LSA PROJECT PERSPECTIVE OF WAFERING TECHNOLOGY

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ABSTRACT

Wafering is a necessary part of ingot technology in the production of silicon sheet for photovoltaic application. The Low-Cost Solar Array (LSA) Project is also pursuing the development of technologies that are capable of producing silicon sheets of required dimensions directly from the melt, hence eliminating the need for wafering. The ultimate choice of one versus the other is driven primarily by the economics and secondarily by maturity, access to technology and scaleability, among other factors. Technical progress made in both the ingot and the non-ingot technologies supported by the LSA Project is described briefly in the context of process economics. It is emphasized that significant breakthroughs in wafering technology are required to make ingot technology competitive with other silicon sheet growth technologies.

INTRODUCTION

The Low-Cost Solar Array (LSA) Project was formally initiated at the Jet Propulsion Laboratory (JPL) in January 1975 with the objective of developing, by 1986, a national technological capability of manufacturing low-cost, long-life photovoltaic modules at production rates that will realize economies of scale and at a price of less than $0.70/W$_p$. (All dollar figures in this paper refer to 1980 dollars.) The LSA Project is part of the Photovoltaics Program of the U.S. Department of Energy (DOE), which is responsible for direction of the national effort to develop cost-competitive photovoltaic systems.

To achieve the stated objective, the LSA Project has emphasized the development of the following key high-risk, long pay-off technologies:

Silicon Material
Silicon Sheet Growth
Encapsulation Material
Solar-Cell and Module Fabrication.

It is extremely important to note that these developments are guided by the price goal. Table 1 shows these goals or targets. These goals take into account the potential trade-offs between solar-cell efficiency, material utilization, material throughput and other indirect costs associated with a silicon-sheet process.

This paper briefly discusses the critical technology element of sheet-growth processes in general and wafering processes in particular, along with

Table 1. LSA Project Summary of \$0.70/W_p Module Price Goals

Module Component		Price Goal
Silicon Material		14.0 \$/kg
Sheet Alternatives	CZ ingot with wafering	27.4 \$/m^2
	Cast ingot with wafering	36.3 \$/m^2
	EFG ribbon	23.3 \$/m^2
	Dendritic web ribbon	38.6 \$/m^2
Cell Fabrication		21.0 \$/m^2
Encapsulation Materials		14.0 \$/m^2
Module Assembly		14.0 \$/m^2

the technical progress made to-date. Finally, the critical areas of research in wafering are delineated and their payoff potential is discussed.

SILICON SHEET TECHNOLOGY

Silicon sheet is the centerpiece of the photovoltaic module. Its growth process, shape and quality impose considerable requirements on the polysilicon material and solar cell and module fabrication. Materials costs dominate the cost of photovoltaic modules; hence, the photovoltaic technology must be based on unique material-conserving sheet processes. The technology strategy of the LSA Project is aimed primarily at developing that base. To that end, the LSA Project is pursuing the development of the following sheet-growth technologies:

Ingot Technology

Advanced Czochralski ingot growth
Ingot casting
Advanced wafering

Ribbon Technology

Edge-defined film-fed growth
Dendritic web growth.

The direction of the development of these technologies has been toward minimizing material utilization while achieving maximum throughput (m^2/h) and higher sheet quality within the bounds of the price guidelines mentioned above. One can exploit the trade-offs between these features. Specific technical goals have been assigned to each process through such trade-off analysis, and progress is measured with respect to those goals. Tables 2 through 7 show the specific technical goals related to material utilization, throughput and sheet quality (solar-cell efficiency) for each of the sheet technologies and the progress made.

The tables also contain other goals that are related indirectly to these three features and that strongly influence the process cost. It should be noted that to achieve the stated price goals, one has to achieve these features simultaneously. For example, achievement of the required throughput cited above is not sufficient if it uses more polysilicon material or results in sheet of unacceptable quality. Also listed in these tables are estimations of add-on sheet price, calculated using Interim Price Estimation Guidelines

Table 2. Advanced Czochralski Growth Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Output/crucible	(kg)	150	150	150
Ingot diameter	(cm)	15	15	15
Growth rate	(kg/h)	4	3.8	2.7
Throughput rate	(kg/h)	2.5	2.2	1.5
Furnaces/operator		4	1	1
Cell efficiency	(% AM1)	16	16	(16)
Equipment cost	($)	160,000	-	(160,000)
Ingot yield	(%)	90	>90	>90
Automation		Full	Partial	Partial
IPEG growth add-on	($/kg)	15.6	-	26.60
IPEG sheet add-on	($/$m^2$)	31.56*	-	64.00**
IPEG sheet add-on	($/$W_p$)***	0.22	-	0.45

*Assumes 0.74 m^2/kg (17 wafers/cm) wafering add-on of $10.48/$m^2$

( ): Estimated

**Assumes 0.70 m^2/kg (16 wafers/cm) wafering add-on of $26.00/$m^2$

***Encapsulated cell efficiency 14.25% AM1

Table 3. Heat Exchanger Method (HEM) Casting Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Yielded ingot mass	(kg)	35	45	35
Ingot dimensions	(cm)	30 x 30 x 15	33 x 33 x 17.7	30 x 30 x 15
Cycle time	(h)	56	Varies	56
Silicon growth rate	(kg/h)	1.3	3.1	1.3
Yield	(%)	86	85	(75)
Cell efficiency	(%AM1)	15	15.7	(14)
Machines/operator		10	(5)	(5)
Machine cost	($)	35,000	(60,000)	(60,000)
Mat'ls & util/cycle	($)	150	(300)	(300)
IPEG Growth add-on	($/kg)	18.12	-	20.78
IPEG Sheet add-on	($/$m^2$)	33.24*	-	50.59**
IPEG Sheet add-on	($$W_p$)***	0.23	-	0.36

*Assumes 1 m^2/kg, $15.12/$m^2$ wafering add-on ( ): Estimated

**Assumes 0.85 m^2/kg, $29.81/$m^2$ wafering add-on

***Module efficiency at 14.24% AM1

Table 4. Ubiquitous Crystallization Process (UCP) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Yielded ingot mass	(kg)	123	17	17
Ingot dimensions	(cm)	48 x 48 x 22	20 x 20 x 15	20 x 20 x 15
Yield	(%)	98	83	83
Material form		Semicrystalline	Semicrystalline	Semicrystalline
Cell efficiency	(% AM1)	15	15	NA
IPEG sheet add-on	($/$W_p$)	0.194	NA	NA

*Assumes 1 m^2/kg, 14.25% AM1 module efficiency

Table 5. Advanced Wafering Technology Status

Technical Feature		Goal		Individual Demonstration		Simultaneous Demonstration	
Wafer size	(cm)	10 x 10	15 dia	10 x 10	15 dia	10 x 10	15 dia
Wafers/cm		25	17	25	17	25	17
Wafer thickness	(mil)	10	14	8	13	7	12
Kerf thickness	(mil)	6	10	8	11	9	12
Wafer throughput	(min^{-1})	1	0.5	0.6	0.25	0.6	(0.25)
Yield	(%)	95	95	98	>90	(90)	>90
Machines/operator		6	6	(3)	(3)	(3)	(3)
Equipment cost	($)	30,000	30,000	-	-	(30,000)	(30,000)
IPEG add-on	($\$/m^2$)	11.58	10.48	-	-	25.71	17.33
IPEG add-on	($\$/W_p$)	0.08	0.07			0.18	0.12

*Encapsulated cell efficiency at 14.25% AM1 ( ): Estimated

(IPEG), a methodology developed at JPL to assess the progress of these technologies toward meeting the price goals. It is obvious that if the technology were frozen at the level of today's simultaneous achievements, the price objective of the LSA Project would not be met. However, the technical path has been very clearly defined by the LSA Project and if the momentum of the development is continued, the silicon-sheet objective of the LSA Project can be met. It is also worth noting that the difference between the price goal and the price estimate based on the frozen technology is smaller for ingot technology than for ribbon technology. That simply reflects the relative maturity of the two technologies. In other words, ribbon technology has stronger potential for improvement in material utilization, throughput and quality than ingot technology, and it requires more development in all those three areas. The potential improvements in ingot technology, on the other hand, lie only in improving material utilization and throughput. Advances in wafering will be a key to achieving those improvements.

Wafering Technology

Ingot technology is the most mature of the sheet technologies and is well entrenched in the photovoltaic industry today. For reasons stated above, without significant breakthroughs in wafering technology, achievement of low-price photovoltaic modules based on ingot technology will be in

Table 6. Edge-Defined Film-Fed Growth (EFG) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Ribbon width	(cm)	10	10	10
Growth rate	(cm/min)	4	4.2	3.3
Ribbon thickness	(μm)	200	150	300
Ribbons/furnace		4	5 (5-cm width) 3 (10-cm width)	3
Furnaces/operator		3	1	1
Cell efficiency	(%AM1)	12	13.2 (5-cm width) 10.5 (10-cm width)	(12)
Equipment cost	($)	49,000	NA	(60,000)
Growth period	(h)	160	15	5
Duty cycle	(%)	90	90	60
Melt replenishment & auto control		Yes	Yes	Yes
Yield	(%)	90	90	55
IPEG sheet add-on	($/m^2)	14.41	-	75.58*
IPEG sheet add-on	($/W$_p$)	0.13	-	0.69**

*Assumes growth period of 116 h
**Module efficiency of 11.4% AM1

( ): Estimated

jeopardy. The LSA Project has recognized this and has continued to focus its effort on this critical element of ingot technology.

The LSA Project has pursued development in inner diameter (ID) wafering, multiblade slurry sawing (MBS) and the fixed-abrasive slicing technique (FAST). The general thrust has been to achieve:

High material utilization (wafers/cm or m^2/kg)
High throughput (wafers/min)
Low expendables costs ($/m^2)
Low labor requirement (machines/operator).

Table 7. Web-Dendrite Growth (Web) Technology Status

Technical Feature		Goal	Individual Demonstration	Simultaneous Demonstration
Ribbon width	(cm)	5	4	3
Growth rate	(cm^2/min)	25	27	15
Ribbon thickness	(μm)	150	150	150
Furnaces/operator		18	1	(2)
Cell efficiency	(%/AM1)	15	15	15
Equipment cost	($)	15,400	NA	(25,000)
Growth period	(h)	72	24	8
Duty cycle	(%)	90	71	71
Melt replenishment & auto control		Yes	Yes (8 h)	No
Yield	(%)	90	70	70
IPEG sheet add-on	($/$m^2$)	18.39	-	116.60*
IPEG sheet add-on	($/$W_p$)**	0.13	-	0.82

*Assumes growth period of 72 h, melt replenishment & auto controls

( ): Estimated

**Module efficiency of 14.25% AM1

Table 5 lists the specific technical goals and the progress made to-date. It is a difficult and challenging area of investigation. The convening of this workshop is an indication of that fact. There is a great need for basic investigations for understanding mechanisms of cutting silicon, exploring ways to increase cutting rates, developing new blade and wire technology, etc. Existing knowledge in these and other critical areas is not sufficient. There are opportunities in wafering technology development, and the risks are worth the long-term payoff.

CONCLUSIONS

From the perspective of the LSA Project, the following conclusions are obvious:

1. Ingot technology is entrenched in the photovoltaic industry today.

2. The potential of ingot technology in achieving Project goals is extremely limited by the wafering component of that technology.

3. Considerable opportunities exist to advance the wafering technology through basic investigations and to achieve the required material utilization and throughput levels.

4. Ribbon technologies have made remarkable advancements; they still require significant development to achieve the goal.

DISCUSSION:

SCHMID: The graph that you put up is very interesting in that the web technology is extremely sensitive to throughput, far more so than any of the slicing.

KOLIWAD: That is correct. We know that, in the web process, the most difficult thing is the throughput. To achieve 25 square cm/min, we are talking of pulling a 5-cm-wide ribbon at 5 cm/min growth rate. If you try to grow 10-cm-wide web with 5 cm/min growth rate, you already get into the limits of the physics of the growth. But if you assume that it can do that, then the curve shows that web technology is much better than any other technology. Keep in mind that that is not the only parameter that goes into the technology analysis, but that was just an example. You may take another parameter where it may be the other way around.