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SILICON RIBBON GROWTH BY A CAPILLARY
ACTION SHAPING TECHNIQUE

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TECHNICAL CONTENT STATEMENT

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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.

ABSTRACT

Progress during the second quarter of the contractual effort is described. The work performed related mainly to ribbon growth by a capillary action shaping technique, and to ribbon characterization.

Actual progress in the crystal growth area includes the evaluation of 10 potential die materials other than carbon and the process development for 25-mm-wide ribbon. From the die study it is concluded that boron carbide, silicon carbide, and silicon nitride may warrant further investigation as die materials. Process development for 25-mm ribbon growth resulted in ribbons of superior surface quality. Potential ribbon-growth problems encountered and discussed include a boron doping anomaly and frozen-in stresses in ribbons.

The characterization effort concentrated on the development of a solar-cell process to be used for ribbon characterization. Material requirements and detailed process procedures are given. Solar cells fabricated by this process are compared with commercially available solar cells and compare favorably.

A transmission electron microscopy study of planar boundaries frequently observed in ribbon crystals is reported. Such

planar boundaries are analyzed as twin boundaries and extrinsic and intrinsic stacking faults. It is shown that twin planes are typical for twinning perpendicular to the $(01\bar{1})$ surface and parallel to the growth axis. Stacking faults are found mixed with twin boundaries for twinning on $(11\bar{1})$ planes, inclined to the ribbon surface and are non-parallel to the growth axis.

Finally, a short review of the economic-evaluation activities is presented.

CHAPTER I

CRYSTAL GROWTH

by

T. F. Ciszek

1. 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 which has been used in our initial studies is shown in Fig. 1 and is similar to the EFG process described by LaBelle (1). The crystal-growth method has been applied to silicon ribbons for several years (2,3,4), and long ribbons up to 25 mm in width have been produced.

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

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

has been achieved on small ribbon segments (2,3), but the structure of large ribbons is marred by planar, line, and point defects, as well as surface irregularities. Our objective in this work is to attain a clearer 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.

The second-quarter progress in crystal growth will be presented in the following two sections: 2. Die Evaluation Studies and 3. Process Development for 25-mm-Wide Ribbon Growth.

Growth of relatively long ribbons was attained with three non-graphite die materials: vitreous carbon, silicon carbide, and boron carbide. For 25-mm ribbon growth from graphite dies, improvements have been made in the surface roughness and density of SiC surface particles and also in the surface cleanliness (freedom from post-solidification vapor deposits).

2. DIE EVALUATION STUDIES

2.1 Materials Investigated

The potential die materials listed in Quarterly Technical Progress Report Number 1 were tested under actual ribbon growth conditions. Hot-pressed "high purity" AlB_{12} , TiB_2 , ZrB_2 , Al_4C_3 , B_4C , and Si_3N_4 were obtained from Atomergic Chemetals Co., a division of Gallard-Schleisinger Chemical Mfg. Corp. The materials were obtained in the form of rectangular blocks 3x10x30 mm in size. A chemical analysis and density determination have not yet been completed. According to the manufacturer, the starting powder particle size is typically 2-5 μm . Vitreous carbon was also obtained from Atomergic Chemetals Co., in the form of 2-mm-thick plates, with properties as shown in Table I. Two sources of silicon carbide were used: one was Crystar silicon carbide from Norton Industrial Ceramics Division; the other was KT silicon carbide from the Carborundum Company. A silicon nitride-bonded silicon carbide was also obtained from Carborundum. The manufacturers' data for these three materials are given in Table II. The Crystar material is nominally 99% pure recrystallized silicon carbide, with Ti, Cr, Co, V, and Al as typical metallic impurities. Purity levels of the Carborundum materials are not known at this time. Pyrolytic boron nitride was also investigated.

TABLE I. Manufacturers' Data for Vitreous Carbon

CHEMICAL CHARACTERISTICS	V25
Maximum operating temperature	>2,500°C
Apparent density	1.50 to 1.55
Apparent porosity (no absorption of oil and mercury)	0
Permeability to gas; at normal temperature at 2,500°C	better than $10^{-8} \text{ cm}^2/\text{s}$ approx. $10^{-6} \text{ cm}^2/\text{s}$
Ash content	0.005% (50 ppm)
Sulphur content	<50 ppm
Boron content	<2 ppm
Oxidation resistance at 600°C	0.1 mg/cm ² /h
at 800°C	2 mg/cm ² /h
MECHANICAL PROPERTIES	
Transverse breaking strength	600 to 800 kg/cm ²
Compressive strength	1,500-2,000 kg/cm ²
Shore hardness	120-125
Hardness Mohs' scale	6-7
Vickers micro-hardness (30 kgm)	150-175
Young's modulus	2,200 kg/mm ²
THERMAL PROPERTIES	
Coefficient of thermal expansion: at 100°C	3.2×10^{-6} by °C
at 650°C	3.5×10^{-6} by °C
Thermal conductivity	
Resistance to thermal shock	0.06 cal/cm/s/°C
Air quenching acceptable from... to room temperature	2,500°C
ELECTRICAL PROPERTIES	
Electrical Resistivity	4,500 microhms/cm

TABLE II. Manufacturers' Data for Various Silicon Carbides

<u>Property</u>	<u>KT Silicon Carbide</u>	<u>REFRAX Silicon Nitride-Bonded Silicon Carbide</u>	<u>CRYSTAR Silicon Carbide</u>
Apparent specific gravity	3.10	2.65	2.6
Working temperature			
Inert atmosphere	4200°F max.	3200°F max.	---
Oxidizing atmosphere	3000°F max.	---	3200°F max.
Modulus of rupture, psi	22,800 (2200°F)	5000-7000 (2500°F)	18,000-22,000 (2730°F)
Modulus of elasticity, psi	56 x 10 ⁶ (70°F) 51 x 10 ⁶ (2200°F)	17 x 10 ⁶ (70°F)	30 x 10 ⁶
Compressive strength, psi	150,000 (70°F)	20,000 (70°F)	100,000
Tensile strength, psi	20,650 (70°F)	3000-3500 (70°F)	---
Thermal conductivity			
Btu in/hr ft ² F°	720 (1140°F mean temp) 465 (1574°F mean temp) 250 (2086°F mean temp) 174 (2292°F mean temp) 94 (2782°F mean temp)	113.5 (2200°F)	180 (1000°F) 165 (1500°F) 145 (2300°F) 135 (2900°F)
Thermal coefficient of expansion			
in/in/°F x 10 ⁻⁶	1.88 (70°-800°F) 2.60 (70°-1800°F) 2.80 (70°-2500°F)	1.8 (70°-400°F) 2.6 (70°-2500°F)	2.7 (70°-2600°F)
Mean specific heat	.34 (70°-2800°F)	.29 (70°-2500°F)	.35 @ 3000°F
Spectral emissivity at 1600°F	.9	.9	---
Permeability	Impermeable	Negligible	---
Porosity	0%	15%	18%

2.2 Use-Test Evaluation of Die Materials

Dies were fabricated from all materials except aluminum carbide, which had crumbled during storage, and boron nitride. The dies were made as shown in Fig. 4, Ch 1, of Quarterly Technical Progress Report Number 1. The dies were 9.5 mm wide with a 0.76-mm top thickness and a 0.56-mm capillary slot thickness. All machining was done with 180 grit diamond wheels. No serious machining problems were encountered, except that vitreous carbon and silicon nitride-bonded silicon carbide chipped easily. Slow machining rates were necessary on silicon carbide and boron carbide to avoid chipping. After machining, the dies were baked out in vacuum at 1500-1600°C for one hour. The AlB_{12} die outgassed severely during bakeout, and the temperature could not be raised above 1400°C without causing the pressure to rise above 2×10^{-4} Torr. This die was considerably eroded and broke after bake-out. The other dies are shown in Fig. 2, prior to use. The Si_3N_4 die was a light tan color; the others were grayish to black.

Our standard growth procedure was used in attempting ribbon growth with the new materials. The crucible was loaded with about 50 grams of silicon, plus enough boron dopant to produce a 2 ohm-cm ribbon (assuming no other impurity source). Crystal growth attempts were made in an argon atmosphere. If the die did not fill with liquid silicon,

(a) TiB_2

(b) ZrB_2

(c) B_4C

(d) KT SiC

(e) Si_3N_4 -
Bonded
SiC

(f) Crystar
SiC

(g) Vitreous
Carbon

(h) Si_3N_4

Fig. 2. Dies fabricated from (a) TiB_2 , (b) ZrB_2 , (c) B_4C , (d) KT SiC, (e) Si_3N_4 -- bonded SiC, (f) Crystar SiC, (g) vitreous carbon, (h) Si_3N_4 .

the system temperature was increased considerably above normal levels to attempt melt rise. If melt rise occurred, crystal growth was attempted. After the growth attempts, the dies were visually checked for durability in molten Si. The appearance of the various die bottoms, where contact with molten Si took place, is shown in Fig. 3. In the case of boron nitride, the capillary rise check was made by placing silicon in a boron nitride crucible with a slotted wall, and melting the silicon.

The results of the evaluation are summarized in Table III. For the particular forms of the die materials used here, only boron carbide, KT silicon carbide, Crystar silicon carbide, vitreous carbon, and, of course, high-density graphite were adequately wettable and durable to allow the growth of long ribbons (>0.5 m). In addition, TiB_2 and ZrB_2 allowed short-ribbon growth, but the dies suffered acute dissolution (Fig. 3a,b). The ribbons grown from experimental die materials are pictured in Fig. 4.

Dies of Si_3N_4 bonded SiC and Si_3N_4 were durable, but showed no sign of capillary rise, although surface wetting appeared to occur at the die bottom (Fig. 3e,h). Boron nitride (pyrolytic) showed no sign of wetting or capillary rise, although it was not appreciably attacked by liquid silicon (Fig. 3j).

3a. TiB_2

3b. ZrB_2

Fig. 3. Die bottoms after contact with molten silicon for more than two hours (sheet 1 of 5).

3c. B_4C

3d. KT SiC

Fig. 3. Die bottoms after contact with molten silicon for more than two hours (sheet 2 of 5).

3e. Si_3N_4 - bonded SiC

3f. Crystar SiC

Fig. 3. Die bottoms after contact with molten silicon for more than two hours (sheet 3 of 5).

3g. Vitreous Carbon

3h. Si_3N_4

Fig. 3. Die bottoms after contact with molten silicon for more than two hours (sheet 4 of 5).

3i. Graphite

3j. BN

Fig. 3. Die bottoms after contact with molten silicon for more than two hours (sheet 5 of 5).

TABLE III. Die Material Evaluation

<u>Material</u>	<u>Capillary Rise</u>	<u>Durable in Molten Si</u>	<u>Ribbon Growth</u>
Aluminum boride ¹	---	---	---
Titanium boride	Yes	No (dissolves)	Short ribbons
Zirconium boride	Yes	No (dissolves)	Short ribbons
Aluminum carbide ²	---	---	---
Boron carbide	Yes	Yes	Long ribbons
Silicon carbide	Yes	Yes	Long ribbons
SiN bonded SiC	No ³	Somewhat	None
Vitreous carbon	Yes	Yes	Long ribbons
Graphite (dense)	Yes	Yes	Long ribbons
Boron nitride	No	Yes	None
Silicon nitride	No ³	Yes	None

1. Vapor pressure too high at 1412°C

2. Decomposed and crumbled during storage

3. Evidence of surface wetting, but no rise in capillary slot.

Fig. 4. Silicon ribbons grown from experimental die materials: (a) KT SiC, (b) Crystar SiC, (c) vitreous carbon, (d) B_4C , (e) TiB_2 , (f) ZrB_2 .

In Fig. 5, 10X photomicrographs of ribbon surfaces 15 cm from the seed attachment point are shown for the die materials which yielded long ribbons. The strong surface morphology features with the B_4C die are probably a result of excessive boron pickup. Wetting and capillary rise were excellent with this die (Fig. 3c). The ribbon resistivity was approximately 0.004 ohm-cm. The surface was very clean, however. A thick surface film was present on the ribbon grown from the vitreous carbon die. In later stages of growth, numerous surface particles were trapped in the ribbon as occurred with early graphite dies. The melt and

Fig. 5. 10x photomicrographs of ribbon surfaces 15 cm from seed attachment:
 (a) B_4C die, ribbon 50811; (b) vitreous carbon die, ribbon 50825;
 (c) Crystar SiC die, ribbon 50805; (d) KT SiC die, ribbon 50809.

wetted region near the die bottom were very clean with vitreous carbon (Fig. 3g) and similar to the appearance of graphite die bottoms (Fig. 3i). The ribbons grown from silicon carbide were quite free of surface particles in the early stages of growth, as indicated in Figs. 5c and 5d, and some large single-crystal regions were seen. Later in growth, these ribbons also incorporated surface particles, but at a low density. For comparison, an old ribbon grown from a graphite die of similar design is shown in Fig. 6.

Fig. 6. 10x photomicrograph of a ribbon surface 15 cm from seed attachment: graphite die, ribbon 50407. Several surface troughs caused by SiC particles are visible.

Further work is planned in purity analysis and structural characterization. At this stage, silicon carbide appears to have considerable potential as a die material. Vitreous carbon shows no obvious improvement over graphite. However, it, as well as boron carbide and silicon nitride, may warrant further investigation. Graphite, of course, has been used extensively to date, and its use will continue.

3. PROCESS DEVELOPMENT FOR 25-MM-WIDE RIBBON GROWTH

3.1 Surface Roughness

In Quarterly Technical Progress Report Number 1, initial efforts on 25-mm-wide ribbon growth were reported. The first ribbons were grown from graphite dies of the type shown in Fig. 4, Ch 1, of Quarterly Report Number 1. The die width was 25 mm, the capillary slot was 0.26 mm thick, and the die top was 0.51 mm thick. The die holder and shields were scaled up accordingly. The lower shield had a 2.4 mm x 28 mm slot, and the upper shield a 4.8 x 30 mm slot. The shields were 1.6 mm thick, and the lower shield had a recess 0.8 mm deep x 8 mm wide x 33 mm long, milled in the bottom side. Surface characteristics of these ribbons were similar to those of 12.5-mm-wide ribbons. The SiC particle density was approximately $5/\text{cm}^2$; the surfaces were generally rough, as in Fig. 7a, and coated with a thin silicon oxide powder

Fig. 7. 21x micrographs of as-grown ribbon surface:
(a) old die design and (b) new die design.

film of yellowish brown color. Our experiments with 25-mm-wide ribbons during the second quarter have primarily been aimed at improving the ribbon surface characteristics. In addition, we have identified two areas which will require further attention. These are transverse dopant anomalies and frozen-in thermal stress.

An experimental die design has been developed which produces a much smoother surface than that possible with the older die. The SiC particle density with the new die is typically less than $0.1/\text{cm}^2$. The entire full-width surfaces of three consecutively grown ribbons were examined for SiC particles. The ribbon lengths were 58, 55, and 27 cm, and the corresponding particle densities were 0.04, 0.10, and 0.03 particles/ cm^2 . Substantial lengths of the ribbons (>10 cm) were particle-free. Particles which do form tend to be located within a few mm of the ribbon edge. In Fig. 7, 21x photomicrographs of the as-grown ribbon surface compare the surface morphology produced with the old and new dies. While the new dies produce a smoother surface, it is observed that twin planes and grain boundaries are still present, as are surface films. During the quarter, 12.6 meters of full-width ribbon were grown with the new die. The ribbon appearance during growth is shown in the photograph of Fig. 8.

Fig. 8. Growth of a 25-mm-wide ribbon.

The longest ribbons grown were $>0.9\text{m}$ long at full width (25 mm). The average maximum thickness of 23 ribbons was 0.62 mm, and the average minimum thickness was 0.38 mm, with the minimum always occurring in the central area and the maximum occurring at the edges. Some preliminary studies were made of the effect of growth rate on ribbon thickness.

In general, faster growth rates produce thinner ribbons; however, the data scatter is large, indicating that some uncontrolled variable is also affecting ribbon thickness. We have grown ribbons at rates of 12 to 31 mm/min, and the central ribbon thickness has ranged from 0.56 to 0.26 mm.

3.2 Surface Films

In an attempt to understand seed-melt interface foreign film problems and ribbon surface film formation, a closed (gas-tight) system modification has been made to the ribbon puller, and the inert argon purge system has been altered to direct the purge gas at the ribbon-melt interface. This has resulted in a cleaner appearance of the melt at the die top and also a cleaner-looking ribbon surface. The seed-melt attachment interface has improved crystallographically, to some extent, also. However, there is still evidence of SiC film formation near the seed interface, and crystal structure still degenerates with increasing ribbon length.

In our previous growth system (Fig. 2, Ch 1, of Quarterly Progress Report Number 1), the argon inlet was at the bottom of the furnace and the purge gas flowed upward past the melt region, exiting through an oval tube at the furnace top. The ribbon was also pulled through this tube, which served as

the transition chamber between the furnace interior and the external air atmosphere.

The modified purge system is shown in Fig. 9. As can be seen, the flow direction is reversed and the ribbon remains in the furnace interior throughout growth. In use, the gate valve is closed and the region below it is evacuated prior to filling with argon through the inlet below the gate valve. When the lower chamber is filled, an argon outlet to a bubbler at the bottom of the chamber is opened. Simultaneously, the plastic bellows section above the gate valve is argon-purged. The seed shaft is initially located in this section. When both sections have been purged an adequate length of time, and the die is at the growth temperature, the argon outlet above the gate is closed and the gate valve is opened. Argon then flows from the inlet at the bellows top and the inlet at the gate valve downward through a water-cooled stainless-steel purge tube which is 55 mm in I.D. and surrounds the ribbon. From the bottom of this purge tube, a 75-mm-long graphite draw tube can be supported. The oval bore of the draw tube causes the purge gas to impinge on the solidification region at the die top. The gas then flows out the bottom of the furnace and through the bubbler. After growth, the ribbon is pulled up into the bellows and the gate valve is closed. The bellows is then

Fig. 9. Modified argon purge system.

opened to remove the ribbon and reseed for subsequent growth attempts. In the present system the routine maximum usable ribbon length at full width is about 0.6 m as compared with about 1.2 m with the old open port system. By reseeded, however, several ribbons can be pulled from one crucible charge.

Experiments with the modified purge system centered upon (1) using various argon purge rates with and without the graphite draw tube present, (2) reversing the flow and disconnecting the bellows (i.e., an open pull-port system), (3) using various pulling speeds with and without the graphite draw tube present, and (4) initial experiments with afterheaters. The die design was held constant, as were the other furnace components. It was found that with the graphite draw tube present, ribbon-growth control was best at low purge rates ($160\text{--}240\text{ cm}^3/\text{sec}$). Higher rates tended to promote asymmetrical spreading of ribbon growth from seed size to full width. However, little qualitative difference is seen in ribbon surface cleanliness and frozen-in stress whether the graphite draw tube is present or absent. Viewing and growth control are best when the graphite tube is not used. Purge rates up to $630\text{ cm}^3/\text{sec}$ could then be applied.

The closed bellows system and argon purge from the top (with or without the graphite draw tube) produce a cleaner ribbon surface than that obtained with an open port system. The

resultant ribbons (Fig. 10) have the shiny metallic gray color of polished silicon wafers. Under certain lighting conditions, the ribbons appear to be covered by a multicolored film. However, this has been demonstrated to be a diffraction grating effect caused by transverse growth striations, and not a film phenomenon. In fact, a spectrum can be projected onto a white surface by using a ribbon as a grating. The striation line density was measured for 9 ribbons, which were grown at rates from 15 to 31 mm/min (see Table IV). Line densities ranged from 620 to 970 lines/cm. The product of the line density and the growth rate yields the striation frequency, which is also given in Table IV. Line density and frequency do not change appreciably with distance along the ribbon, as can be seen from the data for ribbon 51012. With the exception of the anomalously low frequency values for 15 mm/min growth rates, the average striation frequency on the remaining eight ribbons was 29.9 lines/sec with a standard deviation of 2.6 lines/sec. This suggests that 60-cycle ac modulation of the rf generator output power may be responsible for the observed transverse solid-liquid interface striations. A 93x photograph of the striations on ribbon number 51019 is displayed in Fig. 11.

The melt at the die top also appears to remain cleaner with the modified purge system, and the seed-ribbon interface attachment has improved to some extent. However, there is

evidence from TEM examinations that a thin SiC film is grown on the seed tip by chemical vapor deposition during the relatively long time (approximately 5 min) that the seed remains stationary at the die top. A similar film is seen on the ribbon, if growth is halted for several minutes with the ribbon remaining at the die top. During growth at typical speeds, the film is not noticeable but is probably still diminutively present.

Fig. 10. Several 25-mm-wide ribbons grown with the closed bellows system and argon purge from the top.

TABLE IV. Growth Rates, Solid-Liquid Interface Striation Line Densities and Line Frequencies for Ten Ribbons

<u>Ribbon Number</u>	<u>Distance from Seed (cm)</u>	<u>Growth Rate (cm/min)</u>	<u>Line Density (lines/cm)</u>	<u>Frequency (lines/sec)</u>
51007	65	1.5	756	18.9
51012	12	1.9	960	30.4
51012	100	1.9	970	30.7
51014	65	1.7	956	27.1
51017	32	3.1	660	34.1
51019	64	2.9	636	30.7
51022	66	2.0	940	31.3
51023	69	2.2	800	29.3
51027	66	2.5	620	25.8
51107	57	1.5	780	19.5

Fig. 11. Transverse interface striations on silicon ribbon 51019; magnification 93x.

3.3 Doping Effects

Essentially all ribbons grown during the quarter were doped to a nominal 2 ohm-cm resistivity with a boron-silicon alloy powder. This was done to facilitate ribbon characterization via solar-cell performance.

An anomalous doping effect has been observed in the ribbons. The transverse resistivity profile indicates high regions of dopant incorporation at the middle and at the extreme edges of the ribbon (Fig. 12). The cause is not definitively known at the present time.

Fig. 12. Transverse spreading resistance profile of ribbon 50919.

4. SUMMARY OF CRYSTAL-GROWTH ACTIVITIES

Crystal - growth efforts were placed largely in two areas: die material evaluation and process development for 25-mm-wide ribbon growth from graphite dies. Long-ribbon growth was achieved with three non-graphite die materials. These are boron carbide, vitreous carbon, and silicon carbide. Of these, silicon carbide appears to show the most potential as a replacement for graphite.

Improvements in capillary die design and in the method of inert gas-purging the growth furnace have allowed the growth of much smoother ribbons with lower average SiC surface particle densities ($<0.1/\text{cm}^2$ as opposed to approximately $5/\text{cm}^2$) and improved freedom from surface films. Transverse striations parallel to successive solid-liquid interface positions tend to occur at a frequency of 30/sec, and cause a diffraction grating effect on the ribbon surface. These do not appear to be detrimental to ribbon growth.

Several areas requiring further investigation have come to light. Central and edge dips in the transverse resistivity profiles have been observed. Ribbons which occasionally split during scribing or handling indicate the presence of thermal stress during the growth process. Split widths on the order of 2 mm at a distance of 30 cm from the crack

origin have been observed. Careful handling and sawing, however, allow the ribbons to be used in normal solar cell device processing without breakage.

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CHAPTER II

SOLAR-CELL PROCESS FOR RIBBON EVALUATION

by

C. P. Schneider, A. Kran, T. F. Ciszek, and E. W. Hearn

1. INTRODUCTION

One of the major characterization tasks under this contract is the evaluation of solar cells made from ribbons produced by the capillary action shaping technique. Such definition of ribbon quality is based on a solar-cell standard produced from perfect Czochralski-grown silicon.

This chapter describes the solar-cell process developed for the fabrication of such a standard. It also presents characteristics of solar cells obtained from Czochralski silicon wafers processed accordingly. Finally, it compares such solar cells with solar cells commercially available and thought to be representative of the state of the manufacturing art of the industry.

2. SOLAR-CELL PROCESS DEFINITION

2.1 General

This section outlines the material requirements and process procedure developed for small-scale fabrication of solar cells in a laboratory type environment.

2.2 Silicon Material

The starting wafers are boron-doped, p-type, Czochralski-grown, dislocation-free silicon, ~ 0.35 mm thick, 5.72 cm in diameter, and with a resistivity between 1 and 2 $\Omega\text{-cm}$. The wafers are chemically and mechanically polished on both sides.

2.3 Diffusion Procedure

2.3.1 Silicon wafers are cleaned using a 4-step procedure (trichloroethylene, acetone, DI water, and methanol). They are subsequently etched in a 10:1 DI water:HF solution for 45 sec, then DI water-rinsed and spin-dried, prior to being loaded into a quartz boat for blanket diffusion on both sides.

2.3.2 About 40 wafers are placed in the center section of a quartz boat. They are flanked by dummy wafers, spaced in a predetermined sequence to optimize gas flow.

2.3.3 The diffusion process temperature is 925°C.

2.3.4 The empty diffusion furnace quartz tube is pre-doped for 30 min with N_2 carrier gas, which is bubbled through liquid $POCl_3$ kept at $20 \pm 0.5^\circ C$. In addition, O_2 and pure N_2 are purged through the furnace. Then the N_2 carrier gas is shut off for 5 min, while O_2 and pure N_2 flows continue.

2.3.5 Best results are achieved with flow rates as follows:

<u>Wafers</u>	<u>Ribbons</u>
Pure N_2 = 2100 cc/min	2100 cc/min
O_2 = 750 cc/min	500 cc/min
N_2 through $POCl_3$ = 100 cc/min	100 cc/min

2.3.6 The diffusion boat is loaded into the furnace hot-zone and pre-heated for 20 min.

2.3.7 The $POCl_3$ carrier gas is turned on for 15 min.

2.3.8 The $POCl_3$ carrier gas is turned off for 2 min.

2.3.9 The diffusion boat is removed from the furnace and permitted to cool for 10 min.

2.4 Masking Procedure

2.4.1 Acid-resistant electroplaters' adhesive tape is applied to one side of the diffused wafer.

2.4.2 The phosphorous glass accumulated during diffusion is removed from the unmasked (back) wafer surface by a 45-sec P-etch (150-cc HF, 100-cc nitric acid, 3000-cc DI water).

2.4.3 The diffused layer is removed from the unmasked back surface by etching with a solution of 6 parts HF in 80 parts HNO_3 .

2.4.4 The tape is removed, and step 2.4.2 is performed for the front wafer surface.

2.4.5 The wafers are cleaned using the procedure described in 2.3.1.

2.5 Metallization Procedure

2.5.1 Metallization is achieved through vacuum evaporation of Al and Ag by use of a conventional, laboratory type evaporation system. This system consists of a bell jar, an oil diffusion pump with a liquid N_2 cold trap, and a resistance-heated evaporation source.

2.5.2 Up to four Czochralski wafers are mounted on a flippable evaporation plate for metallization.

2.5.3 The solar-cell grid pattern is defined by a 10-mil-thick molybdenum contact mask.

2.5.4 Metals (Al, Ag) are evaporated sequentially and on both sides of the wafer during one pump-down cycle of the system.

2.5.5 The metal deposition rate is monitored through adjustment of evaporation current (Al - 60 A, Ag - 100 A, both at 40V), and evaporation time (Al - 2 min, Ag - 10 min each side).

2.5.6 A tungsten wire basket is used for aluminum evaporation, and an Al_2O_3 boat supported by a tungsten basket is used for silver evaporation.

2.5.7 The metallization is annealed at 400°C in a forming gas atmosphere as follows:

<u>Time (min)</u>	<u>Junction Depth (X_j)</u>
2	$\leq 0.5 \mu\text{m}$
5	$> 0.5 \mu\text{m}$

2.6 Anti-Reflection Coating (Optional)

A commercially available (Emulsitone Comp.) titanium silica anti-reflection coating is deposited by spinning on the liquid solution and drying at room temperature. Both type A (55% TiO_2 , refractive index = 1.80) and type C (84% TiO_2 , refractive index = 1.96) have been used, with no appreciable difference between the two.

3. SOLAR-CELL EVALUATION

3.1 General

Solar-cell performance evaluation techniques are still under development. Our approach consists of simultaneously measuring the level of solar irradiation, the I/V characteristics, and the temperature of the device under test. These data, plus cell dimensions and process-related information, are used as input to an analysis program developed for pertinent data reduction. This program computes performance characteristics, such as conversion efficiency and maximum power point. Program output consists of a data sheet containing cell performance parameters and graphic reproduction of the I/V trace, complete with the calculated maximum power point. Also included in this exhibit (Fig. 1) is the actual I/V trace. The graphical image can be further manipulated in the system (i.e., enlarged) for additional analysis, as shown in Fig. 2.

Since the I/V trace of Fig. 1 has to be digitized for analysis, it is important to know how many data points are required to obtain adequate and accurate representation of the I/V trace for input into the data analysis programs. Described in 3.2-3.4 is an analysis that was done to determine the minimum number of data points necessary for an accurate I/V curve-fitting.

IBM SOLAR CELL(S)
CELL NO: S488.

EFFICIENCY, PCT: 8.66
VOC (VOLTS): 0.56
ISC (MA/SQ CM): 17.70

PMAX (MW/SQ CM): 6.84
AT (VOLTS): 0.43
AND (MA/SQ CM): 15.76

CURVE FACTOR: 0.69

INTSY(MW/SQ CM): 79.00
LIGHT SOURCE: SUN

1 SIZE ·DIA·W·L: 5.72
RESTUTY(OHM-CM):
SHT RES(OHMS/D):
THICKNESS (MM):

DATA POINTS:
MA U

460.00	0.00
450.00	0.30
420.00	0.40
300.00	0.50
0.00	0.56

SOLAR_CELL_DATA

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Fig. 1. Solar cell data sheet, including I/V trace and computer-generated graphical representation.

Fig. 2. Graphical image of I/V trace with maximum power rectangle.

3.2 I/V Data Points for Curve-Fitting

Solar-cell I/V output characteristics are conveniently exhibited on a Tektronix Model 576 Curve Tracer and are documented by a Polaroid print as shown in Figs. 1 and 3. Subsequently, data such as conversion efficiency and maximum power point are calculated by fitting I/V data points to an equation for solar-cell current, with techniques based on nonlinear-least-squares curve-fitting without derivatives.

Fig. 3. I/V trace of solar cell with curved knee.

Since the curves, as shown in Figs. 1 and 3, are not digitized, data points are taken manually from such relatively small prints shown. Thus, a certain degree of error is introduced.

The rest of this section describes an investigation concerned with the number of data points required to obtain adequate and accurate representation of the original I/V trace. It also discusses the additional errors introduced by minimizing the number of data points for the curve-fitting algorithm.

3.3 Minimizing Number of Data Points

The I/V trace of Fig. 1 shows the output of a Czochralski cell with I_{sc} of 460 ma and V_{oc} of 0.56V. This curve shows a reasonably well-defined "knee." The second curve (Fig. 3) comes from a solar cell, with I_{sc} of 210 ma and V_{oc} of 0.5V. This cell shows a considerably high series resistance and a knee which is not well-defined (curved). Though neither cell is representative of the state-of-the-art solar-cell fabrication, both cells were chosen for their merit in demonstrating the following analysis (3.3.1).

3.3.1 Solar Cell with Well-Defined "Knee"

Ten data points, listed in Table I were taken manually from the I/V trace of Fig. 1. They are considered to represent a maximum in terms of data points required to obtain the most accurate fit to the equation

$$I = I_0 (e^{qV/AKT} - 1) - I_{sc}$$

using a nonlinear-least-squares curve-fitting based on a derivative-free analog of the Levenberg-Marquardt algorithm. Figure 4 shows a graphical representation of these calculations. The circles (o) represent the ten manually provided data points, and the (x) the 50 calculated data points. The maximum power rectangle is also plotted.

TABLE I. Voltage and Current Data
Points Taken from I/V Trace
of Fig. 1

<u>Voltage</u>	<u>Current (ma)</u>
0.0	460
0.2	455
0.3	450
0.35	430
0.4	420
0.44	400
0.48	350
0.5	300
0.54	150
0.56	0

Fig. 4. Ten I/V data points (o) and curve (x) fitted to them.

The objective now is to reduce the number of points systematically from 10 per curve to a minimum, which must still adequately reproduce those portions of the curve that are most important to performance evaluation. Obviously, they include I_{sc} , V_{oc} , and the knee. Accordingly, the number of points is now reduced to I_{sc} , V_{oc} , and three points representing the knee. Figure 5 shows the results and, in conjunction with Fig. 6 (two points defining "knee"), establishes that, for our purposes, an insignificant amount of error is introduced by decreasing the number of data points from ten to four.

As the last exercise, the number of data points was reduced to three (Fig. 7). This changed the results by about 3% and, hence, is considered unacceptable. A graphical representation is given in Fig. 8, where Figures 4 and 7 are superimposed. Table II summarizes the data.

3.3.2 Solar Cell with Curved Knee

The analysis proceeded from seven to three data points (Figs. 9 and 10) without appreciable change in results.

3.4 Conclusions

The foregoing is typical of I/V traces analyzed in this manner. It is shown that accurate solar-cell I/V curve analysis by

SOLAR CELL CHARACTERISTICS

Fig. 5. Curve fitted to five data points.

Fig. 6. Curve fitted to four data points.

Fig. 7. Curve fitted to three data points.

SOLAR CELL CHARACTERISTICS

Fig. 8. Difference between 10 and 3 data points (Figs. 4 and 7 superimposed).

TABLE II. Effect of Reducing the Number of Data Points upon Accuracy of Solar-Cell Parameters

No. of Data Points	Efficiency (%)	$P_{\max}$ (mw/cm ²)	CF
10	8.69	6.87	0.70
5	8.66	6.84	0.69
4	8.73	6.90	0.69
3	8.40	6.64	0.66

Fig. 9. Curve fitting with seven data points (curved knee).

SOLAR CELL ELECTRICAL CHARACTERISTICS

Fig. 10. Curve fitting with three data points (curved knee).

standard curve-fitting techniques requires only three or four data points, depending upon the existence or non-existence of a defined knee in the I/V trace. The data points are chosen at the following positions:

<u>"Knee" Defined</u>		<u>"Knee" Not Defined</u>	
<u>Current</u>	<u>Voltage</u>	<u>Current</u>	<u>Voltage</u>
I_{sc}	0	I_{sc}	0
I	0.3V	I	0.3
I	0.45V	0	V_{oc}
0	V_{oc}		

Using the above approach, rather than ~ 10 data points, results in a difference of less than 1% to calculated parameters, such as P_{max} and curve factor.

4. SOLAR-CELL PERFORMANCE ANALYSIS

Using the solar-cell fabrication process described in section 2, solar cells are being fabricated from Czochralski wafers. Their performance is being compared here with several commercially available solar cells and two standard (NASA LeRL) test cells. For this preliminary analysis, six cells were chosen: four 5.7-cm-diameter cells and two 2x1-cm test cells. The outside solar-irradiation measurements were taken in a courtyard, at 11:30 a.m., on December 4, 1975, under bright, sunny conditions, but occasional clouds. Temperature was $\sim 0^{\circ}\text{C}$, and the solar intensity was measured at the beginning and end of the testing period.

Instrumentation for measuring solar irradiation consisted of

an Eppley thermopile and an International Light, Inc., IL700 radiometer, with a SEE-100F detector and neutral-density filter.

The results of the measurements were as follows:

	<u>Start</u>	<u>End</u>	<u>Avg</u>
Eppley (mw/cm^2)	74	68	71 (used)
International Light, Inc. (mw/cm^2)	44.5	45.3	44.9

An I/V trace of each cell was taken with a Tektronix Model 576 curve tracer. Because it more closely coincides with the performance of our standard cell, the average of the two Eppley readings was used as input energy to the solar cells for the performance analysis.

The specific results of this analysis are contained in data sheets presented as Figs. 11-16. The conversion efficiencies are compared in the histogram of Fig. 17. The data are summarized in Table III.

The results of this preliminary analysis suggest that our laboratory type solar-cell fabrication process, developed for evaluation of ribbon silicon, indicates an ability to achieve $\sim 10\%$ efficient solar cells.

VENDOR A SOLAR CELL(S)
CELL NO: .

EFFICIENCY, PCT: 13.50
VOC (VOLTS): 0.61
ISC (MA/SQ CM): 25.40
P_{MAX} (MW/SQ CM): 9.58
A_T (VOLTS): 0.45
A_{ND} (MA/SQ CM): 21.39

CURVE FACTOR: 0.62

INTSY (MW/SQ CM): 71.00
LIGHT SOURCE: SUN

1 SIZE ·DIA·W×L: 5.72
RESTUTY(OHM-CM):
SHT RES(OHMS/□):
THICKNESS (MM):

DATA POINTS:
MA U

650.00	0.00
600.00	0.40
500.00	0.48
0.00	0.61

SOLAR_CELL_DATA

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Fig. 11. Solar cell data sheet (Vendor A).

IBM SOLAR CELL(S)
 CELL NO: S530 60 157

EFFICIENCY, PCT: 12.81
 VOC (VOLTS): 0.58
 ISC (MA/SQ CM): 22.19

PMAX (MW/SQ CM): 9.09
 AT (VOLTS): 0.46
 AND (MA/SQ CM): 19.70

CURVE FACTOR: 0.71

INTSY (MW/SQ CM): 71.00
 LIGHT SOURCE: SUN

1 SIZE DIA-W×L: 5.72
 RESTUTY (OHM-CM): 2.12
 SHT RES (OHMS/□): 0.01
 THICKNESS (MM): 0.39

DATA POINTS:

MA	V
570.00	0.00
550.00	0.40
440.00	0.50
0.00	0.58

SOLAR_CELL_DATA

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Fig. 12. Solar cell data sheet (IBM S530).

VENDOR B SOLAR CELL(S)
CELL NO: .

EFFICIENCY, PCT: 12.64
VOC (VOLTS): 0.62
ISC (MA/SQ CM): 23.46

P_{MAX} (MW/SQ CM): 8.97
A_T (VOLTS): 0.46
A_{ND} (MA/SQ CM): 19.70

CURVE FACTOR: 0.62

INTSY (MW/SQ CM): 71.00
LIGHT SOURCE: SUN

1 SIZE ·DIA·W×L: 5.72
RESTUTY(OHM-CM):
SHT RES(OHMS/□):
THICKNESS (MM):

DATA POINTS:
MA U

600.00	0.00
590.00	0.30
500.00	0.46
0.00	0.62

SOLAR_CELL DATA

100
mA
100
mV

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Fig. 13. Solar cell data sheet (Vendor B).

NASA SOLAR CELL(S)
CELL NO: 286-2.

EFFICIENCY, PCT: 11.36
VOC (VOLTS): 0.56
ISC (MA/SQ CM): 19.80

PMAX (MW/SQ CM): 8.06
AT (VOLTS): 0.45
AND (MA/SQ CM): 18.09

CURVE FACTOR: 0.73

INTSY (MW/SQ CM): 71.00
LIGHT SOURCE: SUN

1 SIZE *DIA *W*L: 1.0 2.0
RESTUTY (OHM-CM):
SHT RES (OHMS/SQ):
THICKNESS (MM):

DATA POINTS:

MA	V
40.00	0.00
39.00	0.30
35.00	0.46
0.00	0.56

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Fig. 14. Solar cell data sheet (NASA 286-2).

IBM SOLAR CELL(S)
CELL NO: 5527 60 158

EFFICIENCY, PCT: 9.84
VOC (VOLTS): 0.58
ISC (MA/SQ CM): 20.79
P_{MAX} (MW/SQ CM): 6.98
AT (VOLTS): 0.41
AND (MA/SQ CM): 16.86
CURVE FACTOR: 0.58

INTSY (MW/SQ CM): 71.00
LIGHT SOURCE: SUN

1 SIZE ·DIA·W×L: 5.72
RESTUTY(OHM-CM): 2.00
SHT RES(OHMS/□): 0.34
THICKNESS (MM): 0.43

DATA POINTS:
MA U

530.00	0.00
510.00	0.30
400.00	0.44
0.00	0.58

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SOLAR_CELL_DATA

Fig. 15. Solar cell data sheet (IBM S527).

NASA SOLAR CELL(S)
CELL NO: 286-12.

EFFICIENCY, PCT: 8.28
VOC (VOLTS): 0.55
ISC (MA/SQ CM): 18.77

P_{MAX} (MW/SQ CM): 5.88
AT (VOLTS): 0.39
AND (MA/SQ CM): 14.97

CURVE FACTOR: 0.57

INTSY (MW/SQ CM): 71.00
LIGHT SOURCE: SUN

1 SIZE ·DIA·W×L: 1.0 2.0
RESTUTY(OHM-CM):
SHT RES(OHMS/□):
THICKNESS (MM):

DATA POINTS:
MA U

37.00	0.00
36.00	0.30
30.00	0.38
0.00	0.55

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SOLAR_CELL_DATA

Fig. 16. Solar cell data sheet (NASA 286-12).

Legend:

1 - Vendor A	13.5%
2 - IBM	12.8%
3 - Vendor B	12.6%
4 - NASA	11.4%
5 - IBM	9.8%
6 - NASA	8.3%

Fig. 17. Comparison of conversion efficiencies.

TABLE III. Solar-Cell Performance Characteristics (0°C)

		<u>Eff (%)</u>	<u>V_{oc} (V)</u>	<u>I_{sc} (mA)</u>	<u>P_{max} (mw/cm²)</u>	<u>CF</u>	<u>A/R Coating</u>
1.	Vendor A	13.5	0.61	25.4	9.58	0.62	Yes
2.	IBM	12.8	0.58	22.2	9.09	0.71	Yes
3.	Vendor B	12.6	0.62	23.5	8.97	0.62	Yes
4.	NASA	11.4	0.56	19.8	8.06	0.73	No
5.	IBM	9.84	0.58	20.8	6.98	0.58	Yes
6.	NASA	8.28	0.55	18.8	5.88	0.57	No

5. ACKNOWLEDGMENT

Technical assistance in solar-cell fabrication was provided by H. L. Stellefson.

CHAPTER III

TRANSMISSION ELECTRON MICROSCOPY ANALYSIS OF PLANAR BOUNDARIES IN SILICON RIBBON CRYSTALS

by

K. H. Yang and G. H. Schwuttke

1. INTRODUCTION

Twinning is a dominant mechanism during ribbon growth and has considerable influence on ribbon perfection. The nucleation frequency of twins is very high during the initial seeding operation and substantially lower during steady-state growth.

Twins in ribbons may have different crystallographic structure and, therefore, can influence solar-cell performance differently. In this context it is important to understand crystallographically the different twin structures present in the material. The following analysis concentrates on twinning in silicon ribbons with the twin plane perpendicular, or with the twin plane inclined, to the ribbon surface.

2. TWIN PLANE PERPENDICULAR TO SURFACE

Steady-state growth conditions of ribbons minimize the faulted area of planar defects present in the crystal. For a (011) ribbon surface, parallel twins develop along the $[2\bar{1}1]$ direction. Thus the $(11\bar{1})$ twin plane is perpendicular to the ribbon surface. This follows clearly from the TEM results presented in Figs. 1. Figure 1a is an electron diffraction pattern obtained from the crystal area shown in Figs. 1c and 1d. This crystal area contains parallel twins, many of them sub-micron in size. Etching techniques cannot resolve such defect patterns.

The analyzed diffraction pattern corresponding to Fig. 1a is shown schematically in Fig. 1b. The pattern indicates the position of the twin reflections that occur for (011) surface orientation and twinning along the $[2\bar{1}1]$ axis. Thus twinning can be visualized as a 180-degree rotation of the (011) matrix pattern around the $[11\bar{1}]$ direction. Twin spots are found at the position $(1/3) \langle 111 \rangle$.

Figures 1c and 1d are the transmission micrographs obtained through the aperture-limited dark-field technique using the $(\bar{2}00)$ matrix spot, indicated by A (Fig. 1c), and its twin satellite spot, indicated by B (Fig. 1d). It can be seen that in Fig. 1c the matrix crystal is in reflection while in Fig. 1d the twin parts are in reflection.

Fig. 1a. Electron diffraction pattern of twinned ribbon area.

Fig. 1b. Analyzed diffraction pattern corresponding to Fig. 1a.

These photomicrographs indicate that the parallel boundaries are twin boundaries with a $(11\bar{1})$ twin plane perpendicular to the (011) surface. The twin bands vary in thickness from approximately $500\text{\AA}$ to several microns.

An additional indication that the parallel boundaries are a result of simple twinning follows from Fig. 1e. The transmission micrograph given in Fig. 1e represents part of the area shown in Fig. 1c (bright field). The recording was taken at the $[143]$ pole by tilting the specimen along the $[1\bar{1}1]$ direction. Thus the boundary plane is tilted from its position parallel to the incoming electron beam into an oblique position, and fringe contrast (wedge fringes) becomes visible. During the tilting it is noted that fringes are added abruptly whenever the wedge thickness changes by approximately one extinction distance. This type of fringe addition during tilting is typical for a twin boundary.

3. TWIN PLANE INCLINED TO SURFACE

Electron channeling patterns (ECPs) of ribbon surfaces show the presence of $[41\bar{1}]$ surface orientation. This orientation can be derived from the $[01\bar{1}]$ surface orientation through twinning. The $[41\bar{1}]$ surface orientation develops into a

4 5 11 orientation through twinning on an inclined 111 plane.

Electron diffraction patterns indicative of this kind of twinning in the ribbons are shown in Figs. 2a-c. The pattern in Fig. 2a represents the $[41\bar{1}]$ crystal matrix. The twin pattern given in Fig. 2b indicates that the twin is close to the $[\bar{1}12]$ orientation but tilts towards the $\{013\}$ pole along the $[13\bar{1}]$ Kikuchi lines. From these data it can be shown that the twin has a $[\bar{4}511]$ surface orientation corresponding to twinning of a $[41\bar{1}]$ matrix in a (111) plane inclined to the ribbon surface. Superposition of matrix and twin spots of this orientation explains the diffraction pattern given in Fig. 1c. Note that the $[3\bar{1}\bar{1}]$ direction of the matrix is identical with the $[13\bar{1}]$ direction of the twin.

More insight into the structure of such planar boundaries is provided through transmission electron micrographs as shown in Figs. 3a-c. These micrographs are recorded using the different (220) reflections indicated in the diffraction pattern of Fig. 2b. The micrographs display four different boundaries at positions B_1 , B_2 , B_3 , and B_4 . Characteristic for these boundaries is the pronounced fringe contrast. Electron-transmission contrast analysis uses such fringes for planar-defect analysis. Using standard procedure the

Fig. 1c. TEM micrograph recorded using (200) matrix reflection.

Fig. 1d. TEM micrograph recorded with (twin) satellite reflection indicated at position B in Fig. 1a.

Fig. 1e. TEM micrograph of crystal area corresponding to Fig. 1c, recorded after tilting specimen. Note fringe contrast typical for twin boundary.

Fig. 2a. Electron diffraction pattern $[41\bar{1}]$ crystal matrix.

Fig. 2b. Electron diffraction pattern twin crystal orientation close to $[\bar{1}12]$.

Fig. 2c. Electron diffraction micrograph of twinned ribbon area corresponding to superposition of diffraction pattern shown in Figs. 2a and 2b.

a. $\bar{2}20$ -recording
(bright field)

b. $2\bar{2}0$ -recording
(bright field)

c. $2\bar{2}0$ -recording
(dark field)

Fig. 3. TEM micrographs of inclined fault planes. Note contrast changes as indicated. D-dark, B-bright, T-B twin boundary.

B_1 boundary is analyzed as a twin boundary while B_2 , B_3 , and B_4 are stacking faults. An exact analysis of the stacking fault fringe contrast in bright- and dark-field micrographs identifies B_2 and B_3 as intrinsic stacking faults, while the fault at B_4 is an extrinsic stacking fault.

4. SUMMARY

Planar boundaries in ribbon crystals consist of twin boundaries and extrinsic and intrinsic stacking faults. Twin planes are typical for twinning perpendicular to the $(01\bar{1})$ surface. Stacking faults are found mixed with twin boundaries for twinning on (111) planes inclined to the surface.

5. ACKNOWLEDGMENT

Technical electron microscopy support was provided by H. F. Ilker.

CHAPTER IV

ECONOMIC EVALUATION AND COMPUTER-AIDED SIMULATION-- OVERVIEW OF ACTIVITIES

by

A. Kran

The silicon ribbon growth program is directed towards the concurrent development of technological and economic data needed to define the potential that silicon ribbon might offer for large-volume production of solar cells. Following is an overview of our approach to developing the required economic data.

Ribbon-growth technology must still be considered as being in an exploratory development stage, with manufacturing process data extrapolated from laboratory observations. Hence, any given economic projection of future ribbon solar-cell cost at this time must be considered speculative, whether derived from high-speed computers or hand-held calculators. Only an aggregation of studies, based upon different viewpoints and assumptions, and increasing in complexity as more technological milestones are achieved, will generate sufficient confidence in the economics of ribbon technology to attract major investment of resources by industry.

Consequently, at the beginning of this program, we searched for an approach to economic data development which, in conjunction with economic studies, would be most effective in building confidence in the potential of silicon ribbon for high-volume production of solar cells. We selected system simulation for economic data development, and in Table I have listed some of the more important criteria of interest to us. This also led to our current approach of analyzing "first order" effects only by considering an idealized "production unit." A model of the silicon ribbon growth system, requiring 14 equations and some 23 parameters to describe, has been completed; an earlier version was documented in our first quarterly report. Output from the model consists of the major cost factors contributing to energy cost at the materials level. Many simulation runs have resulted in what we consider our economic "baseline," or state of the system, containing our assumptions and biases. Work on similar models, describing ingot-slicing and the Czochralski growth process, has been initiated.

As subsequent plateaus in ribbon technology development are achieved, progressively more complex and realistic systems, in terms of assessing material throughput capability, will be described and simulated, so that the existing balance between technological and economic data is maintained.

TABLE I. System Simulation Objectives and Attributes

<u>Objective</u>	<u>Capability/Attribute</u>
Produce a tool to generate data for economic analysis	Automatic computation, readily iterated; computer terminal and interactive programming language (APL) oriented.
Aid in technology development decision-making process	Comparison of alternative approaches in terms of future economics; updating of economic baseline to reflect achievement of milestones.
Provide a structure for communication with others	Capability of converting unstructured data, both technical and economic, into analyzable procedures with explicit assumptions; mathematical model must be simple and easy to validate.
Establish a framework for technology projections through survey of specialists	Rapid survey data input to and output from computer (needed for individual feedback); storage of all survey data for statistical analysis.
Permit comparison of competing approaches (e.g., ribbon vs web dendrite)	Sufficient aggregation of physical variables to permit "apples to apples" comparison; simple and modular model structure.

THIRD QUARTER ACTIVITY PLAN

CRYSTAL GROWTH

- o Thermal optimization of growth system.
- o Implementation of graphite-die bake-out procedures.
- o Optimization of growth system for thin-ribbon growth.
- o Process studies on ribbon perfection.

CRYSTAL CHARACTERIZATION

- o Solar-cell evaluation of 25-mm-wide ribbons.
- o Seed-ribbon interface studies, in progress, for different seed orientations.
- o Detailed orientation measurements, in progress, using the ECP techniques.
- o Assessment, in progress, of the influence of crystal defects in ribbons on minority-carrier lifetime.

ECONOMIC EVALUATION AND COMPUTER-AIDED SIMULATION

- o Development of an ingot-slicing model by system simulation (methodology similar to our ribbon-pulling model).

- o Design of a Czochralski-growth model (methodology similar to the preceding model).
- o Continuation of economic analysis, using the enhanced ribbon-growth model, with emphasis on updating of our "baseline" economic values as technology development progresses.
- o Computer simulations, using the enhanced version of our ribbon-growth model:
 - Redefinition of the "baseline" economic values each time progress occurs in ribbon development.
 - Ribbon technology projection through a survey of specialists.