don't even know whether it's possible: if you could make a force-sensitive cutting, so that if the contact stresses get beyond a certain level, then the saw no longer puts that full force on, but waits until the stress falls below the level, then comes down. All of these things have to be done, and maybe could accomplish the goal of reducing the kerf. I think if we could do all those things, then the blade manufacturers could make the thin-core blades.

AHARONYAN: A lot of t'·ings you mentioned are the things that either we have now, or we're working on in our development. But getting back to the point of centering the ID of the blade, we think that that's a very important factor in cutting efficiency and getting good results. We have a blade mount now, and we're also looking to improve it, which we think can do that job relatively quickly and perhaps as easily as the hydraulic blade mounts that people are using now. But even if it's a little more difficult it may be worthwhile to spend the extra 15 or 20 minutes every two or three days to get the machine to its full capability of using the 100% of the diamonds on the ID.

WOLF: I think we got away from the economic analysis and looked at the technical questions of what can make the results of these analyses come true, which I guess is really the core of the whole thing. The analysis is only as good as the technical improvements that can be realized.

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