SILICON RIBBON GROWTH BY A CAPILLARY
ACTION SHAPING TECHNIQUE

Quarterly Technical Progress Report No. 6

G. H. Schwuttke
T. F. Cizek
A. Kran

MASTER

December 15, 1976

Work Performed Under Contract No. NAS-7-100 954144

East Fishkill Laboratory
International Business Machines Corporation
Hopewell Junction, New York

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161

Price: Paper Copy \$5.00 (domestic)
 \$7.50 (foreign)
 Microfiche \$3.00 (domestic)
 \$4.50 (foreign)

SILICON RIBBON GROWTH BY A CAPILLARY
ACTION SHAPING TECHNIQUE

G. H. Schwüttke, Principal Investigator, 914-897-3140
International Business Machines Corporation
System Products Division, East Fishkill Laboratories
Hopewell Junction, New York 12533

Quarterly Technical Progress Report Number 6
December 15, 1976

prepared by
G. H. Schwuttke, T. F. Ciszek, and A. Kran

Under JPL Contract Number: 954144
(Subcontract under NASA Contract NAS7-100)
(Task Order No. RD-152)
Effective Date of Contract: 5/8/75
Contract Expiration Date: 11/8/77

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *eb*

CONTENTS

	<u>Page</u>
TECHNICAL CONTENT STATEMENT.	iii
RESEARCH PROGRAM PLAN.	iv
SIXTH QUARTER HIGHLIGHTS	v
NEXT QUARTER (7) ACTIVITY PLAN	vi
CRYSTAL GROWTH	1
1.0 INTRODUCTION	1
2.0 IMPURITY DOPANT PROFILES IN SILICON RIBBONS.	4
3.0 THERMAL GEOMETRY CONTROL VIA INERT GAS PURGING	12
4.0 GROWTH OF 38-MM and 50-MM-WIDE SILICON RIBBONS	17
5.0 REFERENCES	21
6.0 ACKNOWLEDGMENTS.	23
APPENDIX I SUMMARY OF RIBBON GROWTH EXPERIMENTS.	24
APPENDIX II DIMENSIONAL PROPERTIES OF LONG SILICON RIBBONS.	48
A GUIDE TO FUTURE SILICON SHEET TECHNOLOGY	52
1.0 INTRODUCTION	52
2.0 MODEL OF SILICON SHEET GROWTH PRODUCTION	52
2.1 The Production Unit.	52
2.2 Model Input Parameters	54
2.3 Result of Model Output	57

3.0	SENSITIVITY STUDY.	59
3.1	Production Unit Elements	59
3.2	Processing Technology Components	61
4.0	RIBBON PARAMETER TRADE-OFF STUDY	64
4.1	Methodology.	64
4.2	Present Silicon Sheet Technology	65
4.3	"Near Future" Technology	67
4.4	Future Technology.	68
5.0	TECHNOLOGY PROJECTION.	72
5.1	Methodology.	72
5.2	Defining Technology Limit.	73
5.3	Introducing Chronology.	76
5.4	Coupling Technology Capability and Time.	79
5.5	Computer Evaluation and Analysis Results	81
6.0	CONCLUSIONS.	82

TECHNICAL CONTENT STATEMENT

This report contains information prepared by the International Business Machines Corporation under JPL contract. Its contents are not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or by the National Aeronautics and Space Administration.

RESEARCH PROGRAM PLAN

OBJECTIVES

1. Technological assessment of ribbon growth of silicon by a capillary action shaping technique.
2. Economic evaluation of ribbon silicon grown by a capillary action shaping technique as low-cost silicon.

SYNOPSIS OF PROGRAM OF STUDY

1. Crystal growth of silicon ribbons.
2. Characterization of silicon ribbons.
3. Economic evaluations and computer-aided simulation of ribbon growth.

SIXTH QUARTER HIGHLIGHTS

- o The effects of capillary die design on dopant distribution are described.
- o A new technique for thermal geometry control utilizing inert-gas purging was implemented.
- o Routine 38-mm-wide ribbon growth was demonstrated.
- o 50-mm-wide ribbon growth in a length over one meter was achieved.
- o A technology projection and guide to future silicon sheet growth was completed.

NEXT QUARTER (7) ACTIVITY PLAN

- o Develop 50-mm-wide ribbon growth.
- o Design a system for 100-mm-wide ribbon growth.
- o Set up procedure for updating of projected energy capacity costs and continuous tracking of price objectives.
- o Continue development work on computer model of photovoltaic solar energy conversion system manufacture.

CRYSTAL GROWTH

by

T. F. Ciszek

1.0 INTRODUCTION

The crystal-growth method under investigation is a capillary action shaping technique. Meniscus shaping for the desired ribbon geometry occurs at the vertex of a wettable die. As ribbon growth depletes the melt meniscus, capillary action supplies replacement material. The configuration of the technique used in our initial studies is shown in Fig. 1 and is similar to the edge-defined, film-fed growth (EFG) process described by LaBelle (1). The crystal-growth method has been applied to silicon ribbons for several years (2,3,4). As our work on silicon ribbon growth has progressed, we have found that substantial improvements in ribbon surface quality could be achieved with a higher melt meniscus than that attainable with the EFG technique. Thus, in our later work we have abandoned the EFG technique in favor of the improved capillary action shaping technique which employs the capillary die design shown in Fig. 2.

It represents a departure from the die types used for edge-defined, film-fed growth, in that the bounding edges of the die top are not parallel or concentric with the growing ribbon. The new dies allow a higher central melt

Fig. 1. A schematic diagram of the capillary action shaping technique for silicon ribbon growth.

Fig. 2. Die for improved capillary action shaping technique ribbon growth.

meniscus (Fig. 3) with concomitant improvements in surface smoothness and freedom from SiC surface particles, which can degrade perfection.

Certain problems still await solution before the technique becomes viable for large-scale economical photovoltaic applications. High-density graphite fulfills the durability and wettability requirements of a die (2) and has been used, to date, for most silicon ribbon growth; it is not, however, completely non-reactive. Good crystallographic perfection has been achieved on small ribbon segments (2,3), but the structure of large ribbons is marred by planar, line, and

Fig. 3. Cross section through die and ribbon: (a) central die top before seeding, (b) near edge of die during growth, and (c) near central region of die top during growth.

point defects. Our objective in this work is to attain a clear technological assessment of silicon ribbon growth by the capillary action shaping technique and to enhance the applicability of the technique to photovoltaic power device material.

In this report, the effects of die design on electrically active dopant distribution are discussed, a new technique for thermal geometry control via inert-gas purging is described, and achievement of 38-mm and 50-mm-wide silicon ribbon growth in lengths over one meter is reported.

2.0 IMPURITY DOPANT PROFILES IN SILICON RIBBONS

Spreading resistance measurements indicate that the dopant

profile in silicon ribbons is influenced by the design of the capillary slots in the shaping die. In our early growth runs, a one-piece, flat-top EFG die was used to grow 10-mm-wide ribbons. The central region of the die was solid. A 0.25-mm-wide capillary slot was cut 2.5 mm deep up each edge of the die and extended along the top of the die at a depth of 0.5 mm. The die top was 0.5 mm thick. Boron-doped ribbons grown with such a die typically exhibited central resistivity minima similar to that shown in Fig. 4. The spreading-resistance measurements were made transverse to the ribbon axis, on a finely lapped surface. In some measurements to be described subsequently, the transverse measurements were made on a beveled surface.

Fig. 4. Dopant profile with 10-mm-wide, one-piece, flat-top die.

Ribbons grown with the 25-mm-wide curved-top capillary action shaping technique die described in Quarterly Technical Progress Report Number 4 again exhibited the central resistivity minima as well as narrow dips near the edges of the ribbon (Fig. 5). The magnitude of the difference between maximum and minimum resistance values was somewhat less with this CAST die than with the 10-mm-wide EFG die.

For initial 38-mm-wide ribbon growth experiments, five cylindrical capillary feed holes were drilled in the central region of the die. These were in addition to the side and top slots which had been used in the smaller dies. Ribbons

Fig. 5. Dopant profile with 25-mm-wide, one-piece, curved-top die.

grown with such a die exhibited resistivity minima near the edges which were similar to those observed using the 25-mm-wide die. However, the central resistivity dip was moderated by the presence of the cylindrical holes (see Fig. 6) and, in fact, was changed to a series of smaller-amplitude minima occurring approximately at the positions between cylindrical feed holes.

These observations indicate that dies should be fabricated with minimal capillary slot obstruction (i.e., as close as possible to a configuration consisting of parallel,

Fig. 6. Dopant profile with 38-mm-wide, one-piece die having five central, cylindrical capillary feed holes.

non-contacting plates). Apparently, there is a build-up and stagnation of dopant between vertical capillary rise channels.

In some growth experiments, a die of the type shown in Fig. 5 was modified by enlarging the top of the transverse channel slot as shown in Fig. 7. The vee groove was cut with a 92-mm-radius saw blade having a symmetrically beveled edge with an included angle of 45° . This was done to determine if the larger channel volume would affect the transverse spreading-resistance profile and also to see if the reduction in the graphite surface area of the extreme die top would affect ribbon perfection. No significant change was seen in perfection. The effect on the spreading-resistance profile was to cause a slight broadening of the central resistivity dip. There was no improvement in transverse resistivity gradient.

To achieve a relatively unobstructed channel, a two-piece die has been designed and a number of ribbons have been grown with such dies. A check of the dopant distribution (Fig. 8) indicated that a flatter profile was obtained with this die than with the one-piece type. However, a smaller amplitude central resistivity dip was still present. Thus, an open channel die improves, but does not completely eliminate, the transverse dopant gradient problem.

Fig. 7. Dopant profile of a ribbon grown from a 25-mm-wide die having a V-shaped top cross section.

Fig. 8. Dopant profile of a ribbon grown from a two-piece die.

On the other hand, dopant gradients in the thickness dimension have been very low—even near the ribbon surface, as shown by spreading-resistance measurements made on a sample adjacent to the 38-mm-wide sample for which the dopant profile shown in Fig. 6 was measured. In this case, the sample was beveled at a 9.83° angle so that measurements could be made from the surface down into the depth of the ribbon. Such measurements were made at a relative minimum and at a relative maximum of Fig. 6. The results (see Fig. 9) indicate that there is no resistivity change even as close as $4\text{ }\mu\text{m}$ from the surface. Similar results were found when using the two-piece die.

Fig. 9. Spreading resistance vs depth into ribbon at positions corresponding to a relative maximum and a relative minimum of the surface spreading resistance.

A final observation on resistivity variations in silicon ribbons is that spreading-resistance measurements made in the vicinity of SiC inclusions, on a flat beveled surface, show large fluctuations (Fig. 10) compared with those seen far from SiC particles.

Fig. 10. Spreading-resistance variations near a silicon carbide particle.

3.0 THERMAL GEOMETRY CONTROL VIA INERT-GAS PURGING

Processes requiring dynamic thermal control over an extended region have incorporated various means of achieving desired thermal profiles. In the case of ribbon crystal growth, for example, radiation shields or ports (5), multiple miniature heaters (5), and shaped "weights" for heat focusing (6) have been employed. Most of these techniques have the disadvantage of not being continuously variable during the process. Miniature heaters are continuously variable, but have several drawbacks; e.g., (a) the available materials of construction for the heater and associated insulators may be contaminants at high temperature in some processes and (b) such heaters add additional heat to a process already undergoing heating and hence do not provide a way of selectively extracting heat.

A system providing a means for growing wide silicon ribbons through thermal profile control which is continuously variable, inert, and capable of heat extraction has been implemented. The device employs multiple inert-gas jets directed at various parts of the hot zone, each with an individually controlled flow adjustment. In Fig. 11 a system of four purge jets and flow-meters in a ribbon growth apparatus is shown. The two end jets impinge on the ribbon growth region at points 38 mm apart (corresponding to the edge positions of a 38-mm-wide ribbon). The two middle jets

Fig. 11. Inert-gas purge system for thermal geometry control: flow monitors are at upper left; purge tubes are at middle right.

are directed so to be at either side of a ribbon being grown and pulled upward through the large central draw tube (which also serves as the exit tube for the inert gas—argon in this case). To use the system, more argon is directed to those parts of the system where the temperature is locally higher than desired.

Several examples of use of the system are presented here. Three thermocouples (TCs) were placed in a blank graphite die-holder block as shown in Fig. 12 (bottom). The spacing

Fig. 12. Temperature response of a ribbon furnace hot zone to argon flow changes.

was 19 mm. The TC junctions were approximately at the growth region of a 38-mm-wide ribbon (edges and middle). The system was heated to approximately 1200°C by an external RF coil.

Example 1 (Fig. 12)

Flows to the four ports were each adjusted to 8.5 cubic feet per hour (CFH). The flow through port 1 was increased in increments, while monitoring temperature at TC1. The temperature decreased approximately linearly with flow at a rate of $-3.2^{\circ}\text{C}/\text{CFH}$ argon (Fig. 12). The time constant for the response of temperature to a flow change was approximately 11 sec. Progressively smaller cooling effects were seen at positions 2 and 3.

Example 2 (Fig. 13)

With equal flows of 8.5-CFH argon at all ports, an asymmetrical thermal profile was present (top). Adjusting the left and right port flows to 16.2 and 29.8 CFH, respectively, provided a flat profile (middle). Thus, the 65°C temperature gradient over a 3.8-cm distance has been flattened to within less than $\pm 1^{\circ}\text{C}$. A symmetrical radially increasing profile could be obtained at flows: $P_1 = 16.2$, $P_2 = 21.3 = P_3$, $P_4 = 29.8$ CFH (bottom). Similarly, radially decreasing temperature profiles could be produced.

Fig. 13. An asymmetrical temperature profile (top) can be flattened (middle) or symmetrically tailored (bottom) with the inert-gas system.

The system has provided the thermal control necessary for stable 38-mm-wide and 50-mm-wide ribbon growth, and has allowed full-width seeding of the ribbons. The geometrical response of a growing, 38-mm-wide ribbon to step changes in argon flow directed at one of its edges has been checked. The growth conditions were first stabilized by adjusting the argon flows, as necessary, to attain full-width growth with no tendency for the ribbon to drift toward either edge of the capillary action shaping technique die. Then a step decrease in argon flow (directed at one edge of the ribbon) of 0.85 CFH was applied and caused the ribbon width to decrease (at that edge) at a rate of 4.1 mm/min /CFH, nearly linearly. A subsequent increase in flow by 0.85 CFH, back to the original level, returned the ribbon to full width at a slower, non-linear average rate of 1.3 mm/min /CFH. The ribbon pulling speed was 14 mm/min.

Since the gas jets are directed at the growth region, it has been possible to use an open pulling port system and still retain clean ribbon surfaces of the type previously obtained only with the closed bellows, top-to-bottom purged furnace system reported earlier (Quarterly Technical Progress Report Number 2, December 15, 1975).

4.0 GROWTH OF 38-MM and 50-MM-WIDE SILICON RIBBONS

Implementation of the inert - gas thermal modifier and concomitant improved control over the thermal profile near

the growth zone have allowed major improvements in 38-mm-wide ribbon growth. About 18 ribbons of average length 0.7 meter have been grown with the system to date. The longest ribbon grown was 1.3 meters in length. Some ribbons have had SiC surface particle densities as low as $0.04/\text{cm}^2$ (counted over the entire ribbon) and good surface smoothness. Capillary action shaping technique dies with a 152-mm-radius top curvature, a 0.8-mm edge thickness, and a 1.52-mm central thickness are suitable for 38-mm-wide growth. Initially, ribbons were grown at 14-15 mm/min and were relatively thick. (In Appendix I, a listing of experimental variables and results for all ribbons grown to date under this contract can be found. Appendix II lists the measured geometrical properties of most long ribbons grown.) As more experience was gained, it was possible to increase growth speeds to as high as 30 mm/min. These ribbons were dog-boned in cross-sectional shape, with edge thicknesses of about 0.5 mm (60% of the die top thickness at the edge) and central thicknesses of about 0.3 mm (20% of the central die top thickness). A transverse section of a ribbon grown at 30 mm/min (Ribbon No. 61016) was beveled at a 4.6° angle to illustrate the type of thickness variations present in the thinner ribbons (see Fig. 14).

Fig. 14. Deviations from flatness in ribbon 61016 (4.6° bevel).

Stress levels in the 38-mm-wide ribbons do not appear to be any worse than in narrow ribbons. M. Liepold of JPL measured a stress of 4,000 psi in one ribbon recently delivered to JPL. Using a similar methodology (measurement of the split width as a function of distance on a split ribbon), we measured a stress level of 3.5×10^8 dynes/cm² (3,900 psi) on a different ribbon. The results are in good agreement. Several ribbons have broken transversely during handling without longitudinal splitting.

A 38-mm-wide ribbon during growth is shown in Fig. 15, and several 38-mm ribbons are pictured in Fig. 16. As can be seen in Fig. 16, straight ribbon growth can be maintained after making initial thermal adjustments with the inert-gas purge-jet system.

Fig. 15. 38-mm-wide silicon ribbon growth.

Since initial results in using a 2-piece die for 38-mm-wide growth were successful, the same design (Fig. 8) was used in scaling up to a 50-mm growth system. A 55-mm-ID x 38-mm-high flat-bottomed crucible was used; it accommodates a 150-gram silicon charge. The same die holder, shield, and susceptor designs which were used in the 38-mm system were also kept and scaled up in size for the 50-mm system. Only half a dozen growth attempts have been

Fig. 16. Four 38-mm-wide ribbons grown with inert-gas thermal trimming.

made to date. A very smooth 44-mm-wide ribbon, 17 cm in length, was grown; and a 50-mm-wide ribbon, 109 cm long at full width, with a somewhat rougher surface, was also pulled. The latter (see Fig. 17) is the largest ribbon grown to date ($5,500 \text{ cm}^2$).

5.0 REFERENCES

1. H. E. LaBelle, Jr., Mater. Res. Bull. 6, 581 (1971).
2. T. F. Ciszek, Mater. Res. Bull. 7, 731 (1972).

Fig. 17. A 50-mm-wide by 109-cm-long silicon ribbon grown by the capillary action shaping technique. The inset shows progression in sizes from 12- to 25- to 50-mm-wide ribbons.

3. T. F. Ciszek and G. H. Schwuttke, Phys. Status Solidi (a) 27, 231 (1975).
4. J. C. Swartz, T. Surek, and B. Chalmers, J. Electron. Mater. 4, 255 (1975).
5. D. L. Barrett, et al, J. Electrochem. Soc. 118, 952 (1971).
6. D. E. Swets, Electrochem. Technology 5, 385 (1967).

6.0 ACKNOWLEDGMENTS

Technical assistance in ribbon growth was provided by F. Newman. Spreading-resistance measurements were made by E. F. Gorey.

APPENDIX I

SUMMARY OF RIBBON GROWTH EXPERIMENTS

May 1975 to November 1976

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50516	12.5	Graphite DFP3-2	New die 805. Flat top 0.5mm top thickness. 0.25mm capillary slot. Die holder, lower, upper shield #13. Pull speed 15mm/min.	43cm ribbon
50517	12.5	DFP3-2	Repeat - operator training	26cm ribbon @ 25mm/min
50518	12.5	DFP3-2	Repeat	No results
50519	12.5	DFP3-2	Repeat	71cm @ 23mm/min
50520	12.5	DFP3-2	Repeat	94 cm @ 22mm/min
50521	12.5	DFP3-2	Remachined susceptor shaft to level susceptor.	No results - die flooded
50522	12.5	DFP3-2	Repeat	No results
50523	10	DFP3-2	New die 805A	No results
50524	10	DFP3-2	Repeat	No results
50525	6.3	DFP3-2	Cylindrical capillary die for silicon tube growth	65cm long tube @ 11mm/min
50526	6.3	DFP3-2	Repeat. Pull speed constant. Temp increased in increments.	109cm long tube @ 11mm/min. Wall thickness decreases with increase in temp.
50601	6.3	DFP3-2	Drilled six 1cm die holes in die holder and shields on 39mm die circle.	Froze
50602	6.3	DFP3-2	Repeat. Vary pull speed from 13-21mm/min. Temp constant.	117cm tube. Wall thickness decreases as speed increases.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50603	6.3	DFP3-2	Repeat	124cm tube
50604	6.3	DFP3-2	Repeat. Pull speed - 8mm/min	Froze
50605	6.3	DFP3-2	Repeat	Froze
50606	12	Crysters SiC	Evaluate die made of SiC.	Irregular short ribbon grown.
50607	12	Crystart SiC	Repeat	Same. Sensitive to temp changes
50608	12.5	DFP3-2	Die type 05. Top protrudes 1mm above holder.	20cm ribbon bad vibration.
50609	12.5	DFP3-2	Repeat	No results
50610	12.5	DFP3-2	Repeat	24cm @ 24mm/min
50611	12.5	DFP3-2	Repeat	52cm @ 21mm/min
50612	12.5	DFP3-2	Repeat	27cm then froze
50701	25.4	DFP3-2	Die, holder, shields, spacers 813 (Capillary action shaping technique die with radiused, beveled top and variable top thickness. Center is thicker than edges.)	No results
50702	25.4	DFP3-2	Repeat	No results, growth drifts to one edge of die.
50703	25.4	DFP3-2	Repeat, thicker seed.	No results, froze at 20mm width.
50704	25.4	DFP3-2	Repeat.	No results, froze
50705	25.4	DFP3-2	Repeat	Could not control drift, froze towards front.
50706	25.4	DFP3-2	Repeat. Rotated die 180°	Drifting problem not caused by die. Froze towards front, short ribbon.
50707	25.4	DFP3-2	Repeat.	93cm @ 21mm/min, 25mm wide.

*Trademark of Norton Industrial Ceramics Division

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50708	25.4	DFP3-2	Repeat	No results
50709	25.4	DFP3-2	Repeat	Froze @ full width
50710	25.4	DFP3-2	Repeat	75cm @ 21mm/min. Split during scribing. Split width 1.1cm after a distance of 57cm.
50711	25.4	DFP3-2	Thermal modifiers added. Same shape as die holder 12.5mm high. 6mm wide, slot 38mm long.	No results. Cannot see to seed.
50712	25.4	DFP3-2	Same as run # 50710	Froze
50713	25.4	DFP3-2	Repeat	Froze
50714	25.4	Graphite HPD3-2	New die # 13	No results.
50715	25.4	HPD3-2	Repeat	No results. Froze @ full width.
50716	25.4	HPD3-2	Repeat	No results. Froze.
50717	25.4	HPD3-2	Repeat	Froze
50718	25.4	DFP3-2	Die #5, new quartz tube. Flat top EFG die.	No results.
50719	25.4	DFP3-2	Same as 50714 plus thermal modifier from run #50711	No results
50720	25.4	DFP3-2	Repeat	No results. Froze @ 4mm width.
50721	25.4	DFP3-2	Repeat	No results. Froze @ 21mm width.
50722	25.4	DFP3-2	Repeat. Varied coil position.	No results
50723	25.4	DFP3-2	Same as 50714. No thermal modifier.	Susceptor broke. No results.
50724	25.4	DFP3-2	New die #13. Adjusted coil	77cm @ 17mm/min
50725	25.4	DFP3-2	Repeat	22cm @ 22mm/min
50726	25.4	DFP3-2	Repeat	No results

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50727	25.4	DFP3-2	Repeat	No results
50728	25.4	DFP3-2	Repeat	No results
50729	25.4	DFP3-2	Repeat	No results
50730	25.4	DFP3-2	Repeat. Doped 2 ohm-cm	86cm @ 16mm/min. Edge thickness .67mm, center thickness .44mm.
50801	25.4	DFP3-2	Repeat	Froze
50802	25.4	DFP3-2	Repeat	25cm @ 17mm/min
50803	25.4	DFP3-2	Repeat	76cm @ 18mm/min
50804	25.4	DFP3-2	Repeat. Rotated die 180°	20cm @ 21mm/min
50805	9.5	Crystark SiC	Evaluation of silicon carbide material	50cm @ 16mm/min. Surface seems smooth
50806	9.5	Crystark SiC	Repeat	81cm @ 17mm/min
50807	9.5	KTxx SiC	Evaluation of silicon carbide die material	28cm @ 15mm/min
50808	9.5	KTxx SiC	Repeat	34cm @ 15mm/min
50809	9.5	KTxx SiC	Repeat	113cm @ 16mm/min. Surface smooth but has Si particles
50810	9.5	Si ₃ N ₄ /SiC	Evaluation of Refraxxx silicon nitride bonded silicon carbide die	Melt will not rise in die capillary slot
50811	9.5	B ₄ C	Evaluation of boron carbide die	35cm ribbon, wets extremely well. Clean surface. Strong morphological features. .004 ohm-cm, p-type.
50812	9.5	B ₄ C	Repeat	No results
50813	9.5	B ₄ C	Repeat, faster speed	Pulled away from melt.
50814	9.5	Si ₃ N ₄	Evaluation of silicon nitride die	Melt wets surface, but will

*Trademark of Norton Industrial Ceramics Division

**Trademark of Carborundum Company

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
				not rise in slot.
50815	9.5	ZrB ₂	Evaluation of zirconium boride die	Short ribbon. Good melt rise, but die dissolves
50816	9.5	TiB ₂	Evaluation of titanium boride die	Short ribbon. Good melt rise, but die dissolves.
50817	9.5	TiB ₂	Repeat	Froze
50818	9.5	TiB ₂	Repeat	Froze
50819	9.5	TiB ₂	Repeat	Froze
50820	9.5	TiB ₂	Repeat	Same as 50816
50821	9.5	TiB ₂	Repeat. Narrower slot in lower shield.	Same as 50816
50822	9.5	TiB ₂	Repeat	Same as 50816
50823	9.5	TiB ₂	Repeat	Same as 50816
50824	9.5	TiB ₂	Repeat	Same as 50816
50825	9.5	Vitreous carbon	Evaluation of vitreous carbon die	44cm long, narrow ribbon, with dark coating on surface. Parallel twinning
50826	9.5	Vitreous carbon	Repeat. Die is 1.5mm lower in holder.	30cm ribbon, same properties as above. SiC particles on surface.
50901	25.4	HPD3-2	Same hot zone as runs 50701-50725. Argon purge system modified by enclosing pull shaft in plastic bellows to completely contain ribbon in Argon during growth. System purged from top to bottom.	Ribbon froze @ 14mm width
50902	25.4	HPD3-2	Repeat. Argon flow increased from 50 to 58 CFH.	Froze
50903	25.4	HPD3-2	Repeat	Froze @ 23mm width
50904	25.4	HPD3-2	Repeat	Froze

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50905	25.4	HPD3-2	Repeat	Froze at full width
50906	25.4	HPD3-2	Repeat	Short full width ribbon then froze.
50907	25.4	HPD3-2	Repeat	Same as above
50908	25.4	HPD3-2	Repeat	8cm. Ribbon then froze. Ribbon drifts to front.
50909	25.4	HPD3-2	Repeat. Increased pull speed.	50cm @ 20mm/min. Ribbon surface clean and melt clean.
50910	25.4	DFP3-2	New die. Installed bubbler on argon outlet to create slight back pressure.	Ribbon froze at full width.
50911	25.4	DFP3-2	Repeat	30cm @ 19mm/min
50912	25.4	DFP3-2	Repeat. Argon flow dropped to 50 CFM	Ribbon and melt still clean.
50913	25.4	DFP3-2	Repeat	Froze
50914	25.4	DFP3-2	Repeat	Froze
50915	25.4	DFP3-2	Repeat	Froze
50916	25.4	DFP3-2	Repeat. Reduced argon flow to 17 CFM	52cm @ 18mm/min. Ribbon still clean.
50917	25.4	DFP3-2	Repeat	Froze
50918	25.4	DFP3-2	Repeat	Froze
50919	25.4	DFP3-2	Repeat	93cm @ 18mm/min. Ribbon and melt residue clean but powder build-up on heat shields
50920	25.4	DFP3-2	Repeat	Froze
50921	25.4	DFP3-2	Repeat	Froze
50922	25.4	DFP3-2	Repeat	Froze

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
50924	25.4	DFP3-2	Repeat	Froze
50925	25.4	DFP3-2	Repeat	Froze
50926	25.4	DFP3-2	Repeat	35cm @ 13mm/min
50927	25.4	DFP3-2	Repeat @ faster pull speed	40cm @ 25mm/min. Fractured during handling.
50928	25.4	DFP3-2	Repeat @ faster pull speed	46cm @ 28-30mm/min
51001	25.4	DFP3-2	Grew CZ crystal to check dopant.	-
51002	25.4	DFP3-2	Removed graphite drawtube. 60CFM argon purge, from top.	Clean ribbon surface, growth easy to control.
51003	25.4	DFP3-2	Repeat	Same
51004	25.4	DFP3-2	Argon purge increased to 75CFM.	Froze at 15mm width.
51005	25.4	DFP3-2	Repeat	Clean surface, 50cm long ribbon
51006	25.4	DFP3-2	Repeat	Froze
51007	25.4	HPD3-2	Repeat, growth speed 15mm/min. New die.	51cm ribbon, 0.45mm thick in middle, 0.73mm thick at edges.
51008	25.4	HPD3-2	Growth speed increased to 22mm/min.	Ribbon 0.43mm thick in middle, 0.66mm thick at edges.
51009	25.4	HPD3-2	Continuation	Froze
51010	25.4	HPD3-2	Continuation	Froze
51011	25.4	HPD3-2	Continuation	Froze - melt level too low.
51012	25.4	HPD3-2	Argon purge 75CFM from bottom of furnace. Exhaust is draw tube and purge tube around ribbon.	91cm long ribbon. Easy to grow. Colored film on surface.
51013	25.4	HPD3-2	Continuation	20cm ribbon as above.
51014	25.4	HPD3-2	New draw tube - 02. Argon flow is 30CFM from top.	54cm long ribbon. Clean surface.
51015	25.4	HPD3-2	Argon flow 20CFM.	85cm long ribbon. Clean surface.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
51016	25.4	HPD3-2	New die. Removed draw tube - 0.2. Argon flow 20CFH from top. 28mm/min pull speed.	Ribbon surface much rougher. 52cm long ribbon. 0.39mm thick in middle, 0.60mm thick at edges.
51017	25.4	HPD3-2	Repeat, but 81.5mm/min pull speed.	Ribbon 0.26mm thick in middle, 0.44mm thick at edges. Rough.
51018	25.4	HPD3-2	Repeat, but 25mm/min pull speed, 65CFH argon purge.	Ribbon smoother. .41mm thick at middle and .67mm at edges.
51019	25.4	HPD3-2	Same as above, but 29mm/min pull speed.	Ribbon 0.35mm thick at middle, 0.55mm thick at edges.
51020	25.4	HPD3-2	Repeat	Froze - widened too fast
51021	25.4	DFP3-2	New die. 19mm/min pull speed.	0.38mm thick at middle, 0.66 at edges.
51022	25.4	DFP3-2	Repeat	0.28mm thick at middle, 0.59 at edges.
51023	25.4	DFP3-2	Repeat, but 24mm/min pull speed.	0.39mm thick at middle, 0.59 at edges.
51024	25.4	DFP3-2	Repeat, but 14mm/min pull speed.	0.26mm thick at middle, 0.64 at edges.
51025	25.4	DFP3-2	Repeat, but 18mm/min pull speed.	0.22mm thick at middle, 0.56 at edges.
51026	25.4	DFP3-2	Repeat of 50916 run conditions.	0.37mm thick at middle, 0.62 at edges.
51027	25.4	DFP3-2	As above, but 25mm/min speed.	0.26mm thick at middle, 0.52 at edges.
51028	25.4	DFP3-2	Continuation of above.	Froze
51029	25.4	DFP3-2	Continuation - attempt 30mm/min pull.	Froze. Could not grow at 30mm/min.
51030	25.4	DFP3-2	60CFH argon purge from top. No draw tube. After heater - 01.	Difficult to grow. Could not reach full width.
51031	25.4	DFP3-2	Repeat	Same problem
51032	25.4	DFP3-2	Repeat	Froze
51033	25.4	DFP3-2	Repeat	Grew 59cm long ribbon, irregular width.
51034	25.4	DFP3-2	Repeat	Grew 59cm long ribbon, irregular

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
				width. Froze upon reaching 25mm width.
51101	25.4	DFP3-2	Basic set-up, but with vertical, "parallel plates" afterheater (22mm wide x 12cm high, spaced 4.7mm)	Ribbon froze to edge of die.
51102	25.4	DFP3-2	Repeat, new seed	Grew 24mm wide ribbon, but control is very unstable.
51103	25.4	DFP3-2	Repeat	Ribbon froze to die.
51104	25.4	DFP3-2	Basic set-up, but with 12.6mm high block graphite afterheater. Central opening tapers from 7mm wide at bottom to 18.5mm at top. 14mm/min.	Easy to grow, surface is duller. More SiC particles. Ribbon was deliberately split. Spread was 4mm over a distance of 380mm.
51105	25.4	DFP3-2	Repeat, at 20mm/min. Argon flow 80CFM.	Same general appearance. Split width was 1.1mm over a distance of 170mm.
51106	25.4	DFP3-2	Repeat, 40CFM argon flow	Froze
51107	25.4	DFP3-2	Repeat, 15mm/min	49cm ribbon, fewer SiC particles. Ribbon .50mm thick at edge .28 at center.
51108	25.4	DFP3-2	Height of quartz insulator increased to 25.5cm (was 23). Afterheater from 51104.	Cooling water failure. Lost die and holder.
51109	25.4	DFP3-2	New die, repeat of 51108.	Froze.
51110	25.4	DFP3-2	Repeat, 10mm/min	Grew 12cm long ribbon, then froze. Split width was 0.5mm over a distance of 130mm. Thickness .55 to .50mm.
51111	25.4	DFP3-2	Repeat	Difficulty in spreading to full width.
51112	25.4	DFP3-2	Repeat	Short ribbon. Much smaller temp adjustment required to spread ribbon with this set-up.
51113	25.4	DFP3-2	Return to basic set-up (23cm	Froze out.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
			quartz insulator, no afterheater, 60CFH argon flow) to make ribbons for solar cell characterization.	
51114	25.4	DFP3-2	Repeat, 23mm/min	48cm ribbon; thickness .50 to .34mm.
51115	25.4	DFP3-2	Repeat, 20mm/min	87cm ribbon; thickness .57 to .30
51116	25.4	DFP3-2	Repeat	Froze upon reaching full width
51117	25.4	DFP3-2	Repeat, changed to 25.5cm quartz insulator.	Same as above
51118	25.4	DFP3-2	Repeat, 21mm/min	57cm ribbon; .46 to .29mm thick
51119	25.4	DFP3-2	Repeat, 22mm/min	54cm ribbon; .46 to .28mm thick
51120	25.4	DFP3-2	Repeat, 23mm/min	21cm ribbon, then froze
51201	25.4	DFP3-2	Return to 51108 run conditions, but with 60 CFH flow 20mm/min	16cm ribbon; .50 to .35 thick
51202	25.4	DFP3-2	Repeat, 12mm/min	60cm ribbon; .52 to .42mm thick
51203	25.4	DFP3-2	Repeat	19cm ribbon; .76 to .38mm thick
51204	25.4	DFP3-2	Basic set-up, with 12.5mm high afterheaters at ribbon edges (vertical, 3mm radius recesses milled out to surround ribbon edge.	Froze during spreading
51205	25.4	DFP3-2	Repeat 18mm/min	36cm ribbon; thickness .50 $\pm$.05mm
51206	25.4	DFP3-2	Repeat	Froze
51207	25.4	DFP3-2	Repeat	20cm ribbon, then froze
51208	25.4	DFP3-2	Repeat 19mm/min	46cm ribbon, .43 $\pm$.07mm thick.
51209	25.4	DFP3-2	Repeat. Argon flow reduced to 40CFH.	53cm ribbon, split width 1.1mm over a 200mm distance.
51210	25.4	DFP3-2	Repeat. 25.5cm high quartz shield 60CFH argon flow. 14mm/min	46cm ribbon. Thicker in center (.65mm) than at edge (.5mm). Three attempts made to split this

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
				ribbon. In each case, the split veered to the edge and would not propagate axially.
51211	25.4	DFP3-2	Repeat, but higher growth rate (23mm/min)	Froze at 23mm width. Difficult to control.
51212	25.4	DFP3-2	Repeat	Froze again. Temp control seems more critical with high quartz insulator.
51213	25.4	DFP3-2	Repeat. Approx 18mm/min	32cm ribbon. Difficult to control. Cross section thick at one edge, but then uniform.
51214	25.4	DFP3-2	Repeat. 16-17mm/min	55cm ribbon. One edge slightly thicker (.45-.41mm at tail end).
51215	25.4	DFP3-2	Die, holder, shields baked out 4 hrs. at 1250 C in wet argon. Followed by normal vacuum backout. Basic set-up, but 25.5cm high quartz shield.	Froze out
51216	25.4	DFP3-2	Repeat, 17mm/min	39cm ribbon, effect on efficiency to be determined.
51217	25.4	DFP3-2	Repeat	57cm ribbon, .75 to .47mm thick
51218	25.4	DFP3-2	Repeat 18mm/min	45cm ribbon. .60 to .50mm thick
51219	25.4	DFP3-2	Repeat	Froze, seed broke
60101	25.4	DFP3-2	Die bake-out 4hrs at 1250 C in wet argon plus anhydrous HCL	Die holder flooded with Si
60102	25.4	DFP3-2	Die bake-out 4hrs. at 1250 C in dry argon plus anhydrous HCL	58cm ribbon; effect on efficiency to be determined.
60103	25.4	DFP3-2	Repeat growth, same die	57cm ribbon
60104	25.4	DFP3-2	Repeat growth, varied seed orientation	60cm ribbon
60105	25.4	DFP3-2	Same set-up, added mock-up of proposed afterheater for	55cm ribbon, thickness uniform between 0.45 and 0.50mm

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
			uniform thickness (14mm/min growth speed)	
60105	25.4	DFP3-2	Repeat, but at 23mm/min	Froze out after 4cm of growth
60107	25.4	DFP3-2	Repeat	Small contaminant particle lodged on die preventing growth
60108	25.4	DFP3-2	New die and holder, repeat of bake-out conditions in 60101	White powder coating on die and Si furnace tube after bake-out (probably SiO ₂). Scraped off. No ribbon.
60109	25.4	DFP3-2	Repeat - Same set-up	No ribbon--froze out
60110	25.4	DFP3-2	Repeat	32cm ribbon; effect on efficiency to be determined.
60111	25.4	DFP3-2	Set up from run 60102/grow full length ribbon	94cm ribbon
60112	25.4	DFP3-2	Repeat	90cm ribbon
60113	25.4	DFP3-2	Repeat	Froze out
60114	25.4	DFP3-2	Repeat	33cm ribbon - then froze out
60115	25.4	DFP3-2	Repeat	36cm ribbon - then froze out
60116	25.4	DFP3-2	Repeat	31cm ribbon - then froze out
60117	25.4	DFP3-2	Repeat, rotated die 180	Still freezing out/uneven spreading
60118	25.4	DFP3-2	Repeat	Froze out, no ribbon
60119	25.4	DFP3-2	Repeat	28cm ribbon--then froze out
60120	25.4	DFP3-2	Repeat	95cm ribbon
60121	25.4	DFP3-2	Repeat, same set-up	Froze out, too little Si
60201	25.4	DFP3-2	Repeat, same as 60121	No results
60202	25.4	DFP3-2	Thermal modifier No. 8. Coil spread to cover afterheater and die 18mm/min	Smooth shiny surface. Thin in center. 96cm ribbon.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60203	25.4	.	Repeat, 14mm/min	25cm ribbon, then froze. Very low stress. Ribbon would not split.
60204	25.4	.	Repeat	Froze reaching full width.
60205	25.4	HPD3-2	Hand lapped die to .39mm edge thickness.	Unable to make ribbon spread. Die edge touching L shield.
60206	25.4	HPD3-2	Repeat	9cm ribbon, froze
60207	25.4	HPD3-2	Die not centered in holder, touching edge	No results
60208	25.4	KTxSiC	KTxSiC die. Top radiused to 3.75 inches. No thermal modifier	No results. Melt between die and holder.
60209	25.4	KTxSiC	Repeat. Grew ribbon from flooded die.	45cm ribbon. Ribbon curved due to rubbing on lower shield.
60210	25.4	KTxSiC	Repeat	Froze
60211	25.4	KTxSiC	Repeat	Froze
60212	25.4	DFP3-2	Standard procedure	55cm ribbon @ 17mm/min
60213	25.4	DFP3-2	Standard procedure	77cm ribbon @ 20mm/min
60214	25.4	DFP3-2	Thermal modifier number 8. Measured thermal vertical gradient	Machine problem. No results.
60215	25.4	KTxSiC	Cleaned die in HF 24hr (die from run 60208)	No results
60216	25.4	KTxSiC	Repeat	40cm ribbon @ 19mm/min
60217	25.4	KTxSiC	Repeat	18cm ribbon @ 20mm/min
60218	25.4	KTxSiC	SiC die with thermal modifier 08	No results. Edge of die too cold.
60219	25.4	KTxSiC	Repeat	No results.
60220	25.4	KTxSiC	Repeat	No results. Froze @ 7mm width.
60301	25.4	KTxSiC	Repeat	No results

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60302	25.4	KT1S1C	Repeat	No results
60303	25.4	DFP3-2	Standard procedure	55cm @ 17mm/min
60304	25.4	DFP3-2	Repeat. Ribbon was split for stress measurements.	55cm @ 20mm/min. Stress results similar to those with thermal modifier 8 5.
60305	25.4	DFP3-2	Standard procedure with thermal modifier 88 and 3mm seed. Neck-in sharply after seeding.	Single crystal short distance at seeding.
60306	25.4	DFP3-2	Repeat	No results
60307	25.4	DFP3-2	Thermal modifier 88	No results. Ribbon drifts to right.
60308	25.4	DFP3-2	Repeat after adjusting rf coil.	No results.
60309	25.4	DFP3-2	Std procedure (Thermal modifier 8 5)	53cm @ 16mm/min. Uniform thickness within 6%, at .45mm.
60310	25.4	DFP3-2	Repeat, faster pull speed	23cm @ 20mm/min, again uniform thickness (.39mm).
60311	25.4	DFP3-2	Repeat	No results, froze.
60312	25.4	DFP3-2	Repeat	41cm @ 21mm/min, thickness is again uniform (.35mm)
60313	25.4	DFP3-2	Argon flow increases from 50 CFH to 67 CFH. Thermal modifier 85.	No results, froze. Argon affects direction of spreading.
60314	25.4	DFP3-2	Repeat @ 50 CFH argon flow.	No results, froze, right side.
60315	25.4	DFP3-2	Repeat @ 17 CFH argon flow.	No results, froze.
60316	25.4	DFP3-2	New die and graphite components. Die top is .52mm thick at edges, .99mm at middle.	No results, froze right side.
60317	25.4	DFP3-2	Repeat, ribbon drifting to right Argon flow 50 CFH	No able to keep centered. Used up all travel and froze.
60318	25.4	DFP3-2	Repeat, rotated die 90°	44cm @ 18mm/min

*Trademark of Carborundum Company

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60319	25.4	DFP3-2	Repeat	No results, froze upon reaching full width
60320	25.4	DFP3-2	Repeat	55cm @ 22mm/min
60321	25.4	DFP3-2	Repeat, <111>(112) seed	No results, froze
60322	25.4	DFP3-2	Repeat, adjusted RF coil	57cm @ 23mm/min. Edge thickness .41, middle .25mm.
60323	25.4	DFP3-2	Repeat, faster pull speed	29cm @ 29mm/min. Edge thickness .32, center .22mm.
60324	25.4	DFP3-2	Repeat	54cm @ 26mm/min. Edge thickness .32, center .24mm.
60325	25.4	DFP3-2	Repeat <110> (100) seed	19cm @ 20mm/min. Edge thickness .50, center .40mm.
60326	25.4	DFP3-2	Repeat	38cm @ 18mm/min
60327	25.4	DFP3-2	Repeat	No results, froze
60328	25.4	DFP3-2	Std procedure	35cm @ 23mm/min
60329	25.4	DFP3-2	Repeat	65cm @ 23mm/min
60330	25.4	DFP3-2	Repeat	43cm @ 27mm/min
60331	25.4	DFP3-2	Thermal modifier 85	No results, froze
60332	25.4	DFP3-2	Repeat	No results, froze
60333	25.4	DFP3-2	Repeat	No results, froze
60334	25.4	DFP3-2	Std procedure, removed thermal modifier.	No results, froze
60335	25.4	DFP3-2	Repeat adjusted RF coil	No results, froze
60336	25.4	DFP3-2	Repeat	No results, froze
60337	25.4	DFP3-2	Repeat	52cm @ 20mm/min. .5mm @ edge, .22mm center

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60338	25.4	DFP3-2	Repeat	No results, froze reaching full width
60339	25.4	DFP3-2	Std procedure. Adjusted RF coil because of uneven spreading	No results
60340	25.4	DFP3-2	Repeat	No results, froze @ full width.
60341	25.4	DFP3-2	Repeat	55cm @ 23mm/min
60342	25.4	DFP3-2	Repeat, increased pull speed to 28mm/min.	No results, froze @ full width.
60343	25.4	DFP3-2	Repeat, reduced pull speed to 20mm/min	No results, froze @ full width.
60401	25.4	DFP3-2	Std procedure	56cm @ 19mm/min
60402	25.4	DFP3-2	Repeat	57cm @ 24mm/min
60403	25.4	DFP3-2	Repeat at faster pull speed.	No results, froze @ seeding.
60404	25.4	DFP3-2	Repeat	76cm @ 27mm/min
60405	25.4	DFP3-2	Std procedure	No results, froze.
60406	25.4	DFP3-2	Repeat	56cm @ 21mm/min
60407	25.4	DFP3-2	Repeat increased speed while lowering temp after full width	56cm @ from 26-29mm/min
60408	25.4	DFP3-2	Repeat @ faster speed	65cm @ 32mm/min. .3mm thick @ edge, .15 @ center
60409	25.4	DFP3-2	Repeat @ faster pull speed	48cm @ 33-36mm/min. .35mm thick @ edge, .10mm center. Note: 9.4 meter of ribbon grown with this die.
60410	24.4	DFP3-2	25cm quartz insulator, thermal modifier 85, new die.	No results, froze
60411	24.4	DFP3-2	Repeat	No results, froze
60412	24.4	DFP3-2	Repeat	No results, froze
60413	24.4	DFP3-2	Repeat	No results, froze

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60414	24.4	DFP3-2	Std procedure, 23cm quartz insulator. No thermal modifier.	56cm @ 27mm/min
60415	24.4	DFP3-2	Repeat	No results, froze
60416	24.4	DFP3-2	Repeat	58cm @ 29mm/min
60417	25.4	DFP3-2	Repeat	No results, froze @ full width.
60418	25.4	DFP3-2	Repeat, seed <121> (111)	54cm @ 26mm/min
60419	25.4	DFP3-2	Repeat	56cm @ 30 mm/min. .32mm thick @ edge, .1mm @ center.
60420	25.4	DFP3-2	Repeat	32cm @ 30mm/min. .35mm thick @ edge, .15mm center.
60421	25.4	DFP3-2	New die baked out @ 1225°C in argon/MCL.	50cm @ 20mm/min
60422	25.4	DFP3-2	Repeat same die.	52cm @ 25mm/min
60423	25.4	DFP3-2	Repeat	No results, froze
60424	25.4	DFP3-2	Repeat	No results, froze
60425	25.4	DFP3-2	Repeat	No results, ribbon drifts to right.
60426	25.4	DFP3-2	Repeat	No results, froze
60427	25.4	DFP3-2	Repeat	No results, froze
60428	25.4	DFP3-2	Repeat, rotated die 90°	No results, froze
60429	25.4	DFP3-2	Std procedure adjusted RF coil spacing	No results, froze
60430	25.4	DFP3-2	Repeat	No results, ribbon drifts to right and froze.
60431	25.4	DFP3-2	Repeat	No results, same as above.
60432	25.4	DFP3-2	Std procedure, rotated die 180°	55cm @ 23mm/min, less drifting.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60433	25.4	DFP3-2	Repeat	No results, froze.
60434	25.4	DFP3-2	Repeat	No results, froze. Drifting to right.
60435	25.4	DFP3-2	Repeat	No results, froze.
60436	25.4	DFP3-2	New die. Std procedure.	53cm @ 28mm/min
60437	25.4	DFP3-2	Repeat	55cm @ 23mm/min
60438	25.4	DFP3-2	Repeat	43cm @ 32-36mm/min. .28mm thick @ edge. .18 @ center.
60439	25.4	DFP3-2	Std procedure	54cm @ 25mm/min
60440	25.4	DFP3-2	Repeat	56cm @ 25mm/min
60441	25.4	DFP3-2	Repeat	No results, froze
60442	25.4	DFP3-2	Std procedure	16cm @ 23mm/min
60443	25.4	DFP3-2	Repeat.	38cm @ 24mm/min
60444	25.4	DFP3-2	Repeat	39cm @ 25mm/min
60445	25.4	DFP3-2	Repeat	No results
60446	25.4	DFP3-2	Std procedure	56cm @ 22mm/min
60447	25.4	DFP3-2	Repeat	58cm @ 21mm/min
60448	25.4	DFP3-2	Repeat	53cm @ 23mm/min
60449	25.4	DFP3-2	Std procedure	No results, ribbon drifting.
60450	25.4	DFP3-2	Repeat, adjusted coil	Seed broke, ruined die.
60451	25.4	DFP3-2	Repeat, using die from run 60435.	No results, froze
60452	25.4	DFP3-2	Repeat	No results, froze
60453	25.4	DFP3-2	Repeat, rotated die 180	No results, froze
60501	38	DFP3-2	New die 38mm wide (No. 15) with five 0.80mm die capillary holes.	No results, froze @ 26mm width.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60502	38	DFP3-2	Repeat	No results, froze @ 25mm width.
60503	38	DFP3-2	Repeat	No results, froze @ 24mm width.
60504	38	DFP3-2	Repeat	No results, froze.
60505	38	DFP3-2	Repeat	10cm @ 16mm/min
60506	38	DFP3-2	std for 38mm die	44cm @ 17mm/min. .5mm thick @ edge, .65mm @ center.
60507	38	DFP3-2	Repeat	No results, froze
60508	38	DFP3-2	Repeat, raised coil.	No results, froze
60509	38	DFP3-2	Std for 38mm die	No results, froze
60510	38	DFP3-2	New die. Std for 38mm.	No results
60511	38	DFP3-2	Repeat	36cm @ 18mm/min. Resistivity decreases in regions between capillary holes.
60512	38	DFP3-2	Std for 38mm die.	No results
60513	38	DFP3-2	Repeat	No results
60514	38	DFP3-2	38mm die cleaned in 3:2:1 etch over weekend.	No results
60515	25.4	DFP3-2	Std procedure 25.4mm die.	No results
60516	25.4	DFP3-2	Repeat	No results
60517	25.4	DFP3-2	Repeat	20cm @ 22mm/min
60518	25.4	DFP3-2	Std procedure	No results
60519	25.4	DFP3-2	Repeat	No results
60520	25.4	DFP3-2	Std procedure, new die 25.4mm.	58cm @ 18mm/min
60521	25.4	DFP3-2	Repeat	91cm @ 21mm/min

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60522	25.4	DFP3-2	Repeat	90cm @ 20mm/min
60523	25.4	DFP3-2	Repeat	60cm @ 23mm/min
60524	25.4	DFP3-2	Std procedure 25.4mm die <121> (101) seed.	No results, froze @ full width
60525	25.4	DFP3-2	Repeat	55cm @ 21mm/min. .45mm thick @ edge. .40 @ center.
60526	25.4	DFP3-2	Repeat <110> (112) seed	58cm @ 24mm/min
60527	25.4	DFP3-2	Repeat	81cm @ 23mm/min
60601	38	DFP3-2	Std procedure 38mm die	No results, froze
60602	38	DFP3-2	New die	Froze @ full width
60603	38	DFP3-2	Repeat	38cm @ 17mm/min
60604	38	DFP3-2	Repeat	Froze
60605	38	DFP3-2	Repeat	No results, froze
60606	25.4	DFP3-2	Top of capillary slot modified to vee groove using a 184mm dia grinding wheel with a 45° included angle.	6.3cm @ 18mm/min
60607	25.4	DFP3-2	Repeat	Froze
60608	25.4	DFP3-2	Repeat	Froze
60609	25.4	DFP3-2	Repeat	Froze
60610	25.4	DFP3-2	Repeat	Froze
60611	25.4	DFP3-2	Repeat. Raised RF coil	50cm @ 20mm/min. Broad central dip in transverse resistivity profile.
60612	25.4	DFP3-2	Repeat	65cm @ 23mm/min
60613	25.4	DFP3-2	Repeat	Froze
60614	25.4	DFP3-2	Repeat	48cm @ 20mm/min

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60615	25.4	DFP3-2	Repeat	91cm @ 20-26mm/min
60616	25.4	DFP3-2	Repeat	No results
60701	25.4	DFP3-2	New die. Duplication of 60606 Baked out in argon/HCL	No results
60702	25.4	DFP3-2	Repeat	85cm @ 18mm/min. .50mm thick at edge, .51mm center
60703	25.4	DFP3-2	Repeat	Froze @ full width
60704	25.4	DFP3-2	Repeat	Froze
60705	25.4	DFP3-2	Repeat. New RF coil	57cm @ 22mm/min
60706	25.4	DFP3-2	Repeat	94cm @ 24mm/min
60707	25.4	DFP3-2	Repeat	Froze
60708	38	DFP3-2	Std procedure	Froze during seeding
60801	38	DFP3-2	New die, 13B with 152mm top curvature, .68mm edge thickness, and 0.4mm capillary slot.	53cm @ 14mm/min. .64mm thick at edge, .68mm center.
60802	38	DFP3-2	Repeat	6cm @ 13mm/min
60803	38	DFP3-2	Repeat	22cm @ 17-19mm/min
60804	38	DFP3-2	Repeat	29cm @ 16mm/min
60805	38	DFP3-2	Repeat	No results
60806	38	DFP3-2	Repeat	Froze @ full width
60807	38	DFP3-2	Repeat. Rotated die 180°	16m @ 21mm/min
60808	38	DFP3-2	New die # 13B. Std procedure	Edge of die touched lower shield. Could not run.
60809	38	DFP3-2	Repeat. Filed away lower shield where die touched.	59cm @ 16mm/min. Ribbon shattered during handling.
60810	38	DFP3-2	New die #15A	10cm @ 13mm/min. Routh

Pun No.	Die Width(mm)	Die Material	Experimental Variables	Result
				ribbon surface.
60811	38	DFP3-2	Repeat. Seed <121>(111)	26cm @ 16mm/min
60812	38	DFP3-2	Repeat	Ribbon drifting. Froze @ full width.
60901	38	DFP3-2	4 port argon thermal modifier system used. Open pull port. Bellows removed.	No results. Froze
60902	38	DFP3-2	New die # 138 plus argon thermal modifier.	Demonstrated that drifting could be reversed by changing argon flow.
60903	38	DFP3-2	Repeat, evaluate argon thermal modifier.	No ribbon
60904	38	DFP3-2	Repeat	No results. Center of die too hot compared to edges.
60905	25.4	DFP3-2	Argon thermal modifier used with flat die.	No results. Froze
60906	25.4	DFP3-2	Repeat.	Froze
60907	25.4	DFP3-2	Repeat using full width seed. <110>(100)	Froze
60908	25.4	DFP3-2	Repeat @ faster pull speed (17mm/min).	Edge colder than center. Ribbon pulled out in center.
60909	25.4	DFP3-2	Repeat. Spreading responds to argon flow changes.	Ribbon froze after short distance.
60910	25.4	DFP3-2	Repeat. Slow pull speed and higher argon flow at ends of ribbon.	Froze after short distance.
60911	25.4	DFP3-2	Repeat @ 11mm/min.	Meniscus hotter in center, ribbon pulled out.
60912	25.4	DFP3-2	Repeat @ 5mm/min.	Same as above.
60913	25.4	DFP3-2	Repeat @ 9mm/min.	Same as above. Center region too hot.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60914	25.4	DFP3-2	Repeat, rotated die 180°. Speed 15mm/min.	Meniscus still too hot in center.
60915	25.4	DFP3-2	Repeat, upper and lower shield openings modified to navette shape. Argon flow about 3 CFH directed @ ends of die.	112cm ribbon @ 14mm/min. Very smooth surface, few SiC particles.
60916	25.4	DFP3-2	Repeat	90cm @ 14mm/min.
60917	25.4	DFP3-2	Repeat with diffuse argon flow of 25 CFH from bottom of furnace in addition to flow @ die ends.	83cm @ 14mm/min.
60918	25.4	DFP3-2	Repeat of conditions in 60915. Study width response to argon flow changes.	Good response of ribbon width changes to argon flow.
60919	38	DFP3-2	New die 815A.	Power failure of RF system.
60920	38	DFP3-2	Repeat.	Die chipped, could not reach full width.
60921	38	DFP3-2	New die 813B. Finer resolution argon flow meters installed. Argon flow @ die ends 3 CFH.	47cm @ 14mm/min.
60922	38	DFP3-2	Repeat.	No results
60923	38	DFP3-2	Repeat.	Froze
60924	38	DFP3-2	Repeat with argon flow of 1.5 CFH @ die ends.	42cm @ 13mm/min.
60925	38	DFP3-2	Repeat with argon flow of 3.5 CFH @ die ends.	Froze
60926	38	DFP3-2	Repeat. Rotated die 90°.	45cm @ 14mm/min.
60927	38	DFP3-2	Repeat, same die as used in run 860918.	20cm @ 17mm/min.
60928	38	DFP3-2	Repeat	Ribbon froze at speed of 19mm/min.

Run No.	Die Width(mm)	Die Material	Experimental Variables	Result
60929	38	DFP3-2	Repeat, attempting higher pull speed.	Seed broke and ruined die.
61001	38	DFP3-2	New die # 15A.	67cm @ 15mm/min.
61002	38	DFP3-2	Repeat at 16 to 18mm/min.	No results.
61003	38	DFP3-2	Repeat.	75cm @ 17 to 27mm/min. At 27mm/min, edge thickness is .55mm. Center thickness is .38mm.
61004	38	DFP3-2	Repeat at 25-30mm/min.	No results, froze.
61005	38	DFP3-2	Repeat	Froze
61006	38	DFP3-2	Repeat	35cm @ 25mm/min. .45mm thick at edge, .40 at center.
61007	38	DFP3-2	Repeat	No result, froze.
61008	38	DFP3-2	Repeat @ 20mm/min.	37cm @ 20mm/min. Smooth surface.
61009	38	DFP3-2	New 2 piece die 17-38A.	No results, froze.
61010	38	DFP3-2	Repeat	122cm @ 18-20mm/min.
61011	38	DFP3-2	Repeat	100cm @ 22-25mm/min. .45mm thick at edge, .3mm center. Less variation in transverse dopant profile than with one piece die.
61012	38	DFP3-2	Repeat @ 30mm/min.	No results.
61013	38	DFP3-2	Repeat.	No results.
61014	38	DFP3-2	Repeat. Argon flow at die ends 6 CFH.	80cm @ 25-30.5mm/min. .45mm thick at edge, .25mm center.
61015	38	DFP3-2	Repeat.	No result, froze.
61016	38	DFP3-2	Repeat @ 25mm/min.	50cm. Controlled width with argon flow rather than temp.
61017	38	DFP3-2	Repeat	131cm @ 25mm/min.
61018	44	DFP3-2	New setup for 50mm growth.	Froze @ 40mm width.
61019	44	DFP3-2	Repeat.	25cm @ 15mm/min. Width 43-44mm Smooth surface.
61020	50	DFP3-2	New 2 piece die 2P501.	Froze reaching 44mm width.
61021	50	DFP3-2	Repeat.	Same as above.
61022	50	DFP3-2	Repeat.	No results.
61101	50	DFP3-2	New die 2P502. Shield slots opened to form a navette shape.	109cm ribbon, 50mm wide @ 14mm/min.

APPENDIX II

DIMENSIONAL PROPERTIES OF LONG SILICON RIBBONS

August 1975 to November 1976

Ribbon Run No.	Seed		Usable Length (cm)	Width (mm)		Thickness (mm)			
	Orientation Axis	Surface		Max	Min	Seed Max	Seed Min	Tail Max	Tail Min
50805	0	0	38	8.6	6.7	1.01	.00	1.03	.00
50806	0	0	65	8.1	6.2	1.00	.00	1.05	.00
50807	0	0	25	8.7	7.6	1.10	.00	1.15	.00
50808	0	0	34	8.4	8.1	1.06	.00	1.21	.00
50809	0	0	114	7.3	6.7	1.01	.00	1.05	.00
50811	0	0	28	8.0	7.1	1.35	.00	1.35	.00
50825	0	0	32	4.7	4.2	1.58	.00	1.60	.00
50826	0	0	32	5.5	3.8	1.25	.00	1.43	.00
50909	0	0	23	26.2	25.8	.70	.35	.67	.39
50911	110	111	24	25.7	24.4	.65	.35	.62	.41
50916	110	100	46	26.0	.0	.73	.54	.62	.33
50919	110	100	90	26.0	.0	.55	.23	.65	.36
50926	110	100	18	26.0	.0	.65	.57	.65	.56
50927	110	100	40	26.0	.0	.53	.40	.54	.34
50928	110	100	45	26.0	.0	.49	.32	.50	.31
51003	110	112	49	25.8	23.6	.67	.51	.63	.46
51005	110	112	50	26.1	24.7	.63	.44	.66	.45
51007	110	112	51	26.4	23.0	.75	.53	.73	.45
51008	110	112	44	25.6	23.7	.63	.40	.66	.43
51012	100	110	91	25.9	24.3	.69	.49	.68	.47
51013	100	110	20	26.0	25.0	.64	.42	.68	.51
51014	100	110	54	25.7	21.2	.69	.62	.62	.34
51015	110	100	84	25.1	23.4	.61	.35	.64	.34
51016	110	100	52	24.8	17.0	.73	.48	.60	.39
51017	110	100	22	24.7	23.8	.64	.45	.44	.26
51018	110	100	23	25.1	25.0	.72	.43	.67	.41
51019	110	100	56	25.0	23.6	.67	.44	.55	.35
51021	110	100	54	26.2	24.4	.65	.49	.66	.38
51022	110	100	63	25.6	23.8	.63	.38	.59	.28
51023	110	100	63	25.5	24.1	.62	.35	.59	.39
51024	110	100	24	26.2	12.5	.63	.35	.64	.26
51025	110	100	58	25.7	23.3	.54	.31	.56	.22
51026	110	100	62	25.4	24.6	.62	.42	.62	.37
51027	110	100	59	24.9	24.5	.51	.29	.52	.26
51102	110	112	12	.0	.0	.00	.00	.00	.00
51104	110	100	59	25.3	23.5	.54	.40	.51	.36
51107	110	112	49	25.5	24.1	.45	.29	.50	.28
51110	110	100	10	25.7	23.3	.55	.50	.55	.50
51114	110	100	48	25.4	24.4	.50	.36	.50	.34
51115	110	100	87	25.6	25.2	.46	.30	.57	.35
51118	110	100	57	25.2	24.8	.46	.31	.45	.29

Ribbon Run No.	Seed		Usable Length (cm)	Width (mm)		Thickness (mm)			
	Orientation Axis	Surface		Max	Min	Seed Max	Seed Min	Tail Max	Tail Min
51119	110	100	54	24.7	24.5	.43	.28	.46	.29
51120	110	100	21	24.9	23.8	.45	.32	.47	.25
51201	110	100	16	24.6	17.4	.47	.50	.50	.35
51202	110	100	60	25.0	24.1	.52	.42	.50	.45
51203	110	100	19	25.5	24.1	.76	.50	.45	.36
51205	110	100	36	25.0	24.9	.55	.45	.50	.45
51207	110	100	20	24.5	22.2	.61	.40	.26	.22
51208	110	100	46	24.6	24.3	.50	.40	.46	.36
51209	110	112	53	.0	.0	.45	.35	.00	.00
51210	110	112	46	24.9	20.6	.67	.50	.65	.50
51213	110	112	32	23.5	14.0	.38	.32	.53	.40
51214	110	100	55	24.8	23.2	.48	.40	.45	.41
51216	110	100	39	25.3	22.7	.71	.52	.73	.45
51217	110	100	57	24.7	23.4	.74	.48	.75	.47
51218	110	100	45	22.9	22.4	.55	.50	.60	.50
60102	110	100	56	25.5	24.9	.53	.39	.50	.33
60103	110	100	51	25.2	24.2	.48	.31	.45	.27
60104	110	112	60	25.4	24.3	.49	.29	.52	.33
60105	110	100	58	24.9	18.8	.50	.45	.50	.45
60110	110	100	46	24.8	23.6	.53	.42	.50	.37
60111	110	100	94	25.4	23.8	.00	.00	.00	.00
60112	110	100	90	24.9	23.4	.45	.35	.50	.27
60114	110	100	33	25.4	22.7	.50	.45	.53	.36
60115	110	100	36	25.2	20.1	.50	.40	.40	.30
60116	110	100	31	25.2	22.4	.53	.42	.37	.28
60119	110	100	28	25.4	25.1	.55	.50	.54	.38
60120	110	100	95	.0	.0	.00	.00	.00	.00
60202	110	100	96	24.6	23.7	.50	.32	.47	.30
60203	110	100	25	25.5	22.2	.57	.38	.55	.25
60206	110	100	9	23.1	18.1	.62	.70	.60	.64
60209	110	100	45	25.9	24.2	.80	.90	.64	.90
60212	110	111	55	25.7	25.1	.60	.50	.60	.40
60213	110	111	77	25.6	25.4	.60	.85	.00	.00
60216	110	100	40	24.6	24.2	.70	.80	.55	.65
60217	110	100	18	24.4	24.2	.60	.85	.42	.52
60303	110	111	55	24.9	22.5	.47	.43	.45	.35
60304	100	110	55	25.5	22.6	.45	.42	.42	.22
60309	100	110	53	25.6	23.4	.47	.50	.42	.45
60310	100	110	23	25.2	23.9	.35	.35	.38	.40
60312	111	110	41	24.7	21.7	.32	.32	.35	.37
60318	100	110	44	25.6	23.7	.44	.40	.45	.37
60320	100	110	55	25.3	24.3	.42	.38	.36	.30
60322	111	112	57	24.7	24.0	.40	.34	.41	.25
60323	111	112	29	24.6	22.0	.30	.27	.32	.22
60324	111	112	54	24.4	22.2	.35	.28	.32	.24
60325	110	100	18	23.9	18.6	.65	.70	.50	.40
60326	110	100	38	25.5	21.9	.45	.38	.54	.46
60328	110	100	35	25.3	25.0	.45	.42	.40	.28
60329	110	112	56	24.8	22.7	.30	.25	.40	.28

Ribbon Run No.	Seed Orientation		Usable Length (cm)	Width (mm)		Thickness (mm)			
	Axis	Surface		Max	Min	Seed		Tail	
						Max	Min	Max	Min
60330	110	112	43	25.4	24.7	.30	.26	.38	.30
60337	100	110	52	25.2	18.0	.40	.27	.50	.22
60341	100	110	55	25.1	23.7	.40	.35	.48	.32
60401	100	110	56	26.2	25.8	.50	.35	.50	.37
60402	100	110	57	25.7	25.2	.45	.32	.45	.30
60404	110	100	76	26.4	24.6	.40	.21	.50	.32
60406	100	110	56	25.8	25.0	.52	.36	.52	.24
60407	100	110	56	.0	.0	.00	.00	.00	.00
60408	100	110	56	25.0	24.2	.30	.16	.30	.15
60409	100	110	48	24.8	23.7	.30	.15	.35	.10
60414	110	100	56	25.6	25.0	.45	.25	.35	.20
60416	100	110	58	25.4	23.6	.45	.22	.38	.18
60418	121	111	54	25.4	20.5	.45	.22	.35	.10
60419	121	111	56	25.2	24.5	.40	.22	.32	.10
60420	121	111	32	25.2	25.0	.32	.19	.35	.15
60421	121	101	50	25.2	22.4	.48	.37	.48	.32
60422	121	101	52	25.0	23.1	.45	.25	.43	.25
60432	100	110	55	24.9	24.7	.40	.30	.00	.00
60436	100	110	52	24.8	24.1	.48	.41	.00	.00
60437	121	111	55	25.2	24.1	.40	.28	.45	.32
60438	121	111	43	25.0	22.9	.35	.23	.28	.18
60439	121	111	54	25.5	24.1	.45	.29	.42	.30
60440	121	111	56	24.5	24.3	.40	.25	.39	.24
60442	121	111	16	24.4	23.1	.42	.27	.42	.25
60443	121	111	38	24.3	20.5	.40	.32	.36	.16
60444	121	111	39	24.4	24.3	.42	.19	.45	.20
60446	100	110	56	24.4	17.2	.38	.25	.38	.22
60447	121	111	58	24.6	19.7	.35	.19	.45	.21
60448	121	101	53	24.4	24.1	.45	.20	.40	.15
60506	100	110	46	38.2	37.8	.55	.65	.50	.65
60511	110	112	36	39.2	37.4	.43	.55	.44	.53
60520	110	112	58	25.2	25.0	.52	.45	.51	.45
60521	121	101	91	24.7	22.7	.40	.38	.40	.28
60522	110	112	90	25.2	24.8	.40	.35	.45	.28
60523	110	112	63	24.7	24.5	.42	.30	.39	.30
60525	121	101	55	24.7	24.6	.45	.40	.45	.40
60526	110	112	58	24.6	23.3	.40	.20	.40	.25
60527	110	112	81	25.0	24.3	.40	.20	.50	.25
60612	110	112	65	24.4	23.7	.47	.42	.40	.32
60702	110	112	85	24.8	23.2	.45	.50	.50	.51
60801	110	112	53	38.1	37.9	.81	.67	.68	.64
60803	110	112	22	38.0	.0	.65	.57	.63	.59
60915	110	100	112	37.7	37.5	.75	.50	.60	.49
60916	110	100	90	37.6	37.4	.92	.74	.71	.60
60917	110	100	83	37.5	37.4	.80	.58	.80	.63
60918	110	100	90	38.0	.0	.77	.64	.83	.68
60920	110	100	54	34.0	.0	.89	.73	.80	.53
60924	110	100	42	38.0	.0	1.04	.75	1.10	.75
60926	110	100	45	38.0	.0	.95	.85	.77	.56

Ribbon Run No.	Seed		Usable Length (cm)	Width (mm)		Thickness (mm)			
	Orientation Axis	Surface		Max	Min	Seed		Tail	
						Max	Min	Max	Min
60927	110	100	20	38.0	.0	1.45	1.15	1.00	.80
60928	110	100	23	38.0	.0	1.05	.82	1.00	.84
61001	110	100	67	38.0	.0	1.10	.80	1.18	.80
61003	110	100	75	38.0	.0	.75	.55	.55	.38
61006	110	100	35	38.0	.0	.65	.58	.45	.40
61008	110	100	37	38.0	.0	.48	.47	.50	.48
61010	110	100	122	38.0	.0	.68	.50	.63	.40
61011	110	100	100	38.0	.0	.48	.42	.44	.32
61014	110	100	80	38.0	.0	.56	.50	.43	.28
61016	110	100	50	38.0	.0	.40	.28	.60	.27
61017	110	100	131	38.0	.0	.60	.41	.55	.35
61019	110	100	21	43.6	41.4	.70	.43	.78	.68
61020	110	100	17	43.7	42.9	1.40	.82	1.50	1.10
61101	110	100	109	49.5	49.1	1.20	.60	1.20	.50

A 0.0 ENTRY INDICATES NO MEASUREMENT WAS MADE.

A GUIDE TO FUTURE SILICON SHEET TECHNOLOGY

by

A. Kran

1.0 INTRODUCTION

An important aspect of this program is the rapid and systematic development of a technological and economic data base, which is required to define the potential of silicon sheet growth for large-scale photovoltaic applications. In support of this effort, interactive computer simulation models have been developed. These models can be viewed as tools for automatic computation and conversion of unstructured data, as the data become available, into analyzable procedures with explicit assumptions.

This activity has led to a clearer understanding of the economics of silicon sheet growth and provided a guide to future silicon ribbon technology.

2.0 MODEL OF SILICON SHEET GROWTH PRODUCTION

2.1 The Production Unit

The production unit concept reduces the complexity of interaction among processing sectors in a manufacturing

operation. It was chosen for the study of the technological prospects of low-cost silicon sheet material.

A production unit may be thought of in terms of three elements: processing technology, capital equipment resources, and raw materials. To a computing system, this model is described as a specific combination of manpower, crystal-growing equipment, and polycrystalline silicon needed to progress through the crystal-pulling sector in a solar-cell manufacturing operation.

Two management approaches and production environments, aimed at resulting in low-cost silicon sheet material, are contrasted. The first is characterized by simplicity, as one might compare a steel mill to a large-scale integration (LSI) semiconductor plant. This means a relatively simple, single-ribbon growth process, and nearly unattended, around-the-clock operation. Crystal pullers are envisioned as single-purpose machines, completely automated, producing, for instance, 100-mm-wide, 0.3-mm-thick ribbon, and nothing else.

The second approach is characterized by sophistication in manufacturing technology and flexibility in terms of product mix, achieved by means of complex processing systems.

To quantify the future prospects of silicon sheet and to

differentiate between the two approaches to high-volume production, they will subsequently be referred to as single (simple) versus multiple (sophisticated) ribbon growth.

2.2 Model Input Parameters

To present the most elementary comparison between the two production units, or approaches to sheet growth, only those parameters pertaining directly to the respective growth systems are projected independently. In other words, Fig. 1 lists those variables and their assigned values that are used for both single- and multiple-ribbon growth systems. The three parameter values represent the baseline, a near-future point in time, and the future. Corresponding information is provided in Table I, which highlights the difference between the two production units. It also groups production unit parameters into three major elements - processing technology, capital equipment resources, and raw material - which are discussed next.

The important components of processing technology are ribbon width and growth-rate capability.

As part of this technology assessment, two options are being evaluated for their effect on silicon sheet material cost: 10-cm-wide ribbons achieved through single-ribbon growth, and a 15-cm-wide capability attained through growing three

RIBBON DATA FROM SIMULATIONS 1 4 5 DATED 03/02/76

3 RIBBON GROWTH RATE, M/HR - 1.50 2.49 3.59 ..OR AS PCT 30 40 50
4 RIBBON THICKNESS, MM - 0.30 0.20 0.15
5 YIELD OF "CELL QUALITY" RIBBON, PCT - 70 80 90

DIRECT COST

7 EQUIPMENT LIFE, YEARS - 7.0 8.0 10.0
8 INTEREST RATE, PERCENT - 10.0 10.0 10.0
PERSONNEL PER SHIFT PER MACHINE

10 11 NO. OF SUPVS - 0.05 0.05 0.05 AT 8 - 25000 25000 25000
12 13 NO. OF ENGRS - 0.10 0.10 0.10 AT 8 - 20000 20000 20000
14 15 NO. OF TECHN - AT 8 - 10000 10000 10000
16 POLY SILICON COST, DOLS/KG - 65 45 30
17 POLY YIELD TO RIBBON, PERCENT - 80 85 90

SERVICES AND SUPPLIES

18 CRUCIBLE/DIE/PARTS COST PER WEEK - 150 125 100 DOLLARS
19 POWER COST AT - 0.05 0.05 0.05 DOLLARS PER KWH
20 ENERGY TO OPERATE EQUIPMENT - 12 11 10 KW

21 22 Q/H - 50 50 50 PCT OF PERS+ 10 10 10 PCT OF RAW MATL COST
23 G AND A - 10 10 10 PERCENT OF DIRECT COST+OVERHEAD

24 PROFIT BEFORE TAX, PERCENT - 10 10 10 OF DC+O/H+G+A

MISCELLANEOUS

25 WORKWEEK, HOURS - 168 168 168
26 CONVERSION EFFICIENCY, PERCENT - 8.00 10.00 12.00
27 ENERGY DENSITY AT AM1, KW/SQ M PEAK - 1 1 1

Fig. 1. List of jointly-used ribbon parameters and their assigned values.

TABLE I. Technology Projection List of Production-Unit Parameters.

Processing Technology	Single-Ribbon Growth System			Multiple-Ribbon Growth System		
	Present	→ Future		Present	→ Future	
Ribbon width (cm)	2.5	5.0	10.0	2.5	3.0	5.0
Simultaneous ribbons	N/A	N/A	N/A	1	2	3
Growth rate (% of max)	30	40	50	30	40	50
Ribbon thickness (mm)	0.30	0.20	0.15	0.30	0.20	0.15
Resources						
Ribbon puller (\$)	50,000	25,000	20,000	175,000	150,000	125,000
Availability (% of time)	70	80	90	60	70	80
Technicians (No.)	0.50	0.25	0.15	1	1	1
Raw Materials						
Polysilicon cost (\$)	65	45	30	60	45	30

simultaneous ribbons, each 5 cm wide.

Growth-rate capability is anticipated to be the same for single- as for multiple-ribbon growth systems. At present, 0.3-mm-thick ribbons are pulled at 1.5 m/hr, which is 30% of the theoretical maximum growth rate. The growth rate is expected to increase from 30 to 50% (3.8 m/hr) of theoretical maximum.

Single-ribbon growth systems can be implemented today through modification of commercially available Czochralski type crystal pullers at a total cost of about \$50,000. Assuming a significant future market for photovoltaic products, next-generation sheet pullers must be standardized, mass-produced, and sold as special-purpose equipment for about \$20,000. Such systems are expected to be highly reliable, featuring machine availability of up to 90%, and will require no more than one technician to operate about 10 systems.

Because of the significantly greater complexity of multi-ribbon growth production systems, the market for such equipment is expected to be much smaller. Today's estimated capital cost of \$175,000 might decrease to about \$125,000 with an increase in system availability from 60 to 80%. Required manpower is envisioned to remain constant at one technician full time per system.

The cost of polycrystalline silicon in bulk form has remained unchanged at about \$65/kg for a number of years, which is why \$30/kg was assumed a reasonable input to the model as the "future" parameter value. However, at this point, it appears that \$30/kg is the maximum amount allowable, and any number above \$30/kg is insufficient to achieve the 1985 \$500/kWE energy-capacity cost objective.

2.3 Result of Model Output

The output from the model is summarized in Table II, and used throughout the remainder of this report. The results show that, for the single-ribbon growth system, single-crystal silicon cost decreases from the baseline value of \$678/m² to \$38/m² for some time in the future. The respective energy-capacity costs range from \$8476/kWE to \$314/kWE. The corresponding values for multiple-ribbon growth systems range from \$1292/m² (\$16,152/kWE) to \$59/m² (\$489/kWE).

Figure 2 summarizes the model output information in graphical form, comparing cost at the level of silicon sheet material.

The histograms to the right (double-hatched) refer to multiple-ribbon growth and, as can be seen, are higher by

TABLE II. Model Output Summary: Silicon Sheet Material and Energy-Capacity Costs

	$\$/\text{m}^2$	$\$/\text{kWE}$
<u>Single-Ribbon Growth</u>		
Present	678.00	8,476.00
Near-future	132.00	1,319.00
Future	38.00	314.00
<u>Multiple-Ribbon Growth</u>		
Present	1,292.00	16,152.00
Near-future	249.00	2,486.00
Future	59.00	489.00

Fig. 2. Silicon sheet material cost.

almost a factor of two. Because of both the higher cost of silicon sheet material and the greater complexity of the multiple-ribbon growth system, this analysis favors single-ribbon growth.

3.0 SENSITIVITY STUDY

3.1 Production Unit Elements

Sensitivity analysis is useful in providing additional information to strengthen the case for a decision among alternatives, such as the choice between single- and multiple-ribbon growth systems. In this instance, we wish to gain additional confidence in the finding for single-ribbon growth.

This study tests the sensitivity of the baseline silicon sheet material cost of the two production units to future advances in the previously defined three major production unit elements: processing technology, resources, and raw material costs. It is accomplished by projecting the parameters of the components within the particular element, while keeping the remaining production unit parameters at the baseline values.

The result is shown in Fig. 3. From the baseline, or reference, on the left, the effect of advancing process

Fig. 3. Single- to multiple-ribbon growth: comparison by major production-unit elements.

technology, decreasing the cost of capital equipment resources, and reducing polycrystalline silicon raw material cost is depicted. It implies that advancing processing technology is of first-order importance, in terms of achieving low silicon sheet material cost, followed by less costly crystal-pulling systems and inexpensive polycrystalline silicon material.

Furthermore, it suggests that low-cost silicon sheet material objectives can be achieved by pursuing either single- or multi-ribbon growth. However, about twice as much effort is required to reach the low-cost objective by means of multi-ribbon, as compared with single-ribbon growth technology. Consequently, this examination confirms the previously reached determination favoring single-ribbon growth systems.

Now that the choice between single- and multiple ribbon growth systems has been made, the individual components of the most sensitive single-ribbon production unit element will be evaluated next.

3.2 Processing Technology Components

Single-ribbon growth and its key element, processing technology, will be evaluated to determine where additional development effort should be directed to produce the lowest-cost silicon sheet.

The methodology consists of selecting a processing-technology component, e.g., ribbon width, and, while holding all other production unit parameters at the baseline value, iterating the model in equal increments between the two projected limits (i.e., 2.5 to 10 cm). This is done until a sufficient number of data points for curves, such as shown in Fig. 4, can be collected.

Fig. 4. Single-ribbon system: silicon sheet cost vs processing-technology parameters.

Figure 4 suggests that increasing ribbon width from 2.5 to 10 cm has the most pronounced effect on cost, reducing silicon sheet material by 64%, or from the baseline of $\$678/\text{m}^2$ to $\$247/\text{m}^2$. The effect of reducing ribbon thickness, by itself, is insignificant. Improving growth rate from 30 to 50% of theoretical maximum ranks between the two, reducing cost by 35%, from $\$678/\text{m}^2$ to $\$443/\text{m}^2$. Since ribbon growth rate and ribbon thickness are related, Fig. 5 compares the potential of their combined improvement, a reduction of 57% from $\$678$ to $\$292/\text{m}^2$. However, this figure is still higher than $\$247/\text{m}^2$, which results from increasing

Fig. 5. Single-ribbon system: silicon sheet cost vs combined processing-technology parameters.

ribbon width from 2.5 to 10 cm. The combined improvement of all parameters within this production unit element yields an improvement of 84%, or future silicon sheet material cost at \$112/m².

Additional perspective is provided in Fig. 6, where silicon sheet material cost vs width is presented. It should be noted that increasing ribbon width from 2.5 to 5 cm, an objective just about achieved, will reduce sheet material cost from \$678/m² to \$390/m², or by almost a factor of two. Doubling ribbon width again, from 5 to 10 cm, will further lower material cost to \$247/m², an additional 14%.

Fig. 6. Single-ribbon system: silicon sheet cost vs ribbon width.

4.0 RIBBON PARAMETER TRADE-OFF STUDY

4.1 Methodology

In order to further clarify important technological-economic questions, which must be answered before the desired energy-capacity cost objective of 50 cents/watt can be met, a computer-aided trade-off study of such parameters as solar-cell conversion efficiency, ribbon thickness, ribbon width, and polysilicon cost was undertaken. Three points in time and their respective (projected) energy-capacity costs are analyzed: "Present" - \$8476/kWE, "Near-future" - \$1319/kWE, and "Future" - \$314/kWE.

To derive a specific relationship between any three of these parameters, technological or practical limits are assigned to two parameters, while the third one is kept constant. For instance, thickness is permitted to vary between 0.1 and 1.0 mm, conversion efficiency between 5 and 20%, and projected polysilicon cost is held constant at \$65/kg. Specific parameter values required for each calculation are obtained by stochastically sampling between these limits, and then calculating the resultant energy-capacity cost at the level of silicon sheet material. By accepting as valid data points only parameter values that result in the specified energy-capacity cost (e.g., \$8476/kWE, $\pm 0.5\%$ to limit the number of computer iterations), and rejecting all others, the model is iterated until the relationship (if one exists) between the input parameters and the specified output (dollars/kWE) is determined.

Subsequent iterations of the model, with polysilicon cost held constant at \$6/kg, \$30/kg, and \$45/kg, respectively, result in the other three curves of Fig. 7.

4.2 Present Silicon Sheet Technology

The conclusions derived from this computer simulation provide important guidelines for our ribbon program.

* Simulations refer to Annual Report.

Fig. 7. Present silicon ribbon technology: conversion efficiency vs ribbon thickness (energy-capacity cost, \$8476/kWE).

From Fig. 7 we conclude that semiconductor-grade-quality polycrystalline silicon cannot be abandoned in favor of inferior-quality material, sometimes referred to as solar-cell grade. It is apparent that inferior-quality polysilicon is not acceptable as long as it leads to an appreciable reduction of solar-cell conversion efficiency. For instance, inferior-quality polysilicon (for 0.3-mm-thick ribbon) comes close to being cost-effective only if a price reduction of at least one order of magnitude (from \$65/kg to \$6/kg) can be achieved. This would allow the conversion efficiency of solar cells to be somewhat reduced (from 8% to 7%).

Ribbon thickness plays a relatively insignificant role in determining energy-capacity cost. Hence, a thickness (0.3 to 0.4 mm) should be selected that is compatible with subsequent mechanical handling of the material during cell fabrication. For instance, reducing thickness from 0.3 mm by a factor of 2 to about 0.15 mm eases the requirement on conversion efficiency by about one half of a percentage point, from 8 to 7.4%. Similarly, there is little penalty for increasing thickness from 0.3 to 0.5 mm, which would require an improvement in conversion-efficiency capability of less than one percentage point.

4.3 Near-Future Technology

Polysilicon cost of \$30-45/kg must be obtained during this period, as can be seen from Fig. 8. The alternative, assuming a \$65/kg polysilicon cost, is a 13% cell. In other words achieving either of the two will produce the near-future energy-capacity cost objective of \$1319/kWE. Furthermore, the purity of the \$30-45/kg polysilicon must be such that 10% conversion efficiency solar cells, made from 0.3-mm-thick ribbon, are readily achievable.

Ribbon thickness, at a polysilicon cost of less than \$10/kg, is insignificant as a factor contributing to energy-capacity cost. However, at the \$30-45/kg level, thickness cannot be ignored. Reducing ribbon thickness from 0.3 to 0.2 mm is

Fig. 8. Near-future silicon ribbon technology: conversion efficiency vs ribbon thickness (energy-capacity cost, \$1319/kWE).

equivalent to lowering polysilicon cost from \$45/kg to \$30/kg, or reducing the solar-cell conversion-efficiency requirements from 11.5 to 10%.

4.4 Future Technology

The likelihood of achieving a "future" energy-capacity cost of \$314/kWE is examined three ways: (1) conversion efficiency vs ribbon thickness (four polysilicon cost levels); (2) conversion efficiency vs ribbon width (four polysilicon cost levels), and (3) conversion efficiency vs ribbon width (four capital equipment cost levels).

1. A polysilicon cost above \$30/kg makes the energy-capacity cost objective of \$314/kWE unachievable, as can be deduced from Fig. 9. At \$30/kg, a 0.3-mm-thick cell would need to be 17% efficient to reach the \$314/kWE cost objective, an unlikely prospect.

At a polysilicon cost of approximately \$10/kg, there is sufficient flexibility, in terms of ribbon thickness and conversion efficiency, to make \$314/kWE a reasonable goal.

Fig. 9. Future silicon ribbon technology: conversion efficiency vs ribbon thickness (energy-capacity cost, \$314/kWE).

2. Figure 10, the relationships between ribbon width, conversion efficiency, and polysilicon cost, suggests there is little hope of achieving an energy-capacity cost objective of \$314/kWE, given a polysilicon cost above \$30/kg. At the \$30/kg cost level, the goal of \$314/kWE can be reached only if solar cells of 12% efficiency can be made from 10-cm-wide ribbons. However, at a polysilicon cost level of about \$10/kg, the energy-cost objective of \$314/kWE can be reached with 10% efficient cells made from 7.5-cm-wide ribbons. This goal appears readily achievable.

Fig. 10. Future silicon ribbon technology: conversion efficiency vs ribbon width for polysilicon cost levels (energy-capacity cost, \$314/kWE).

3. Figure 11 indicates that sheet-material cost is rather insensitive to variation in capital equipment cost, if the equipment is highly reliable (machine availability 90%) and capable of being utilized over a prolonged period of time (12 years). Under those conditions, doubling capital equipment cost from the future projected value of \$20,000 to \$40,000 is insignificant. It is equivalent to achieving, by other means, either a one-half percent higher conversion efficiency

Fig. 11. Future silicon ribbon technology: conversion efficiency vs ribbon width for crystal system costs (energy-capacity cost, \$314/kWE).

(12 to 12.5%) or 1-cm-wider ribbon (10 to 11 cm). Similarly, lowering capital equipment cost to an unrealistically low \$4,000 is negligible in reducing the production technology requirements of the sheet material.

In sum, highly reliable, long-lasting capital equipment is more cost-effective than trying to minimize an initial capital investment.

5.0 TECHNOLOGY PROJECTION

5.1 Methodology

Technology assessment differs from technology projection in that the former is concerned with assessing future (no specific timeframe) technology capability, whereas the latter also provides specific reference to time.

Using system simulation and probability concepts, this particular technology projection technique, developed as part of the contract, associates individual technology parameters projected in time with an estimated probability of the event's occurring at a specific point. This results in a composite cost profile, or a specific cost (\$/kWE) versus time relationship, and in an ability to compare our projections of future sheet material cost with ERDA

projections for solar-array costs.

Application of this technique requires a technical understanding of what the technology is capable of achieving, an assessment of state-of-the-art, and, finally, judgment with respect to the timing of subsequent implementation. Once a matrix suitable for computer manipulation has been set up, however, monitoring technology progress becomes a matter of routine.

The procedure for forecasting manufacturing technology consists of four steps:

1. Specify specific production unit.
2. Define technology limit of parameters.
3. Introduce chronology.
4. Evaluate numerically to obtain cost vs time relationship.

5.2 Defining Technology Limit

After specifying a baseline ("present") production unit (Section 2.0) technology limits are defined through intermediate points ("near-future," "future," "limit"), as seen in Table III.

TABLE III. Silicon Ribbon Technology Projection

Item No.	Parameter	Present	Near-Future	Future	Limit
2	Ribbon width (cm)	2.5	5	10	25
3	Ribbon growth rate (% of $V_{\max}$)	30	40	50	60
4	Ribbon thickness (mm)	0.30	0.20	0.15	0.10
5	Yield of "cell grade" ribbon (%)	70	80	90	95
6	Ribbon furnace cost (\$ x 10^3)	50	25	20	15
7	Equipment life (years)	7	8	10	12
9	Equipment availability (%)	70	80	90	95
14	Number of technicians	0.50	0.25	0.15	0.10
16	Polysilicon cost (\$/kg)	65	45	30	6
17	Poly yield to ribbon (%)	80	85	90	95
18	Services and supplies (\$/day)	30	25	20	10
20	Energy to operate equipment (kWE)	12	11	10	3
26	Cell conversion efficiency (%)	8	10	12	15

Using these three points in time as input to our production-unit model results in Table IV, where simulation numbers 43, 44, and 45 represent the "near-future," "future," and "limit" projections. Accordingly, we conclude at this point that silicon sheet growth, as a technology, has the capability of providing the material at the required cost to meet a \$500/kWE array-cost objective. This will occur at a somewhat later point in time than represented by simulation number 44 (\$314/kWE), but well before the technology limit is reached (simulation number 45, \$42/kWE). This projection is plotted in Fig. 12.

TABLE IV. Near-Future, Future, and Limit Projection
of Silicon Ribbon Technology

SIMULATION DI AND NO.: 11/04/75	43	44	45
RIBBONS GROWN SIMULTANEOUSLY	1.00	1.00	1.00
RIBBON WIDTH, CM	5.00	10.00	25.00
AUG YIELDED GROWTH RTE, SQ M/HR	0.08	0.29	1.19
COMBINED YIELD FACTOR	0.68	0.81	0.90
DIRECT COST IN DOLS/SQ METER			
EQUIPMENT CAPITAL RECOVERY	7.01	1.33	0.22
PERSONNEL	36.13	8.17	1.79
POLY SILICON COST	30.84	12.94	1.55
SERVICES/SUPPLIES	14.88	3.60	0.61
SUBTOTAL:	88.86	26.04	4.16
OVERHEAD COST IN DOLS/SQ METER	20.16	5.13	1.03
G&A EXPENSES IN DOLS/SQ METER	10.90	3.12	0.52
PROFIT IN DOLLARS/SQ METER	11.99	3.43	0.57
TOTAL COST IN DOLS/SQ METER	131.92	37.72	6.29
DOLLARS PER KW	1319.22	314.36	41.92

Fig. 12. Silicon ribbon technology projection.

5.3 Introducing Chronology

The concept of chronology is introduced by estimating the probability of meeting the objective associated with the technology parameter at a stated point in time. From this probability density function, the cumulative probability distribution function is derived. The latter function is evaluated numerically, thus providing a set of input parameters to the production-unit model. Calculation, followed by subsequent iteration of this procedure, and final statistical analysis of the accumulated output from the model form the basis for the projected energy-capacity cost versus time relationship.

Ribbon-width capability is used to illustrate this technique. As can be seen from Table V, we project for 1980, with a probability of only 0.05, that ribbons between 2.5 cm wide, our current baseline, and 5 cm wide will be routinely pulled. In other words, we are convinced that this capability will be achieved. We estimate the same probability to be 0.65 that ribbon width will be between 10 and 25 cm. The probabilities are mutually exclusive and add up to 1. For 1985, the probabilities are 0.02, 0.28, and 0.70, respectively. A graphical representation of the foregoing is shown in Fig. 13 for 1980 and Fig. 14 for 1985.

TABLE V. Ribbon-Width Capability

	<u>Present</u>		<u>Near-Future</u>		<u>Future</u>		<u>Limit</u>	
<u>Width (cm)</u>	2.5	↑	5	↑	10	↑	25	
<u>Probability</u>								
1980:		.05		.65		.30		= 1.0
1985:		.02		.28		.70		= 1.0

Fig. 13. Ribbon-width capability vs 1980 probability.

Fig. 14. Ribbon-width capability vs 1985 probability.

The probability is continuous and even for each point between the three intervals, as is seen from the 1980 cumulative distribution function shown in Fig. 15, where we transform a uniformly distributed sequence of random numbers (y-axis) into one that is non-uniformly distributed and that is based upon our estimated probability distribution (x-axis). This cumulative probability distribution function for the two years is then evaluated numerically, as seen in Figs. 16 and 17.

Fig. 15. Ribbon-width capability vs 1980 cumulative probability.

Fig. 16. Ribbon-width capability vs 1980 cumulative probability: example of numerical evaluation technique.

Fig. 17. Ribbon-width capability vs 1985 cumulative probability: example of numerical evaluation technique.

5.4 Coupling Technology Capability and Time

As stated before, each technology parameter, in order to introduce chronology, is coupled to a point in time by means of an estimated probability that the projection will, in fact, materialize. Subsequently, the cumulative probability distribution function is evaluated numerically by computer, using a (pseudo) random-number generator. The computer program operates on a predefined 27-row by 8-column matrix. Although similar matrices could be developed for each year, only two were defined (1980, 1985), shown as Tables VI and VII. The first column of each matrix corresponds to the production-unit parameter item number. The next column represents the baseline, the following three are the projections, and the remaining three the estimated probabilities. Only the latter are changed to simulate the progression of time. For instance, the second row refers to ribbon width, with values previously shown in Tables I and III.

TABLE VI. 1980 Technology Projection and Estimated Probability Matrix

Item No.	Near-				Probability		
	Present	Future	Future	Limit			
1	.00	1.00	1.00	1.00	1.00	1.00	1.00
2	2.50	5.00	10.00	25.00	.05	.65	.30
3	30.00	40.00	50.00	60.00	.20	.60	.20
4	.30	.20	.15	.10	.25	.60	.15
5	70.00	80.00	90.00	95.00	.40	.50	.10
6	50000.00	25000.00	20000.00	15000.00	.60	.30	.10
7	7.00	8.00	10.00	12.00	.10	.60	.30
8	.00	10.00	10.00	10.00	1.00	1.00	1.00
9	70.00	80.00	90.00	95.00	.40	.50	.10
10	.00	.05	.05	.05	1.00	1.00	1.00
11	.00	25000.00	25000.00	25000.00	1.00	1.00	1.00
12	.00	.10	.10	.10	1.00	1.00	1.00
13	.00	20000.00	20000.00	20000.00	1.00	1.00	1.00
14	.50	.25	.15	.10	.30	.60	.10
15	.00	10000.00	10000.00	10000.00	1.00	1.00	1.00
16	65.00	45.00	30.00	6.00	.60	.30	.10
17	80.00	85.00	90.00	95.00	.35	.60	.05
18	30.00	25.00	20.00	10.00	.15	.50	.35
19	.00	.05	.05	.05	1.00	1.00	1.00
20	12.00	11.00	10.00	9.00	.20	.60	.20
21	.00	50.00	50.00	50.00	1.00	1.00	1.00
22	.00	10.00	10.00	10.00	1.00	1.00	1.00
23	.00	10.00	10.00	10.00	1.00	1.00	1.00
24	.00	10.00	10.00	10.00	1.00	1.00	1.00
25	.00	168.00	168.00	168.00	1.00	1.00	1.00
26	8.00	10.00	12.00	15.00	.30	.40	.30
27	.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE VII. 1985 Technology Projection and Estimated Probability Matrix

Item No.	Near-				Probability		
	Present	Future	Future	Limit			
1	.00	1.00	1.00	1.00	1.00	1.00	1.00
2	2.50	5.00	10.00	25.00	.02	.28	.70
3	30.00	40.00	50.00	60.00	.10	.40	.50
4	.30	.20	.15	.10	.10	.60	.30
5	70.00	80.00	90.00	95.00	.10	.65	.25
6	50000.00	25000.00	20000.00	15000.00	.05	.70	.25
7	7.00	8.00	10.00	12.00	.10	.30	.60
8	.00	10.00	10.00	10.00	1.00	1.00	1.00
9	70.00	80.00	90.00	95.00	.10	.60	.30
10	.00	.05	.05	.05	1.00	1.00	1.00
11	.00	25000.00	25000.00	25000.00	1.00	1.00	1.00
12	.00	.10	.10	.10	1.00	1.00	1.00
13	.00	20000.00	20000.00	20000.00	1.00	1.00	1.00
14	.50	.25	.15	.10	.10	.60	.30
15	.00	10000.00	10000.00	10000.00	1.00	1.00	1.00
16	65.00	45.00	30.00	6.00	.10	.50	.40
17	80.00	85.00	90.00	95.00	.10	.60	.30
18	30.00	25.00	20.00	10.00	.10	.40	.50
19	.00	.05	.05	.05	1.00	1.00	1.00
20	12.00	11.00	10.00	9.00	.10	.30	.60
21	.00	50.00	50.00	50.00	1.00	1.00	1.00
22	.00	10.00	10.00	10.00	1.00	1.00	1.00
23	.00	10.00	10.00	10.00	1.00	1.00	1.00
24	.00	10.00	10.00	10.00	1.00	1.00	1.00
25	.00	168.00	168.00	168.00	1.00	1.00	1.00
26	8.00	10.00	12.00	15.00	.05	.35	.60
27	.00	1.00	1.00	1.00	1.00	1.00	1.00

5.5 Computer Evaluation and Analysis of Results

Using this method, the production-unit computer model was iterated 600 times for each of the two years (1980, 1985). Each time, from a different set of input variables, energy-capacity cost at the level of sheet material was computed.

A subsequent statistical analysis resulted in an energy-capacity cost projection for 1980 of \$750/kWE. For 1985, the projected value is \$350/kWE.

An important consideration is whether or not this "bottoms-up" process-related analysis supports the projections of future energy-capacity cost arrived at by other means. To analyze this further, "established silicon array costs" projected by ERDA/JPL are plotted together with the results of this study in Fig. 18.

Generally speaking, the value of single-crystal silicon material should not exceed 30% of array cost. For the remainder of this decade, our projection of energy-capacity cost at the silicon sheet material level is somewhat less than half of the array cost projected by ERDA and thus within the accuracy level of this type of projection. From 1980 through 1985, however, this band narrows to a point where, in 1985, projected energy-capacity cost at the level of sheet material (\$350/kWE) comes uncomfortably close to the ERDA-projected array cost (\$500/kWE).

Fig. 18. Plot and log plot of projected silicon sheet material and array cost vs time.

6.0 CONCLUSIONS

The following represents a summary of our conclusions and our current outlook for large-area silicon sheet growth:

1. 1980 and 1985 energy-capacity costs of \$750/kWE and \$350/kWE, respectively, at the level of silicon sheet material, are projected and

considered possible from today's vantage point.
However, there is little margin for error.

2. Ribbon silicon growth techniques, such as CAST, should concentrate on wide (100-mm) ribbon growth.

3. Processing-technology improvements are the key elements for reducing the cost of silicon sheet material.

Emphasize: Ribbon-width capability.

Higher growth rate.

4. Single-ribbon growth systems offer the best potential for achieving low-cost silicon sheet material within the shortest period of time.

Emphasize: Equipment reliability.

Unattended growth capability.

Automatic melt replenishment.

5. Low-cost (\$6-10/kg) semiconductor-grade-quality polycrystalline silicon must be developed, since it is a prerequisite to achieving the ERDA-projected future energy-capacity cost of \$500/kWE.

6. Ribbon thickness is a relatively insignificant factor in determining energy-capacity cost. Hence, a thickness of 0.3 to 0.4 mm should be selected, which is compatible with solar-cell processing.

De-emphasize: Thinner ribbon development.