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Solar Array Project

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A.R. Mokashi

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Prepared for
U.S. Department of Energy
Through an Agreement with
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ABSTRACT

Some photovoltaic modules are made from solar cells using ribbon silicon. Most solar cells, however, are produced from wafers sliced from crystalline silicon ingots. Unfortunately, the cost of the slicing process is a major part of the cost of producing silicon sheet. Any attempt to reduce the cost of photovoltaic modules, therefore, must involve the development of less expensive wafering technologies.

This study presents the current status (1981) of the inside-diameter sawing, (ID), multiblade sawing (MBS) and fixed-abrasive slicing technique (FAST) processes with respect to the estimated price each process adds on to the price of the final photovoltaic module. The expected improvements in each process, based on the knowledge of the current level of technology, are projected for the next two to five years and the expected add-on prices in 1983 and 1986 are estimated. Assuming that the projected progress is made, the ID and FAST processes are expected to achieve the price allocation of $\$18.15/m^2$ for square ingots and $\$13.70/m^2$ for circular ingots to conform with the earlier price goal of the Flat-Plate Solar Array Project (FSA) of $\$0.70/W_p$ of PV module (price estimates are expressed in 1980 dollars). MBS technology projections, however, indicate that its progress will not be sufficient to achieve the allocated price goal before 1986.

EXECUTIVE SUMMARY

The advanced inside-diameter (ID), multiblade slurry (MBS) and fixed-abrasive slicing technique (FAST) processes for slicing square and circular cross-section silicon ingots into wafers are being developed, respectively, by Silicon Technology Corp. of Oakland, New Jersey; Norlin Industries, Inc., of Carlisle, Pennsylvania, and Crystal Systems, Inc., of Salem, Massachusetts. These development efforts are being carried out for the U.S. Department of Energy-sponsored Flat-Plate Solar Array Project (FSA) at the Jet Propulsion Laboratory. Based on the FSA price goal of $0.70/$W_p$ of PV module, the price allocation for wafering is $13.7/$m^2$ of circular ingot wafers and $18.15/$m^2$ of square ingot wafers. (Prices are expressed in 1980 dollars.) The price goal is set to make the conversion of solar energy by photovoltaic technology economically competitive.

FSA Project efforts for the last five years in developing the ingot growth and wafering technologies have yielded positive and encouraging results. Commensurate with the achievements in Cz ingot growth, the advancements made in wafering technologies during this period are also impressive. Automation has resulted in reducing the labor requirement. The introduction of automatic wafer recovery and blade deflection control mechanisms have improved the yields in ID technology. Ingots as large as 15 cm in diameter are being sliced. The wafering workshop organized by FSA in Phoenix, Arizona in June 1981 was effective in bringing together the technical community involved in various phases of wafering, identifying critical problems and exchanging ideas.

For ID technology, based on industry survey, the add-on price for a 5-MW factory using 1980 and 1982 technologies are of the order of $80/$m^2$ and $40/$m^2$ respectively. For the MBS and FAST technologies the price estimates based on laboratory data are of the order of $180/$m^2$.

The present study, based on the current level of technology (1981), reports price estimates for wafering 10-cm square and 15-cm-dia round ingots, using each of the three slicing methods. Assuming that development efforts are continued, prices are also estimated using the projected levels of technology for 1983 and 1986.

Using the 1981 ID technology and assuming certain production levels, the price is estimated to be of the order of $50/$m^2$ for slicing 10 cm square ingots. This price is expected to be reduced to the order of $10/$m^2$ by the year 1986, with continued development. The price estimates for slicing 15 cm diameter round ingots are of the order of $38/$m^2$ and $9/$m^2$ using the 1981 and 1986 technologies respectively.

The results of the analysis indicate that both ID and FAST technologies are likely to achieve the price allocation goal during the period 1983 to 1986. The projections for MBS technology, however, indicate that this time frame may not be sufficient for this particular technology to achieve the price allocation. A shift in emphasis of FSA goals has resulted in discontinuation of federal support for the development of these silicon-slicing technologies. Obviously, if the development efforts decrease, the time required for the ID and FAST technologies to achieve the price allocation is likely to be prolonged.

The price goals are still valid for the photovoltaic industry to be competitive with conventional energy sources. It may be for the private industries to take up the challenge to continue working toward the achievement of these goals. The analysis presented is helpful in identifying the critical factors and the direction of developmental efforts.

CONTENTS

SECTION I

INTRODUCTION

Silicon, in the form of wafers (sheet), is the basic material of solar cells used in photovoltaic modules. Silicon sheet is manufactured basically in two forms: ribbon and wafered ingots.

Silicon ribbons, grown directly from polysilicon by two processes called edge-defined film-fed growth (EFG) and dendritic web growth (web), are currently being developed under DOE/JPL and private-industry support.

Silicon is grown in the form of ingots by processes such as Czochralski (Cz) and the heat-exchanger method (HEM). These ingots then are sliced into wafers. The technologies that are considered in this analysis are advanced inside-diameter sawing (ID), multiblade slurry sawing (MBS) and fixed-abrasive slicing technique (FAST).

The Flat-Plate Solar Array Project (FSA), sponsored by the U.S. Department of Energy, has been responsible for the development of the sequential technologies needed to manufacture photovoltaic modules: production of purified silicon, its slicing into wafers, cell fabrication, encapsulation, and module assembly. The Project's goal was to develop the appropriate technologies to achieve the price goal of $0.70/$W_p$ (all prices, throughout this document, are given in 1980 dollars) by the year 1986.

The ID, MBS, and FAST technologies for the production of silicon wafers have been under development during the last five years. The price goal of $0.70/$W_p$ translates into a price allocation of $27.4/$m^2$ of round wafers obtained by slicing ingots grown by the Cz process and $36.3/$m^2$ of square wafers obtained by slicing ingots grown by the HEM process (Reference 1). The price allocation for wafers derived from Cz ingots is less than that for wafers obtained from HEM ingots because of the lower packing efficiency (78%) of round wafers compared to that of square wafers (95%). The price allocations include the add-on price for growing ingots and the add-on price for the production of wafers. If we assume that half of this price allocation is for the production of wafers, this comes to $13.70/$m^2$ for circular wafers and $18.15/$m^2$ for square wafers at the slicing rate of 23 to 25 slices/cm. If the parametric goal of 23 to 25 slices/cm is not achieved, more material will be required per unit area of wafer. The add-on price for ingot growth will increase correspondingly, resulting in a lower price allocation for slicing.

For the semiconductor industry, ingots grown by the Cz process are in the smaller size range of 7.5 cm to 10 cm dia. To achieve an ingot-growth price of the order of $14/kg, it is necessary to grow ingots of larger size (Reference 2). Efforts are under way to grow ingots as large as 15 cm in diameter. Ingots grown by the HEM process are cast and measure 30 x 30 x 30 cm. These ingots are sectioned into 10 x 10 x 30-cm ingots. The production of wafers from 15-cm-dia round Cz-grown ingots and 10-cm square HEM ingots are considered in the analysis.

The advanced ID sawing process is being developed by Silicon Technology Corp. (STC) of Oakland, New Jersey. The ingot is passed through the inner space of an annular blade that has its cutting edge on the internal edge. Rotating at high speed, the blade cuts the ingot into wafers.

The MBS sawing process is being developed by Norlin Industries, Inc., of Carlisle, Pennsylvania. A set of blades (numbered in hundreds) is fixed with suitable spacers into a blade head. Depending on the machine design, either the blade head or the workpiece (an entire ingot) is moved reciprocally to slice the ingot into wafers. Silicon carbide particles in a slurry are used as abrasive.

The FAST sawing process is being developed by Crystal Systems, Inc., of Salem, Massachusetts. In this process, steel wires impregnated with diamond particles are used for slicing the ingot. A set of wires suitably spaced is fixed in a head that is moved reciprocally to cut the ingot into wafers.

Based on industry survey for a 5-MW factory, add-on prices for ID wafering using 1980 and 1982 technologies are estimated to be of the order of $\$80/m^2$ and $\$40/m^2$ respectively (Reference 3). The add-on price estimates for MBS and FAST technologies using 1980 laboratory data are of the order of $\$180/m^2$ (Reference 4). Sensitivity analysis of add on prices for wafering silicon ingots using advanced ID, MBS and FAST processes is presented in an earlier study (Reference 5).

Add-on prices attributed to the production of wafers are estimated using the Interim Price Estimation Guidelines procedure (IPEG-2) (Reference 6). These add-on prices are expressed in 1980 dollars using the appropriate coefficients of the Improved Price Estimation Guidelines (IPEG).

Details of the IPEG equations used are given in the next section. The price-estimation results are presented in the subsequent section, and a summary is provided in the last section. The data used in the analysis for each of the silicon wafer production technologies are given in Appendix A.

SECTION II

ADD-ON PRICE ESTIMATION PROCEDURE

Add-on prices for each of the three wafer-production processes considered (ID, MBS and FAST) are calculated using the IPEG-2 equation (Reference 3). The IPEG equation computes the average annual cost of producing a certain quantity of a product using a particular process. Twenty percent of return on investment is included in the estimation of average annual revenue; the latter also is referred to as Annual Manufacturing Cost (AMC). More accurate price estimates can be obtained by using the simulation procedure of the Standard Assembly-Line Manufacturing Industry Simulation (SAMIS) (Reference 7) and the Solar Array Manufacturing Industry Costing Standards (SAMICS) (Reference 8) which is more expensive to use, requiring more computer time. In estimating the add-on price for a single process, or comparing prices for alternative processes, the IPEG procedure is considered to be sufficiently accurate.

The AMC is expressed as a summation of the following linear functions:

(1) EQPT: total installed cost of the equipment ($).

(2) AREA: area required by the process equipment and its operators (ft^2).

(3) DLAB: annual cost of direct labor ($/yr).

(4) MATS: annual cost of materials and supplies ($/yr).

(5) UTIL: annual cost of utilities ($/yr).

The equation used is:

$$AMC = C1 \times EQPT + C2 \times AREA + C3 \times DLAB + C4 \times (MATS + UTIL) \quad (1)$$

where

C1 = The coefficient corresponding to EQPT, a function of equipment lifetime (ELT); it declines as the ELT increases. ELT is assumed to be 10 years for all of the equipment considered in this analysis:

C1 = 0.83 for ELT of 3 years

= 0.65 for ELT of 5 years

= 0.57 for ELT of 7 years

= 0.52 for ELT of 10 years

= 0.48 for ELT of 15 years

= 0.46 for ELT of 20 years

C2 = The coefficient corresponding to AREA ($\$/ft^2/yr$)

C2 = 109.0

C3 = The coefficient corresponding to DLAB, function of whether the labor pay rates used in computing DLAB include fringe benefits or not

C3 = 2.1 if fringe benefits are included in DLAB

= 2.8 if fringe benefits are not included in DLAB

C4 = The coefficient corresponding to MATS and UTIL

C4 = 1.2

EQPT, AREA, DLAB, MATS and UTIL are referred to as cost parameters. The add-on price is estimated by the following equation:

$$\text{PRICE } (\$/m^2) = \text{AMC } (\$/yr)/\text{QTYPYR } (m^2/yr) \quad (2)$$

where

QTYPYR = The quantity of wafers produced per year (m^2/yr)

The quantity of wafers produced per year (QTYPYR) is calculated considering a single production unit and continuous operation (3 shifts). The machine downtime per year is considered to be 20 days, including time for preventive maintenance, breakdown, repairs, etc. The data used for calculating QTYPYR and AMC, for all three processes, are presented in Appendix A.

SECTION III

PRICE ESTIMATE RESULTS

For all three wafer-producing technologies (ID, MBS and FAST) the required data were gathered from the respective contractors working in the research and development of these technologies. They were asked to supply data applicable to present-day technology (1981) if used for production. Assuming that development efforts are continued to reduce the price, the contractors were also asked to project possible advances and improvements in the technologies that may be available in 1983 and in 1986.

Prices are estimated in this analysis for the production of wafers from 10-cm square and 15-cm-dia round silicon ingots. One way to reduce the price is to increase the throughput by slicing multiple ingots simultaneously. Thus, for each of the three wafer-processing processes, prices are estimated for slicing both single and multiple 10-cm square and 15-cm-dia round ingots using the technologies of the years 1981, 1983 and 1986.

Some data such as equipment lifetime, labor pay rate, electric power rate, and machine downtime are considered to be the same for all cases. Equipment lifetime is considered to be 10 years, labor pay rate is considered to be \$6/hr excluding the fringe benefits, electric power rate is considered to be \$0.05/kWh and machine downtime is considered to be 20 days/yr. The results and the relevant data for each wafer-producing process are presented below.

A. ADVANCED ID SAWING

The add-on price estimate results for producing wafers from 10-cm square silicon ingots by ID sawing are presented in Table 1.

By 1986, the add-on price for slicing single ingots is expected to drop from the present value of \$48.90/m^2 to \$9.70/m^2. This improvement is expected to be accomplished by an almost quadrupled throughput rate by 1986 (the current 32 mm/min increased to 125 mm/min). A reduction in the AMC is also expected to be achieved by a reduction in labor cost as a result of automation; the number of machines per operator will increase from 5 to 10. In addition, the price of each blade is expected to be reduced from \$90 to \$60 and the blade life is expected to increase from 2000 to 5000 slices.

Similarly, the estimated add-on price using current technology and a machine capable of slicing two ingots simultaneously is \$27.50/m^2. By 1983, this price is expected to be reduced to \$16.61/m^2 by increasing throughput through increase in slices/cm (from 17 to 20) and slicing rate (from 51 mm/min to 76 mm/min). The reduction in AMC will be accomplished by a decrease in the price of each blade from \$120 to \$100 and an increase in blade life from 1500 slices to 3000. Labor cost also is expected to be reduced by increasing the

Table 1. Add-On Price Estimate Results for Wafering 10-cm Square Silicon Ingots by Advanced ID Sawing

Year	1981		1983		1986	
Ingots per Run	1	2	1	2	1	3
Add-On Price ($/m^2)	48.90	27.50	22.42	16.61	9.70	6.20
AMC* ($/yr)	72,974	172,885	66,399	114,899	57,509	88,928
QTY** (m^2/yr)	1,492	4,650	2,961	6, 916	5,929	14,335
Price Breakdown (%)						
Equipment	29	28	31	32	36	29
Area	13	7	14	8	16	10
Direct Labor	45	26	35	20	28	19
Materials	12	38	18	39	18	41
Utilities	1	1	2	1	2	1
Total	100	100	100	100	100	100
Relevant Data for Comparison						
Slices/cm	25	17	25	20	25	23
Slicing Rate (mm/min)	32	51	64	76	125	102
Process Yield (%)	95	95	95	95	98	98
Equipment (x $1000/ea)	40	70	40	7	4	50
Area (ft^2/ea machine)	84	84	84	84	84	84
Labor Pay Rate ($/h)	6	6	6	6	6	6
Machines per Operator	5	5	7	7	10	10
Blade Price ($/ea)	90	120	90	100	60	80
Blade Life (slices)	2000	1500	3000	2000	5000	4000
Power (kW/ea machine)	2	2	2	2	2	2
Energy Price ($/kWh)	0.05	0.05	0.05	0.05	0.05	0.05

*AMC: Annual manufacturing cost
**QTY: Quantity of wafers produced per year

number of machines per operator from 5 to 7. Obviously, the reduction of wafer thickness (increased slices/cm) results in obtaining more sheet area from the same size ingot. This then has direct impact on ingot growth cost and the price allocation for sheet, which includes both ingot growth and the production of wafers.

By 1986, the multiple-ingot-slicing saw is expected to slice three ingots simultaneously, resulting in a further reduction in price to $\$6.20/m^2$. Projections show improvements in throughput parameters such as slices/cm (expected to be increased to 23) and the slicing rate, expected to increase to 102 mm/min. Also expected to be improved are equipment cost (to be reduced from $70,000 to $50,000 for each machine) and blade price (expected to be reduced from $100 to $80 each). The blade life is expected to be increased from 3000 slices to 5000 slices.

The following observations may be made from the price breakdown in terms of the costs given in Table 1. The equipment cost amounts to approximately 30% of the price (28% to 36%). Area cost amounts to approximately 10% (7% to 16%). The utilities cost amounts to only 1% to 2%. The balance of contributions to the price is shared by direct labor cost and materials cost. The labor contribution is reduced from 45% for the case of one ingot in 1981 to 19% for the case of three ingots in 1986. Correspondingly, the material cost of 12% for the single ingot example in 1981 is increased to 41% for the case of three ingots in 1986.

The price estimates and the relevant data for the slicing of single and multiple 15-cm-dia round ingots are presented in Table 2. Multiple ingot slicing was not attempted in 1981. Projections are made, however, of data for slicing two ingots simultaneously by the years 1983 and 1986. The price estimates are encouraging. With 1981 technology, the price estimate for slicing a single ingot is $\$37.60/m^2$. The price is expected to be reduced to $\$6.56/m^2$ by 1986 by slicing two ingots simultaneously. The throughput by 1986 also is expected to be increased by increasing the slices/cm from 17 to 20, the slicing rate from 44 to 102 mm/min, and the yield from 95% to 98%. Equipment cost is expected to be reduced from $70,000 to $50,000 for each machine. Machines per operator are expected to be increased from 5 to 10, and the blade life to be increased from 2000 to 3000 slices.

The price breakdown, in terms of cost parameters, is similar to the case for 10-cm square ingots. Equipment cost contributes about 35% to 46%, area costs from 8% to 15%, and utilities cost from 1% to 2%. The contribution of direct labor cost (37% for present technology) would be reduced to 22% by 1986; correspondingly, the contribution of 12% from materials for present technology will increase to 30% by 1986.

If development efforts are continued by industry and the technical parameters (slices/cm, slicing rate, yield, blade life, etc.) are achieved as per the projections, ID technology would meet the price allocation guidelines.

B. MBS

The multiblade sawing technology, however, needs considerable development to achieve the price allocation for the production of wafers.

Table 2. Add-On Price Estimate Results for Wafering 15-cm-Dia Round Silicon Ingots by Advanced ID Sawing

Year	1981	1983		1986	
Ingots per Run	1	1	2	1	2
Add-On Price ($/m^2)	37.40	22.52	13.17	8.73	6.56
AMC* ($/yr)	90,331	79,115	108,040	61,528	74,483
QTY** (m^2/yr)	2,415	3,514	8,207	7,048	11,361
Price Breakdown (%)					
Equipment	40	46	41	42	35
Area	10	12	8	15	12
Direct Labor	37	30	22	27	22
Materials	12	11	28	14	30
Utilities	1	1	1	2	1
Total	100	100	100	100	100
Relevant Data for Comparison					
Slices/cm	17	20	17	22	20
Slicing Rate (mm/min)	44	64	76	125	102
Process Yield (%)	95	95	95	98	98
Equipment (x $1000/ea)	70	70	85	50	50
Area (ft^2/ea machine)	84	84	84	84	84
Labor Pay Rate ($/h)	6	6	6	6	6
Machines per Operator	5	7	7	10	10
Blade Price ($/ea)	120	100	100	80	80
Blade Life (slices)	2000	3000	2000	5000	3000
Power (kW/ea machine)	2	2	2	2	2
Energy Price ($/kWh)	0.05	0.05	0.05	0.05	0.05

*AMC: Annual manufacturing cost
**QTY: Quantity of wafers produced per year

Thus far, development efforts are limited to the slicing of 10-cm square ingots, one at a time. Projections are made for slicing 15-cm-dia round single ingots by 1983 and 1986. It is not practical to project the data for slicing multiple ingots simultaneously because of lack of experience. The price estimates and the relevant data for slicing 10-cm square and 15-cm-dia round ingots are presented in Table 3.

The add-on price of $\$52.87/m^2$ for slicing 10-cm square ingots using 1981 technology is expected to be reduced to $\$32.29/m^2$ by the year 1986. The material cost is the primary cost factor, contributing 57% to 64% to the price. Material cost includes both the blade pack and the abrasive slurry costs. The price estimate of $\$33.29/m^2$ by 1986 is almost twice that of the price allocation of $\$18.15/m^2$ for square ingots.

Similarly, by 1983, the price for slicing 15-cm-dia round ingots, one at a time, is estimated to be $\$51.58/m^2$. It is expected to be reduced to $\$29.98/m^2$ by 1986, compared with the price allocation of less than $\$13.70/m^2$ for circular ingots sliced at 17 to 19 slices/cm. In this case, the material cost contribution is in the range of 33% to 49%. The price could be reduced by increasing the throughput. It is not now possible, however, to project an increase in the slicing rate unless there is a breakthrough in slurry usage that results in cost reduction. Unless it becomes possible to slice two to three ingots simultaneously, with all other parameters remaining the same, it will be difficult for the MBS technology to achieve the price allocation.

C. FAST

The FAST machine, with two blade heads that can be operated at the same time, is designed to slice two ingots simultaneously. Development efforts now are limited to slicing only one ingot at a time. This technology needs development to achieve sustained high yields. Because of current (1981) low yields and high labor content of one machine per operator, the price estimates using 1981 data are abnormally high. Based on present technology and experience, however, and assuming that developmental efforts continue, the data for slicing two 10-cm square ingots and 15-cm-dia round ingots are projected for 1983 and 1986. The price estimates and the relevant data are presented in Table 4.

The price for slicing two 10-cm square ingots simultaneously is expected to be $\$20.32/m^2$ by 1983 and to be reduced to $\$6.68/m^2$ by 1986. Slices/cm are expected to be increased from 19 to 25 and the slicing rate by 0.10 to 0.15 mm/min. Equipment cost is expected to be reduced from $50,000 to $35,000 each. Machines per operator are expected to be increased from 5 to 10, the wire pack price to be reduced from $150 to $100 per twin pack and the wire pack life to increase from 3 runs to 5. If the developmental efforts are continued and are successful, and if all of these projections are achieved by 1986, the price estimate of $\$6.68/m^2$ is attractive and the technology appears to be promising.

Table 3. Add-On Price Estimate Results for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by MBS

	Ingot Type				
	10-cm Square			15-cm-dia Round	
Year	1981	1983	1986	1983	1986
Ingots per Run	1	1	1	1	1
Add-On Price ($/m^2)	52.87	41.62	33.29	51.58	20.98
AMC* ($/yr)	82,042	71,409	83,269	41,529	52,864
QTY** (m^2/yr)	1,552	1,707	2,501	805	1,763
Price Breakdown (%)					
Equipment	24	23	17	40	26
Area	5	5	5	9	7
Direct Labor	13	12	13	16	16
Materials	57	59	64	33	49
Utilities	1	1	1	2	2
Total	100	100	100	100	100
Relevant Data for Comparison					
Slices/cm	20	22	22	17	19
Slicing Rate (mm/min)	0.08	0.08	0.11	0.04	0.08
Process Yield (%)	95	95	95	95	95
Equipment (x $1000/ea)	42	36	30	36	30
Area (ft^2/ea machine)	36	36	36	36	36
Labor Pay Rate ($/h)	6	6	6	6	6
Machines per Operator	15	20	15	25	20
Blade Pack Price ($/ea)	70	77	77	72.40	81
Blade Pack Life (runs)	1	1	1	1	1
Abrasive (lb/run)	9	4.50	1.80	4.50	1.80
Abrasive Price ($/lb)	2.60	2.60	2.60	2.60	2.60
Vehicle (gal/run)	3.00	1.50	0.60	1.50	0.60
Vehicle Price ($/gal)	4.95	4.54	3.85	4.54	3.85
Power (kW/ea machine)	1.60	1.60	2.00	1.60	2.00
Energy Price ($/kWh)	0.05	0.05	0.05	0.05	0.05

*AMC: Annual manufacturing cost
**QTY: Quantity of wafers produced per year

Table 4. Add-On Price Estimate Results for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by FAST

	Ingot Type			
	10-cm Square		15-cm-dia Round	
Year	1983	1986	1983	1986
Ingots per Run	2	2	2	2
Add-On Price ($\$/m^2$)	20.32	6.68	19.94	10.05
AMC* ($/yr)	97,587	61,632	92,545	57,959
QTY** (m^2/yr)	4,802	9,220	4,642	5,766
Price Breakdown (%)				
Equipment	26	29	28	31
Area	9	14	9	15
Direct Labor	34	27	36	29
Materials	29	27	25	22
Utilities	2	3	2	3
Total	100	100	100	100
Relevant Data for Comparison				
Slices/cm	19	25	19	19
Slicing Rate (mm/min)	0.10	0.15	0.08	0.10
Process Yield (%)	90	90	90	90
Equipment (x $1000/ea)	50	35	50	35
Area (ft^2/ea machine)	80	80	80	80
Labor Pay Rate ($/h)	6	6	6	6
Machines per Operator	5	10	5	10
Wire Pack Price ($/twin pack)	150	100	150	100
Wire Pack Life (runs)	3	5	2	3
Power (kW/ea machine)	3.73	3.73	3.73	3.73
Energy Price ($/kWh)	0.05	0.05	0.05	0.05

*AMC: Annual Manufacturing Cost
**QTY: Quantity of Wafers Produced per Year

Similarly, for slicing two 15-cm-dia round ingots simultaneously, the price estimate is $\$19.94/m^2$ by 1983 and it is expected to be reduced to $\$10.05/m^2$ by 1986. This reduction in price is expected to be achieved by increasing the slicing rate from 0.08 to 0.10 mm/min and the wire-pack life from two runs to three runs. All other improvements are expected to be the same as those for 10-cm square ingots.

For both 10-cm square ingots and 15-cm-dia round ingots the price estimates for 1986 are attractive and meet the price allocation.

SECTION IV

SUMMARY

Developmental efforts by FSA for the past five years have resulted in technology with increased automation, reduced labor, automatic wafer recovery technique, better blade deflection control mechanism and improved yields. Ingots as large as 15 cm in diameter are being sliced by ID technology. The wafering workshop held in June 1981 in Phoenix, Arizona, sponsored by FSA has been responsible for bringing the technical community involved in various phases of wafering together in one place. This workshop was helpful in identifying the critical problems and in the exchange of ideas.

Based on industry survey for a 5-MW factory, add-on prices for ID wafering using 1980 and 1982 technologies are estimated to be of the order of $\$80/m^2$ and $\$40/m^2$ respectively (Reference 3). The add-on price estimates for MBS and FAST technologies using 1980 laboratory data are of the order of $\$180/m^2$ (Reference 4). A sensitivity analysis of add-on prices for wafering silicon ingots using advanced ID, MBS and FAST process is presented in an earlier study (Reference 5).

A comparison of the price estimates for slicing 10-cm square ingots and 15-cm-dia round ingots by using ID, MBS, and FAST technologies is presented in Table 5. Price estimates are given both for present technology for each of the three methods of slicing considered and for the projected levels of each of the technologies for the years 1983 and 1986. These results are presented in Table 6 in ascending order, according to the year of technology.

Compared with the price allocation of $\$18.15/m^2$ for square ingots, both the ID and FAST technologies are expected not only to meet the price allocation but to do better. The prices are estimated to be in the range of $\$9.7$ to $\$6.7/m^2$ by 1986. Similarly, for round ingots, both ID and FAST technologies are expected to achieve the price allocation of $\$13.70/m^2$ by 1986. The prices are estimated to be in the range of $10 to $\$6.6/m^2$. Conventional MBS technology is not capable of achieving the price allocation by 1986 for either square or round wafers. Efforts may have to be made to attain multiple-ingot slicing at a faster rate and with reduced material requirement for MBS technology to achieve the price allocation.

Table 5. Add-On Price[a] Estimate Results for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by ID, MBS and FAST Technologies[b]

10-cm Square Silicon Ingots				
Year	1981	1983	1986	FSA Price Goal
ID (Single Ingot)	48.90	22.42	9.70	18.15[c]
ID (Multiple Ingots)	27.50	16.61	6.20	18.15
MBS	52.87	41.62	33.29	18.15
FAST	--	20.32	6.68	18.15

15-cm-dia Round Silicon Ingots				
Year	1981	1983	1986	FSA Price Goal
ID (Single Ingot)	37.40	22.52	8.73	13.70[d]
ID (Multiple Ingots)	--	13.17	6.56	13.70
MBS	--	51.58	29.98	13.70
FAST	--	19.94	10.05	13.70

[a]All the prices are in $\$/m^2$

[b]For ID technology based on industry survey, the add-on price for a 5-MW factory using 1980 and 1982 technologies amounts to $\$80/m^2$ and $\$40/m^2$ respectively (Reference 3). For the MBS and FAST technologies the price estimates based on 1981 laboratory data are of the order of $\$180/m^2$ (Reference 4).

[c]Allocation for HEM ingot growth and slicing is $\$36.30/m^2$ of wafer (Reference 1). Half of this allocation is assumed for slicing square wafers.

[d]Allocation for Cz ingot growth and slicing is $\$27.40/m^2$ of wafer (Reference 1). Half of this allocation is assumed for slicing round wafers.

Table 6. Add-On Price Estimates for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by ID, MBS, and FAST Technologies, Arranged in Ascending Order

			Add-On Price ($\$/m^2$)	FSA Price Goal $\$/m^2$
		1981		
ID	10-cm Square	(Multiple Ingots - 2)	27.50	18.15[a]
ID	15-cm-dia Round	(Single Ingot)	37.40	13.70[b]
ID	10-cm Square	(Single Ingot)	48.90	18.15
MBS	10-cm Square	(Single Ingot)	52.87	18.15
		1983		
ID	15-cm-dia Round	(Multiple Ingots - 2)	13.17	13.70
ID	10-cm Square	(Multiple Ingots - 2)	16.61	18.15
FAST	15-cm-dia Round	(Multiple Ingots - 2)	19.94	13.70
FAST	10-cm Square	(Multiple Ingots - 2)	20.32	18.15
ID	10-cm Square	(Single Ingot)	22.42	18.15
ID	15-cm-dia Round	(Single Ingot)	22.52	13.70
MBS	10-cm Square	(Single Ingot)	41.62	18.15
MBS	15-cm-dia Round	(Single Ingot)	51.38	13.70
		1986		
ID	10-cm Square	(Multiple Ingots - 3)	6.20	18.15
ID	15-cm-dia Round	(Multiple Ingots - 2)	6.56	13.70
FAST	10-cm Square	(Multiple Ingots - 2)	6.68	18.15
ID	15-cm-dia Round	(Single Ingot)	8.73	13.70
ID	10-cm Square	(Single Ingot)	9.70	18.15
FAST	15-cm-dia Round	(Multiple Ingots - 2)	10.05	13.70
MBS	15-cm-dia Round	(Single Ingot)	29.98	13.70
MBS	10-cm Square	(Single Ingot)	33.29	18.15

[a]Allocation for HEM ingot and slicing is $\$36.30/m^2$ of wafer (Reference 1). Half of this allocation is assumed for slicing ingot ingot into square wafers.

[b]Allocation for Cz ingot and slicing is $\$27.40/m^2$ of wafer (Reference 1). Half of this allocation is assumed for slicing ingot into round wafers.

In the case of ID and FAST technologies, if some of the projections for the parametric goals are not achieved, the price would range between the price estimates for 1983 and 1986 technologies. In fact, the 1983 price estimates for both ID (multiple ingots) and FAST do meet the price allocation. Even though both ID and FAST technologies may fail to achieve the 1986 price estimates, they may not be far from the price-allocation guidelines.

In order to utilize the advances already made in the ingot growth technology and for PV technology to be economically competitive for producing energy, the price goal of FSA is still valid. Initial developmental efforts have been made by FSA. Continuation of the efforts by the government is not possible because of lack of funding. It is for the private industries to take up the challenge and work toward achieving the goals.

The analysis and the results presented in this study may be helpful in identifying critical areas and in directing developmental efforts.

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APPENDIX A

Add-On Price Estimation Data

for

ID, MBS and FAST Technologies

for Slicing 10-cm Square and 15-cm-dia Round Silicon Ingots

Table A-1. Data Used for Estimating Add-On Prices for Wafering 10-cm Square Silicon Ingots by Advanced ID Sawing

Year	1981		1983		1986	
Ingots per Run	1	2	1	2	1	3
Ingot Length (cm)	61	61	91	91	100	100
Ingot Breadth (cm)	10	10	10	10	10	10
Ingot Depth (cm)	10	10	10	10	10	10
Slices/cm	25	17	25	20	25	23
Plunge Rate (mm/min)	32	51	64	76	125	102
Ingot Setup Time (min)	30	30	30	30	30	30
Saw Setup Time (min)	30	30	30	30	30	30
Non-Production Time (days/yr)	20	20	20	20	20	20
Process Yield (%)	95	95	95	95	98	98
Machine Cost (x $1000/ea)	40	70	40	70	40	50
Machine Life (yr)	10	10	10	10	10	10
Area Per Machine (ft^2)	84	84	84	84	84	84
Labor Pay Rate ($/h) (Excluding Fringe Benefits)	6	6	6	6	6	6
Machines per Operator	5	5	5	5	5	5
Blade Price ($/ea)	90	120	90	100	60	80
Blade Life (Slices)	2000	1500	3000	2000	5000	4000
Other Consumables ($/run)	2	2	2	2	2	2
Ingot Support ($/run)	3	3	3	3	3	3
Power Consumption (kW/machine)	2	2	2	2	2	2
Energy Rate ($/kWh)	0.05	0.05	0.05	0.05	0.05	0.05

Table A-2. Data Used for Estimating Add-On Prices for Wafering 15-cm-Dia Round Silicon Ingots by Advanced ID Sawing

Year	1981	1983		1986	
Ingots per Run	1	1	2	1	1
Ingot Length (cm)	91	91	91	100	100
Ingot Diameter (cm)	15	15	15	15	15
Slices/cm	17	20	17	22	20
Plunge Rate (mm/min)	44	64	76	125	102
Ingot Setup Time (min)	30	30	30	30	30
Saw Setup Time (min)	30	30	30	30	30
Non-Production Time (days/yr)	20	20	20	20	20
Process Yield (%)	95	95	95	98	98
Machine Cost (x $1000/ea)	70	70	85	50	50
Machine Life (yr)	10	10	10	10	10
Area per Machine (ft^2)	84	84	84	84	84
Labor Pay Rate ($/h) (Excluding Fringe Benefits)	6	6	6	6	6
Machines per Operator	5	7	7	10	10
Blade Price ($/ea)	120	100	100	80	80
Blade Life (Slices)	2000	3000	2000	5000	3000
Other Consumables ($/run)	2	2	2	2	2
Ingot Support ($/run)	3	3	3	3	3
Power Consumption (kW/machine)	2	2	2	2	2
Energy Rate ($/kWh)	0.05	0.05	0.05	0.05	0.05

Table A-3. Data Used for Estimating Add-On Price for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by MBS

	Ingot Type				
	10-cm Square			15-cm-dia Round	
Year	1981	1983	1986	1983	1986
Ingots per Run	1	1	1	1	1
Ingot Length (cm)	22.75	22.75	22.75	22.75	22.75
Ingot Breadth (cm)	10	10	10	-	-
Ingot Depth (cm)	10	10	10	15	15
Slices/cm	20	22	22	17	19
Slicing Rate (mm/min)	0.08	0.08	0.08	0.08	0.08
Setup Time (min)	75	75	75	75	75
Non-Production Time (days/yr)	20	20	20	20	20
Process Yield (%)	95	95	95	95	95
Machine Cost (x$1000/ea)	42	36	30	36	30
Machine Lifetime (yr)	10	10	10	10	10
Area per Machine (ft^2)	36	36	36	36	36
Labor Pay Rate ($/hr) (Excluding Fringe Benefits)	6	6	6	6	6
Machines Per Operator	15	20	15	25	20
Blade-Pack Price ($/ea)	70	77	77	72	81
Blade-Pack Life (runs)	1	1	1	1	1
Abrasive (lb/run)	9	4.50	1.80	4.50	1.80
Abrasive Price ($/lb)	2.60	2.60	2.60	2.60	2.60
Vehicle (gal/run)	3.00	1.50	0.60	1.50	0.60
Vehicle Price ($/gal)	4.95	4.54	3.85	4.54	3.85
Ingot Support ($ run)	1	1	1	1	1
Power Consumption (kW/machine)	1.60	1.60	2.00	1.60	2.00
Energy Price ($/kWh)	0.05	0.05	0.05	0.05	0.05

Table A-4. Data Used for Estimating Add-On Price for Wafering 10-cm Square and 15-cm-Dia Round Silicon Ingots by FAST

	Ingot Type			
	10-cm Square		15-cm-dia Round	
Year[a]	1983	1986	1983	1986
Ingots per Run	2	2	2	2
Ingot Length (cm)	30	30	30	30
Ingot Breadth (cm)	10	10	-	-
Ingot Depth/Diameter (cm)	10	10	15	15
Slices/cm	19	25	19	19
Slicing Rate (mm/min)	0.10	0.15	0.08	0.10
Setup Time (min)	60	60	60	60
Non-Production Time (days/yr)	20	20	20	20
Process Yield (%)	90	90	90	90
Machine Cost (x$1000/ea)	50	35	50	35
Machine Lifetime (yr)	10	10	10	10
Area per Machine (ft^2)	80	80	80	80
Labor Pay Rate ($/h) (Excluding Fringe Benefits)	6	6	6	6
Machines per Operator	5	10	5	10
Wire-Pack Price ($/twin pack)	150	100	150	100
Wire-Pack Life (runs)	3	5	2	3
Other Consumables ($/run)	8	5	8	5
Power Consumption (kW/machine)	3.73	3.73	3.73	3.73
Energy Rate ($/kWh)	0.05	0.05	0.05	0.05

[a]Current (1981) data are not presented because experiments are done at present by slicing one ingot per run using one machine per operator, and the yields are low. This will result in an abnormal add-on price and is not comparable to projected 1983 and 1986 price estimates.