SILICON RIBBON GROWTH BY A CAPILLARY ACTION
SHAPING TECHNIQUE

Quarterly Technical Progress Report No. 5

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September 15, 1976

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East Fishkill Laboratory
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ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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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.

FIFTH QUARTER HIGHLIGHTS

1. MOS C-t measurements are used to characterize lifetime in CAST crystals and its dependency on crystal defects.
2. Four classes of ribbon perfection are defined. These perfection categories are coordinated with lifetime ranges and efficiency ranges of solar cells.
3. Lifetime degrading properties of different defects are qualitatively discussed in terms of "electrical activity."
4. Electrical activity measurements of crystallographic defects in ribbons are made through the SEM EBIC techniques using Schottky contacts and p-n junction for EBIC contrast.
5. Quantitative "electrical activity" measurements of line defects in ribbons are made through carrier diffusion length measurements. Line defects are shown to decrease minority-carrier lifetime by one to two orders of magnitude.

6. Low-cost, polycrystalline silicon of semiconductor-grade quality, at \$10/kg, is a prerequisite to achieving a future energy capacity cost objective set at \$314/kWE.
7. Ribbon thickness is a relatively insignificant factor in determining energy-capacity cost. A thickness compatible with efficient solar-cell processing in the range of 0.3 to 0.4 mm should be selected.
8. Ribbon-growth techniques, such as CAST, should concentrate on wide ribbon growth. A width of 75 to 100 mm is desirable.

NEXT QUARTER (6) ACTIVITY PLAN

- o Optimize 38-mm ribbon growth.
- o Continue lifetime solar-cell efficiency studies on ribbons.
- o Consolidate and summarize studies and projections of silicon ribbon growth for photovoltaic applications.
- o Continue work on computer model of photovoltaic solar-energy conversion system manufacture.
- o Using the above computer model, perform an economic study of silicon sheet fabrication based upon Czochralski crystal growth.

LIFETIME CHARACTERIZATION OF SILICON RIBBONS

by

G. H. Schwuttke, K. H. Yang, and R. Hezel

1.0 INTRODUCTION

This report provides further insight into the crystallographic structure of ribbons grown by the capillary action shaping technique. The influence of crystal defects, such as surface inclusions, dislocations, twins, and grain boundaries, on generation lifetime of minority carriers is investigated through MOS C-t measurements. Lifetime data of different samples 25 x 60 mm in size are obtained and compared with the efficiency of solar cells made from such samples. The electrical activity of crystal defects in ribbons is investigated through charge collection microscopy and carrier diffusion length measurements.

2.0 EXPERIMENTAL

Lifetime measurements are made using the approach described by Fahrner and Schneider (1). Their technique allows relatively fast large-scale measurements of generation lifetime in the range ~ 1 msec to $\ll 0.1$ nsec. For the measurements a metal oxide semiconductor (MOS) capacitor is biased into strong inversion and subsequently switched into

deep depletion. An appropriate experimental setup prints out or displays a typical MOS recovery time, which is introduced into a computer fed by a theoretical generation-lifetime model and the pertinent wafer data. Thus minority-carrier generation lifetime values of the silicon under the MOS capacitor (depletion zone) are obtained. The error limit of this technique, compared with a Zerbst plot, is less than 20% for lifetime values $\tau \leq 10 \mu\text{sec}$. For $\tau > 1 \text{ msec}$ the error can increase to 100%. Best lifetime values encountered in ribbons are approximately $500 \mu\text{sec}$ compared with Czochralski silicon wafers, where lifetimes of over $1000 \mu\text{sec}$ are encountered.

2.1 Fabrication of MOS Capacitors

Ribbon sections of full width (25.4 mm) doped to approximately 2 ohm-cm, p-type, and 60 mm in length are processed to contain two groups of circular MOS capacitors. Each group consists of 36 capacitors of different dot size. One group uses 1.5-mm-diameter dots, and the other 0.5-mm dots. Before oxidation, ribbon sections are first etched for 30 seconds in a mixture of 3 parts nitric, 2 parts acetic, and 1 part hydrofluoric acid. Subsequently, the ribbon sections are MOS-processed using standard techniques. They are cleaned in $\text{NH}_4\text{-H}_2\text{O}_2$, $\text{HCl-H}_2\text{O}_2$, and HF solutions. Subsequently, a 5000Å-thick oxide is grown at 1000°C using a dry-wet-dry oxidation cycle. Aluminum metallurgy is used.

After metallization the wafers are annealed for 15 minutes at 400°C in forming gas. A photomicrograph of a processed ribbon is shown in Fig. 1. For comparison, 57-mm-diameter Czochralski wafers of zero dislocation density, p-type, and 2 ohm-cm are also MOS-processed.

To prepare lifetime histograms of ribbon sections, at least 36 MOS capacitors distributed across the ribbon surface are evaluated. Lifetime histograms are generated through a

Fig. 1. Photomicrograph of MOS-processed ribbon section.

computer program developed for rapid and systematic analysis of lifetime generation data. From lifetime generation measurements, entered by terminal into a timeshared APL/SV system, a statistical analysis of the data for each ribbon is performed and printed together with a histogram to show frequency distribution. Wafer data are stored for subsequent printout and summary reports (2).

2.2 Fabrication of Solar Cells

For solar-cell processing, lifetime-evaluated ribbon sections and Czochralski standards are stripped of all MOS capacitors and subsequently solar-cell-processed and measured as described in Quarterly Technical Progress Report Number 2.

3.0 MEASUREMENTS

Ribbon crystals grown by the capillary action shaping technique display a unique defect structure. Under steady state growth conditions the defect structure is dominated by linear boundaries parallel to the ribbon edges. In Quarterly Technical Progress Report Number 3 it was shown that our best ribbons obtained have a surface orientation close to $[011]$ and twin boundaries in the $[211]$ growth direction. An example of a ribbon section with parallel twinning only is shown in Fig. 2a, and a less perfect section is given in Fig. 2b.

a

b

Fig. 2. Ribbon sections of various perfection

- a. Steady-state grown, parallel twinning only**
- b. Parallel twinning and grain boundary**

Ribbon sections, as shown in Fig. 2a, can display excellent lifetime distributions. Examples of such measurements are given in Figs. 3a,b, which compare lifetime distributions obtained in our best ribbon sections with lifetime distribution typical for standard Czochralski-grown wafers. In general, however, ribbon sections vary considerably in their lifetime properties. Examples are given in Fig. 3c. Such variations indicate that the ribbon defect pattern must be a more complicated one than parallel twinning. Defect patterns typical for parallel twinned ribbon sections are given in Figs. 4. These pictures represent micrographs of ribbons after Sirtl etching.

Wafer ID: 287 42 287 420

IBM Wafer or Lot Description: Ribbon No: 1

Number of capacitors 36
 Max lifetime (μsec) 415.000
 Min lifetime (μsec) 0.367

Mean lifetime 78.166
 Standard deviation 123.622
 Median 19.950

a

Fig. 3. Lifetime distribution of samples shown in Fig. 2

a. Parallel twinning

Wafer ID: 277 1

Czoehralski Control Wafer: 3120 3.0 ohm-cm p-type

Number of capacitors 18
 Max lifetime (μsec) 993.000
 Min lifetime (μsec) 31.900

Mean lifetime 482.383
 Standard deviation 283.778
 Median 441.500

b

Wafer ID: 278 43 278 430

IBM Wafer or Lot Description: Ribbon No: 1

Number of capacitors 36
 Max lifetime (μsec) 4.010
 Min lifetime (μsec) 0.071

Mean lifetime 0.421
 Standard deviation 0.653
 Median 0.270

c

Fig. 3. Lifetime distribution of samples shown in Fig. 2

b. Czoehralski control wafer

c. Parallel twinning and grain boundary

a. Twinning in perfect crystal
Lifetime range : 73 ~ 17.0 μsec

b. Twinning and dislocations
Lifetime range : 0.67 ~ 1.4 μsec

Fig. 4. Defect patterns typical for ribbon surfaces

Figure 4a is a ribbon section of highest perfection. The crystal section between the twin boundaries is very perfect. A less perfect twin section is shown in Fig. 4b. Note the etch pits - indicating dislocation - in the left and right crystal section. The middle section between the twin boundaries is free of etch pits. Additional defect configurations found in steady-state grown ribbon sections are given in Figs. 5. A small-angle grain boundary is shown in Fig. 5a. Note the dislocation pits right and left from the boundary. A silicon carbide surface inclusion is shown in Fig. 5b. The corresponding lifetime values typical for the defect patterns shown in Figs. 4 and 5 are obtained by placing MOS capacitors in these areas. The measured lifetimes are noted in each figure for each defect pattern. Additional results are given in Figs. 6.

On the basis of such measurements we arrive at the following qualitative classification of ribbon quality:

- Class I: Parallel Twinning and Single Crystal
- Class II: Parallel Twinning and Dislocations
- Class III: Grain Boundaries and Dislocations
- Class IV: Silicon Carbide Dendrites and Inclusions

a. Low-angle grain boundary and dislocations
Lifetime range: 0.01 ~ 0.03 μ sec

b. Surface inclusion lifetime: not measurable due to leaky oxide

Fig. 5. Defect patterns in ribbon surfaces

a. Perfect crystal
Lifetime: 825 μ sec

b. Dislocations in boundary and in left crystal section
Lifetime: 1.5 μ sec

c. Dislocations and active boundaries
Lifetime: 0.145 μ sec

d. Dislocations and low-angle boundary
Lifetime: 0.02 μ sec

Fig. 6. Defect pattern and lifetime distributions

Lifetime values typical for the different classes are summarized in Table I.

TABLE 1. Influence of Crystal Defects on Lifetime

Class	Lifetime Range (usec)
I	1 to 10
II	0.01 to 1
III	$\lesssim 0.01$
IV	Not measurable
Standard (Czochralski Wafer)	10 to 100

The conversion efficiency of silicon solar cells depends on a variety of factors and their complex interactions. Most important in this context is the presence or absence of non-radiative recombination centers. Also of great influence on the efficiency is the presence of transition metals in the silicon. There is very little doubt that crystallographic defects in silicon can influence solar-cell efficiency. Surprisingly enough, hardly any data are available correlating the influence of crystal defects with solar-cell efficiency. The reason for this lack of

information is undoubtedly the fact that very detailed information about a "structure-electrical" relationship of a specific defect is needed for such a correlation, which is difficult to obtain. We are attempting such a correlation. The first results look promising and, so far, have served us as a valuable guide in classifying ribbon material. These results are as follows: on the basis of the lifetime measurements presented in Table I we have grouped the solar cells, obtained by processing the same ribbon sections used for the lifetime measurements, and have found efficiencies which correlate with the defect pattern as shown in Table II.

TABLE II. Influence of Crystal Defects on Solar-Cell Efficiency

Class	Solar-Cell Efficiency (%) (Measured without anti-reflection coating)
I	5 to 8
II	3 to 5
III	1 to 3
IV	-
Standard (Czochralski Wafers)	8 to 12

Very interesting is a comparison of the data presented in Tables I and II. Every lifetime range seems to correspond to a specific solar-cell efficiency range. Note that the standard Czochralski wafer, a defect-free wafer, has the best lifetime and also the best solar-cell efficiency.

Such measurements confirm our contention that high-efficiency solar cells require excellent - crystallographically perfect - silicon.

Another interesting result, typically, for ribbon quality is discussed in the following. Lifetime of minority carriers in ribbon, as measured by MOS capacitors, depends strongly on the position of the MOS dot relative to the edges of the ribbon. The better lifetimes are found for dots located in the center of the ribbon. This is illustrated in Figs. 7a,b,c. These figures summarize lifetime measurements made on ribbon sections cut at different positions from the seed for three different crystals (Ribbons 51202, 60303, and 213). In these figures the generation lifetime, in microseconds, is plotted as the ordinate and the position of the MOS dot relative to the ribbon edge as the abscissa. The dots A and G are close to the left and to the right edges of the ribbon. The solid line in the figures connects lifetime values obtained by averaging the single-lifetime values per column and plotting this averaged column value against the distance from the edges for the different ribbon

Fig. 7a. Position dependency of lifetime values in ribbon surfaces: ribbon 51202.

Fig. 7b. Position dependency of lifetime values in ribbon surfaces: ribbon 60303.

Fig. 7c. Position dependency of lifetime values in ribbon surfaces: ribbon 213.

sections. The ratio of average lifetime for dots located in the middle of the ribbon and for those located close to the edge can be as large as 200. Perfection studies made on these ribbon sections indicate that the degradation of lifetime correlates with the crystal perfection, which improves towards the center.

Lifetime values larger than 500 μ sec have been measured in defect-free sections of CAST ribbons. This again would indicate that ribbons grown from carbon dies have an excellent potential for high-efficiency solar cells.

Another lifetime problem is caused by the occurrence of β -SiC dendrites. The dendrites are observed on ribbon surfaces, where they deposit epitaxially during ribbon growth. (Their mechanism of growth was discussed in the Annual Report.) An example of such dendritic structures is shown in Fig. 8. The density of the dendrites is highest near the seed-ribbon interface and decreases rapidly with increasing distance from the interface. The dendrites cause leaky MOS devices. This problem is eliminated by removing a thin layer ($\sim 10 \mu$ m) of the as-grown surface through etching in a mixture of 3 HNO₃-2 HAC-1 HF acid. It was found that etching the ribbons before processing also relieves the problem of breakage, which is more pronounced for as-grown ribbons. Similar problems are caused by β -SiC inclusions formed by solution growth, as discussed in Quarterly

Fig. 8. Dendritic surface structure consisting of β -SiC on silicon ribbons.

Technical Progress Report Number 1. However, the frequency of occurrence of such inclusions is very low and, presently, of no concern.

The results of lifetime measurements made on ribbons as grown and on ribbons lightly etched before processing are summarized in Table III. It can be seen that, because of the presence of β -SiC dendrites, the occurrence of leaky MOS dots is very high on ribbon sections cut as far as 40 cm from the interface. Etching before processing eliminates this problem.

TABLE III. Influence of β -SiC Dendrites on Lifetime of Silicon Ribbons

Ribbon Number	Distance from Seed (cm)	Dot Size (mil)	Range of Lifetime (μ sec)	Average Lifetime (μ sec)	Relative Area Containing SiC (%)
60337 (as grown)	6-12	20	0.011-10.5	2.26	0.680
60337 (as grown)	18-24	20	0.001-1.64	0.20	0.524
60337 (as grown)	30-36	20	0.005-6.48	1.07	0.313
		60	0.081-1.13	0.34	0.586
60337 (as grown)	42-48	20	0.020-52.7	2.50	0.122
		60	0.028-2.42	0.44	0.214
60305 (as grown)	Unknown	20	0.0003-0.096	0.034	0.773
60305 (etched)	Unknown	20	0.039-44.3	6.54	0
60305 (etched)	Unknown	60	0.011-29.0	5.93	0

4.0 DISCUSSION

Generation lifetime is a structure-sensitive parameter and, consequently, strongly affected by crystal defects. The influence on lifetime of crystal defects in silicon is very complex and depends on parameters such as the thermal history of the crystal, which, in turn, determines the impurity cloud (Cottrell atmosphere) around a particular crystal defect. The influence of a crystal defect on lifetime is best described by its "electrical activity." Measurements indicate that the electrical activity of a defect is strongly influenced by crystal growth and process parameters. This is illustrated in Fig. 9, which summarizes measurements on oxidation-induced stacking faults in epitaxial silicon. Accordingly, the correlation between lifetime and defect density can be expressed as $t = A d_{st}^{-1.05}$, where t = generation lifetime in microseconds, A is a constant, and d_{st} = number of stacking faults/cm². The "electrical activity" of the particular defects is described by the constant A , and experience shows that it can vary significantly within a sample and also from sample to sample.

A similar correlation between defect density and lifetime, as obtained for stacking faults in epitaxial silicon, is not yet possible for defects in ribbons, because ribbons contain a variety of defects and, presently, their influence on

lifetime cannot be investigated separately. Likewise, the defect number in ribbons cannot be varied in a controlled manner.

Typical for ribbon crystals are large variations in lifetime found for areas with similar defect content. Such variations are most noticeable when twin boundaries are

Fig. 9. Influence of oxidation-induced stacking faults on lifetime in silicon.

present. This is somewhat surprising because parallel twinning should have no, or only very little, influence on minority-carrier lifetime. The equilibrium defect structure (steady-state growth) found typical for ribbon (Quarterly Technical Progress Report Numbers 3 and 4) consists of parallel boundaries along the $\langle 211 \rangle$ growth axis. These boundaries are caused by first-order twinning on $\{111\}$ planes perpendicular to the $\{110\}$ ribbon surface. Such boundaries are pure twin boundaries and have no effect on lifetime. However, since lifetime measurements in ribbons indicate that planar boundaries reduce minority-carrier lifetime by orders of magnitude, steady-state grown ribbons must also contain parallel boundaries in $\langle 211 \rangle$ directions that can influence lifetime significantly.

A special class of crystal defects, which is also typical for silicon, is the lateral or noncoherent twin. This kind of twin generally appears in groups and is connected with twinning dislocations. Noncoherent twinning in silicon causes changes in the nearest-neighbor situation because of bond rotation and leads to considerable lattice strain. Therefore, such boundaries can exert significant influence on lifetime. Such cyclic twins must be present in ribbon crystals. An electron microscopic study of such defects is in progress, and details of it will be reported in the future.

Differences in the electrical activity of twin boundaries are displayed with the help of the Scanning Electron Microscope (SEM) operated in the Electron Beam Induced Current (EBIC) mode. This technique is useful in non-destructive imaging of electrically active defects in silicon. EBIC investigations of ribbons as grown are done with Schottky contacts (3). Solar cells are investigated in the EBIC mode through use of the diffused p-n junctions (4).

Figure 10a shows an optical micrograph of a ribbon solar-cell section. The two fingers of the Al-Ag metal grid are visible and can be used for area identification. The parallel lines perpendicular to the fingers are the twin boundaries typical for ribbons grown under steady-state conditions. Note the high density of twin lines. Figure 10b is the corresponding EBIC picture. The dark horizontal lines are the Al-Ag fingers. The dark vertical lines and bands in the EBIC picture indicate a local reduction in the beam-induced current when the beam scans over these areas. This is caused by crystal defects which act as preferred recombination centers. The dark bands correlate well with the crystal sections that show etch pits (dislocations) after Sirtl etching, while the sharp boundary lines correspond to electrically active twin or grain boundaries. The areas which appear white in the EBIC picture are free of electrically active defects and have better lifetimes than the areas which appear dark in the EBIC picture.

a. Optical micrograph of solar-cell surface

b. Corresponding EBIC picture

Fig. 10. Electrical activity of defects in solar cells

Another example of line defects displayed through EBIC contrast using Schottky contacts is shown in Figs. 11. The optical micrograph shows again a large number of parallel lines and is given in Fig. 11a. The area covered by the Schottky contact is circled by a dashed line. Of particular interest in this picture is the strong defect at position "a" close to the edge of the contact. In the EBIC picture

Fig. 11. Electrical activity of defects in ribbons as grown

a. Optical micrograph

b. Corresponding EBIC picture

this line appears as a black line indicating a strongly reduced beam current. This is shown in Fig. 11b. Note that all other lines are only faintly visible. More quantitative data on the lifetime-degrading effect of line defects can be obtained through diffusion-length measurements.

Measurements of minority carrier diffusion length " L_n " (L_n diffusion length of electrons in p-type substrate) are carried out by slowly scanning the electron beam of the SEM along a line towards or away from the edge of an Al dot (Al/p-Si Schottky contact). At the same time, the beam-induced current (I) is recorded as a function of the scanning distance x from the contact edge (Fig. 12). The current (I) varies exponentially with distance x according to equation

$$I = \exp (-x/L_n)$$

The value of L_n is determined as the slope of the $\log I$ vs distance (x) curve. The corresponding minority carrier lifetime τ_n is calculated from the Einstein relation

$$\tau_n = L_n^2/D_n \text{ where } D_n = (kT/q)\mu_n$$

with D_n = electron diffusion coefficient, μ_n = electron mobility, k = Boltzmann constant, T = temperature, and q = electron charge.

Fig. 12. Principle of diffusion-length measurement.

Results obtained by this procedure are shown in Fig. 13. The line scans were made at 30 kV beam voltage and at 2×10^{-9} A current. Curve I shows the current-versus-distance dependency obtained by scanning below and parallel to the line "a." According to the corresponding EBIC picture the scan is made in an area free of electrically active defects. From this curve the carrier diffusion length is obtained as $L_n = 38 \mu\text{m}$. Interesting are the results obtained by scanning across the line defect. These measurements are summarized in curve II. This curve consists of three parts. The first is a short linear portion near the Al dot, where the L_n - value is $33 \mu\text{m}$. This value is approximately equal to the L_n value obtained in the defect-free area (curve I). In approaching and crossing the defect line the slope of curve II changes drastically. The corresponding L_n value is $7.7 \mu\text{m}$. This value is a factor of 5 to 6 lower than that in the

Fig. 13. Measurement of diffusion length.

defect-free area. The corresponding reduction in lifetime caused by this defect would be of a factor of 25 to 36. The last part of the curve yields a carrier diffusion length of $38.5 \mu\text{m}$, which is typically for the defect-free area. This measurement is, of course, for a specific ribbon, and L_n will vary according to the particular growth parameters of the ribbon. However, it appears reasonable that lifetime variations of two orders of magnitude can be caused by electrically active twin boundaries.

The lifetime-degrading properties of dislocations in ribbon are indicated through the measurements summarized in Figs. 5. EBIC pictures confirming these results are given in Figs. 14.

In addition to dislocations and planar boundaries, silicon-carbide dendrites have a major impact on lifetime degradation in ribbons. This follows directly from the EBIC picture shown in Figs. 15a,b. Figure 15a is the SEM image of dendrites covering the silicon surface. The corresponding EBIC image, using Schottky contacts, is given in Fig. 15b. The dendrites are very strong recombination centers. The efficiency of solar cells is dramatically reduced to the 1 to 3% range if dendrites are present. An EBIC image of such a solar-cell surface, using p-n-junction contrast, is given in Fig. 16. Such measurements are also in good agreement with the MOS-lifetime data.

Fig. 14. Influence of (a) dislocation structure on (b) EBIC current.

a

b

Fig. 15. (a) SEM micrograph of SiC and (b) EBIC picture of SiC using Schottky contrast.

Fig. 16. EBIC picture of SiC using p-n-junction contrast.

5.0 SUMMARY

Using MOS C-t measurements, lifetime degrading defects in silicon ribbons are classified into four groups according to the severity of their impact on lifetime: silicon carbide dendrites, grain boundaries and dislocations, parallel twinning and dislocations, and parallel twinning and single crystal.

The impact of these defects on solar-cell efficiency is established, and solar-cell efficiency ranges are given for the four different perfection states encountered in ribbons.

Lifetime-degrading properties of different defects are qualitatively discussed and displayed through SEM EBIC contrast using Schottky contacts and solar-cell p-n junctions.

Quantitative data about the electrical activity of twin boundaries are obtained through carrier diffusion-length measurements. Such measurements indicate that electrical active twin boundaries reduce minority-carrier lifetime by one to two orders of magnitude.

6.0 ACKNOWLEDGMENTS

Electrical measurements, solar-cell processing, and solar-cell measurements were made by C. P. Schneider, H. F. Ilker, and H. L. Stellefson.

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ECONOMIC ASSESSMENT OF RIBBON TECHNOLOGY THROUGH RIBBON
PARAMETER TRADE-OFF STUDIES

by

A. Kran and G. H. Schwuttke

1.0 INTRODUCTION

An important aspect of this contract is the rapid and systematic development of a technological and economic data base leading to a clearer understanding of the economics of silicon sheet growth. In the beginning of this program it was hoped that, in due course, it would become possible to substitute facts for guesses in areas of unresolved economic issues. In return, it was hoped that good economic judgment thus developed could guide the future technological progress of ribbon programs. This study reports a step in this direction. It uses technological insight into ribbon growth gained under this program and conducts a computer simulation aimed at clarifying important technological-economic questions which must be answered before the desired energy-cost objective of \$300 to \$500/kWE can be met. A trade-off study of such parameters as solar-cell conversion efficiency, ribbon thickness, ribbon width, and polysilicon cost is reported.

Such an important investigation has finally become possible.

It is based on a computer-simulation model of silicon ribbon growth (see Quarterly Technical Progress Report Numbers 3 and 4) and on an elegant application of high-speed data-processing techniques. As a result of this study we have re-aligned our technological goals and we believe that cost projections as modeled in this report can be met.

2.0 DATA DEVELOPMENT PROCEDURE

The ribbon parameter trade-off study is based on the effective use of the computer model of ribbon growth presented in Quarterly Technical Progress Report Numbers 3 and 4. This study answers certain questions of the "if" type, which normally, from a computational standpoint, are impractical to resolve. Using high-speed data processing, it is shown that through iteration of the simulation model timely answers can be provided to specific questions on how to conduct future ribbon growth. The conclusions drawn from such investigations are based on the answers provided for the following two questions:

1. If we assume that the projected energy-capacity cost objectives must be met, what kind of trade-off possibilities exist between such parameters as polysilicon cost, conversion efficiency, and ribbon thickness?

2. If we assume that the projected future energy-capacity cost of \$314/kWE must be met, again what kind of trade-off possibilities exist between such parameters as polysilicon cost, conversion efficiency, and ribbon width?

Following is the computational approach to obtain answers to such questions. This approach serves also as an illustration of the "inherent power" of our simulation model.

To answer the first question, we analyze polysilicon cost, conversion efficiency, and ribbon thickness. The values assigned previously to these parameters (see simulation 44, Table IV, p.52, of Quarterly Technical Progress Report Number 4) were \$30/kg, 12%, and 0.15 mm, respectively. These values yielded an energy-capacity cost of \$314/kWE at the level of silicon-sheet material.

To derive a specific relationship between these three parameters, we assign technological (practical) limits to two parameters and keep the third one constant. The ribbon thickness is permitted to vary between 0.1 and 1.0 mm, conversion efficiency can vary between 5 and 20%, and the projected polysilicon cost is held constant at \$6/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 (\$314/kWE, $\pm 0.5\%$), 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.

Data points for this particular curve are gathered as shown in Table I, which also points out that 2205 iterations of the model were needed to arrive at the 20 data points. This number is considered adequate for plotting a curve. Subsequent iterations of the model, with the polysilicon cost held constant at \$30/kg, \$45/kg, and \$65/kg, respectively, results in curves 2, 3, and 4 of Fig. 4 (in section 3.0). As a further illustration of this technique, the APL function defined and documented for this exercise is shown in Fig. 1.

TABLE I. Data Points for Future Silicon Ribbon Technology

ITEM NO.	ITERATION	EFF.(%)	THICKNESS(M)	ENERGY CAPACITY COST(DOLS/KW)
1	160	8.00	.19	313.44
2	464	12.40	.82	314.80
3	465	8.16	.22	314.76
4	481	13.44	.98	315.07
5	1176	11.84	.73	314.74
6	1235	9.44	.39	312.97
7	1483	8.00	.19	313.44
8	1638	12.00	.86	313.36
9	1646	9.60	.41	314.11
10	1660	11.04	.62	315.47
11	1669	8.00	.31	314.96
12	1789	12.64	.84	314.11
13	1810	8.00	.31	314.96
14	1935	10.88	.59	314.50
15	1960	9.44	.40	315.13
16	1969	12.16	.77	313.14
17	2011	12.80	.86	314.98
18	2083	10.88	.59	312.63
19	2204	10.40	.52	313.39
20	2205	9.20	.37	313.99

```

      DATA:K:IL
[1]  AA  FUNCTION FOR DEVELOPING DATA USED IN
[2]  AA  RIBBON PARAMETER TRADE-OFF STUDY
[3]  A
[4]  A  SET RANDOM LINK TO REPRODUCE RESULTS, IF NEEDED
[5]  DRL=123456
[6]  K=L=0
[7]  Z= 20 5 10
[8]  A  RESET PARAMETER VALUES
[9]  GUARS2
[10]      ITEM NO.  ITERATION  EFF.(PCI)  THICKNESS(MM)  ENERGY CAPACITY COST(DOLS/KW)
[11]  '
[12]  '
[13]  LOOP:
[14]  A  EXIT AFTER COLLECTING 20 DATA POINTS
[15]  +((L-20)*0
[16]  K=K+1
[17]  A  COST OF POLY SI
[18]  LP=316
[19]  A  RANDOM PICK WITHIN DEFINED LIMITS OF ENERGY
[20]  A  CONVERSION AND THICKNESS PARAMETER VALUE
[21]  EC=4.16*((?100)+100
[22]  RT=0.1+0.9*((?100)+100
[23]  A  CALCULATE ENERGY CAPACITY COST BASED ON SELECTED PARAMETERS
[24]  CALC
[25]  A  ACCEPT DATA ONLY IF WITHIN 0.5 PCT OF SPECIFIED VALUE
[26]  +(((NC-312.5)*(NC-315.5))/LOOP
[27]  Z(L))= 1 5 *((L+L+1),K,EC,RT,NC(1)
[28]  12 0 12 0 12 2 10 2 25 2 *Z(L))
[29]  -LOOP

```

Fig. 1. APL function for data development;

3.0 RESULTS AND DISCUSSION

The procedure described in section 2.0 gives the results summarized in Figs. 2 through 5. The calculations presented use previously defined ribbon technology terms, such as present, near-future, and future. Each figure contains a set of curves for a specific energy-cost objective (e.g., \$314/kWE) and shows possible trade-offs between conversion efficiency, ribbon thickness, and ribbon width for several polysilicon-cost levels.

The following conclusions drawn from each set of curves in Figs. 2 through 4 answer the first question and present important guidelines for our ribbon program.

"Present" Silicon Ribbon Technology (Fig. 2)

- o Semiconductor-grade-quality polycrystalline silicon cannot be abandoned in favor of inferior quality (solar-cell grade?). The desired "solar grade" quality of polysilicon is not allowed to reduce solar-cell conversion efficiency. Inferior-quality polysilicon (for 0.3-mm-thick ribbon) is cost-effective only if a price reduction of at least one order of magnitude (from \$65/kg to \$6/kg) can be achieved.

- o 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 more compatible with the necessary mechanical handling of the material. 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.

*Simulations refer to Annual Report.

Fig. 2. Present silicon ribbon technology: conversion efficiency vs ribbon thickness (energy capacity cost, \$8476/kWE).

"Near-Future" Silicon Ribbon Technology (Fig. 3)

- o Polysilicon cost of \$30-45/kg must be obtained. Otherwise there is no reasonable chance of achieving the energy-capacity cost objective of \$1319/kWE. In addition, the silicon purity must be such that an approximate 10% conversion efficiency for solar cells using 0.3-mm-thick ribbon is guaranteed.

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

Fig. 3. Near-future silicon ribbon technology: conversion efficiency vs ribbon thickness (energy capacity cost, \$1319/kWE).

"Future" Silicon Ribbon Technology (Fig. 4)

- o A polysilicon cost above \$30/kg makes the energy-capacity cost objective of \$314/kWE unachievable. 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. 4. Future silicon ribbon technology: conversion efficiency vs ribbon thickness (energy capacity cost, \$314/kWE).

To answer the second question, we examine "future" relationships of ribbon width, conversion efficiency, and polysilicon cost. The results are summarized in Fig. 5 and support the conclusions listed above.

- o There is little hope of achieving an energy-capacity cost objective of \$314/kWE for a polysilicon cost above \$30/kg. At this cost level, the goal of \$314/kWE can be reached only if solar cells of 12% efficiency can be made from 10-cm-wide

Fig. 5. Future silicon ribbon technology: conversion efficiency vs ribbon width (energy capacity cost, \$314/kWE).

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 achievable.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions (in addition to those contained in Quarterly Technical Progress Report Numbers 3 and 4) represent our present outlook for large-area silicon ribbon growth:

- o. Low-cost (\$10/kg) semiconductor-grade-quality polycrystalline silicon is a prerequisite to achieving a future energy-capacity cost objective of \$314/kWE
- o. Ribbon thickness is a relatively insignificant factor in determining energy-capacity cost. Hence, a thickness of 0.3 to 0.4 mm can be selected. This thickness is compatible with solar-cell processing.
- o. Ribbon silicon growth techniques, such as CAST, should concentrate on wide ribbon growth. A width of 75 mm to 100 mm is desirable.

LOW COST SILICON FOR SOLAR ENERGY APPLICATION*

by

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ABSTRACT

Economically viable means of producing silicon solar cells for the conversion of solar energy into electric power are discussed. Emphasis is given to the discussion of crystal growth techniques capable of growing single crystal silicon ribbons directly and inexpensively from molten silicon. The recently developed capillary action shaping technique has this potential and is discussed in detail. The successful application of this technique to ribbon growth is demonstrated and problems which must be overcome to achieve the goal of low cost silicon are pointed out.

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The JPL Low-Cost Silicon 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.

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LOW COST SILICON FOR SOLAR ENERGY APPLICATION

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INTRODUCTION

The widespread application of silicon solar cells to direct photovoltaic energy conversion is presently held back primarily by cost. Energy Research and Development Agency (ERDA) officials calculate the average cost today of a cell capable of generating one watt of electricity to be \$20. They assert that this cost must come down to 50 cents per watt for cells to begin to compete with other energy sources. The ERDA goal is to achieve this figure in 1985.

According to ERDA's economists the present cost of \$20 per watt of solar cells translates into a capital cost of \$20,000 per peak kilowatt of generating capacity for a utility's solar cell system in a central generating station. The economists claim that for an add-on needed storage capability, of three to six hours of the stations output, present cost would rise to \$40,000 to \$50,000 per peak kilowatt. For such a system to compete with fossil fueled or nuclear power plants, it is estimated that the cost would have to come down to \$1,000 per peak kilowatt calculated in today's dollars.

In producing electricity from solar cells most of the expense is in the manufacturing of the cell. Solar cells are predominantly made from silicon the second most abundant element on earth. It is usually found in the compound form of sand. Gaining silicon from sand in the needed purity is a very expensive process. But efforts are being made to shrink this expense. Research sponsored by ERDA aims at producing solar-grade silicon at less than \$10/kg at a production level in excess of 2,000 metric tons per year by the year 1985. The selection process involved in this research examines and re-examines processes for preparing silicon used in the past as well as those that are commercially employed today. In addition over 200 chemical reactions are considered by which the preparation of silicon might have been possible through the reduction of readily available compounds. Today, up-grading the metallurgical-grade silicon process is deemed the most probable means of meeting ERDA goals for solar grade silicon.

The second major expense is in the fabrication of solar cell blanks from Czochralski grown silicon crystals.

Fabrication of cell blanks from Czochralski grown silicon boules is a wasteful and expensive process. One-half to two-thirds of the boule is lost in saw kerfs and polishing operations. In addition large parts of the solar cell manufacturing involves batch operation.

A process for continuous growth of ribbon crystals is envisioned to permit continuous automatic device fabrication. Such a process would overcome wasteful manufacturing processes and thus substantially reduce cost. Many attempts have been made to provide such a solution, including the dendritic web process(1,2), the Stepanov technique(3) as applied by Boatman and Goundry(4) and the Edge Defined Film-fed Growth (EFG) technique (5) first applied to silicon by Ciszek (6,7).

Ribbon growth programs in the USA aim at continuous growth of silicon ribbons at high growth speeds (7.5cm/minute). The ribbons should be 7.5cm wide, 0.1mm thick and yield a solar cell efficiency of 10%. In anticipation of this goal, IBM is involved in a research program pursuing the growth of silicon ribbons by a capillary action shaping technique (CAST) as shown in Fig.1. Some of this work is reviewed in the following.

RIBBON GROWTH

At our laboratory, ribbon growth is conducted as described by Ciszek(6,7) in a vertical quartz tube furnace. A flat-bottomed quartz crucible 50mm in diameter and 25mm in height contains the molten silicon. The crucible rests in a conductive susceptor which is rf-heated. The rim of the susceptor supports a die holder which in turn engages the die. Horizontal heat shield plates, with a central elongated slot through which the growing ribbon

is passed, rests on the die holder (see Fig. 2). All ribbons discussed in this paper are grown from high-density graphite dies (density 1.8g/cm and grain size about 25 μ m). As discussed in Ref. 6, graphite dies are not completely non-reactive with silicon, but are among the few practical materials at this stage of silicon ribbon growth development. The effects of carbon will be further elaborated. Ideally, the die material should be wetted by molten Si, be durable in molten Si, and be completely non-reactive with molten Si.

The dies are typically machined to the width of the desired ribbon and a die top thickness of 0.5mm. The capillary slot is 0.25mm in thickness. Because of the thin molten zone at the die top, isotherm control in the growth region is quite critical. The isotherms must conform to the geometry of the top surface of the die and must be constant with time. Since the isotherm shape at the solidification front is in part determined by latent heat of fusion, an optimum pulling speed exists for any given growth set-up at which the freezing isotherm follows the die surface. In our growth set-up, this speed is typically 1.8cm/min. However, various heat shields, die and die holder configurations were examined and optimum growth speeds ranged from (0.8 to 3.3)cm/min. To achieve temperature stability, a closed loop control system is employed. An optical radiation detector with (0 to 10)mV output, focused on the susceptor, serves as the sensor. A solid-state current-adjusting-type (C.A.T.) controller provided rate, reset, and proportional control action.

Growth is initiated by touching a seed crystal to the melt. The upward pulling speed and the temperature are then adjusted to gradually widen the ribbon. Growth is conducted in an argon atmosphere. Ribbons were grown up to 1.5m in length and 38mm in width and 0.4mm thick.

DIE PROBLEMS

During silicon ribbon growth small SiC crystallites form in the orifice of the die. Such crystallites are also found floating in the meniscus at the top of the die. More or less frequently such a particle becomes attached to the silicon ribbon thus destroying the perfection of the ribbon(7). Similar observations are made on the outside of a carbon die in contact with the molten silicon. An accumulation of crystallites in the orifice of a carbon die is shown in Fig. 3a and on the outside of a die in Fig. 3b. Scanning electron micrographs of such small crystals scraped from the orifice and from the side of the die are shown in Figs. 4. These crystals appear equi-axed and expose mainly (111) and (100) surfaces. The morphology of the SiC crystals is in agreement with the growth from a liquid phase by precipitation. Some of these crystals are found in clusters bonded to each other with a very limited area where their orientations are identical. It is obvious that beautiful small SiC crystals are grown by this technique as an unwanted "side-product" of Si ribbon pulling

RIBBON QUALITY

It has been our experience that crystallographic perfection of capillary action grown silicon ribbons rapidly deteriorates as ribbon length increases - particularly in the case of wide ribbons(7). This is due in part to the effects of carbon in silicon. Mechanical and thermal perturbations may, because of the very thin melt boundary between the die and the growth interface, also contribute to the degradation. However, it is difficult to isolate their contribution in the presence of the carbon effects.

Major problems exist during the seeding operation. Single crystal growth is difficult to achieve during this initial phase. Presently, it is not possible to control the "seeding operation" sufficiently to influence the surface orientation and perfection of the ribbon grown during "steady state". Because of silicon carbide formation during seeding, the original seed/crystal relation is rapidly lost and the final ribbon quality is mostly dominated by twin lines in the $\langle 112 \rangle$ direction. An x-ray topograph of a typical crystal-seed interface is given in Fig. 5 and shows clearly the catastrophic collapse of seed orientation due to heavy twinning. All twins inclined towards the growth direction grow out relatively fast. If the inclusion of silicon carbide particles in the ribbon surface can be avoided, steady-state growth is dominated by surface orientations close to a $\langle 110 \rangle$ direction.

To define the surface orientation of ribbons grown under steady-state conditions, we introduce the convention summarized in Fig. 6. Accordingly, the angle between the growth direction and the twin boundaries is called α . The resultant tilt angle, θ_r , gives the actual surface orientation of the ribbon. This surface orientation is measured as a misorientation against the [011] direction and has the two components θ_g and θ_a , where θ_g is the tilt along the growth direction and θ_a is the tilt around the growth direction perpendicular to it.

Figure 7 summarizes typical surface orientations obtained for different seed orientations. On the basis of these and other results, we conclude that control of surface orientation of ribbon grown under steady-state conditions does not, at present, exist. It can be noted that surface misalignment covers a range between 5 and 15 degrees against the [011] surface. Ribbons with twin planes inclined almost perpendicular to the surface and a surface tilt of $\theta_r = \theta_a = 8$ degrees (with $\theta_g = 0$) have been grown. For such ribbons the twin boundaries are parallel to the [211] growth direction.

Examples of ribbon surfaces are shown in Figs. 8. Figure 8a shows a ribbon surface with parallel twinning, Fig. 8b is a ribbon surface containing non-parallel twinning and grain boundaries.

A higher complexity of surface disorder is seen in Fig. 8c. This ribbon section contains different grains, silicon carbide inclusions and different types of twinning. All these defects are normally encountered during ribbon growth and once analysed by transmission electron and scanning electron microscopy, are readily interpreted through optical microscopy.

Surface orientations and the nature of boundaries encountered in Fig. 8c were analysed through the electron channeling technique (ECP) in the SEM. The results obtained are summarized in Fig. 9a. An example of the ECP analysis is given in Fig. 9b.

ELECTRICAL MEASUREMENT

This section discussed briefly lifetime and solar cell measurements made on silicon-ribbons.

In addition to twins and grain boundaries ribbon sections may contain large numbers of dislocations. However, the actual ribbon perfection obtained under steady state growth conditions is dominated by parallel twinning (Fig. 8a). Such ribbon sections can display excellent lifetime properties and in this respect compare well with lifetime distributions observed in Czochralski wafers.

Lifetime measurements performed on ribbon sections of 25x60mm are shown in Figs. 10. Such lifetime distributions are measured with

an MOS technique based on the evaluation of the capacitance vs. time curve (C-t) as described previously(8,9). Each ribbon section contains 36 MOS capacitors of 1.5mm diameter. Minority carrier lifetimes of (400 to 500) μ sec have been measured in ribbon sections grown with carbon dies.

The ribbon sections processed for lifetime measurements were subsequently solar cell processed. The corresponding solar cell data are shown in Figs. 11. As expected samples with good lifetime distributions give good solar cell efficiency; however, no correlation is attempted at this stage. Maximum solar cell efficiency obtained in ribbon cells of 25x60mm dimension are close to 6% without anti-reflective coating. This would indicate to us that the original ERDA goal of 10% efficiency for ribbon cells, is achievable for cells fabricated from ribbons grown with carbon dies.

CONCLUSIONS

The IBM Capillary Action Shaping Technique (CAST) for silicon ribbon growth has several potentially promising characteristics. CAST could provide continuous lengths of (wide) silicon ribbon for continuous processing and eliminate the need for crystal slicing. Melt replenishment for long-ribbon growths should

be achievable, since the melt reservoir could be thermally decoupled from the solidification front. Pulling speeds are a factor of ten or more higher than those in Czochralski growth; and, if the crystallography is good, lifetime values are comparable to those encountered in Czochralski crystals.

Crystal structure perfection of CAST ribbons is un-conventional if compared to Czochralski silicon crystals. Cast crystals are plagued by uncontrolled twinning and grain boundaries. Good sections contain parallel twinning only. Such sections have excellent lifetime distributions and yield solar cells with an efficiency approaching 10%.

The un-conventional crystal perfection of CAST ribbon relates directly to the carbon die and is attributable in part to carbon solubility in Si and SiC formation.

The task of finding a totally non-reactive die for high-purity silicon growth is redoubtable. Even if the ideal die material is available, the task of growing continuous, wide ($>50\text{mm}$), thin ($<0.5\text{mm}$) ribbons with flat surfaces is encumbered by the exacting thermal control requirements imposed by the thin melt zone. The mechanical problem of maintaining a long flexible ribbon accurately positioned over the die top in the presence of gas flow and pulling transport perturbations is also substantial. These two problems are of the same order of difficulty as the thermal and mechanical control requirements in dendritic web growth.

The high pulling rate of ribbons is more than negated by a low production rate. A Czochralski crystal 75mm in diameter grown at 2mm/min yields eight times as much silicon per unit time as a 75mm wide ribbon, 0.5mm thick, grown at 30mm/min.

Dislocation-free Czochralski crystals of the above size are a present reality, whereas the widest dislocation-free capillary-grown ribbons reported to date are 5mm, and these occur in short lengths only. Dislocated, multi-crystalline ribbons have been grown in 40mm widths.

The major problems to be faced in ribbon growth are development of a non-reactive die and the solution of exacting thermal and mechanical control requirements for the growth of wide ribbons with sufficient crystallographic perfection.

ACKNOWLEDGMENT

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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.

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Fig. 1. Schematic of Capillary Action Shaping Technique (CAST).

Fig. 2. Photograph of ribbon growth furnace.

Fig. 3a. Accumulation of SiC in orifice of carbon die.

Fig. 3b. Accumulation of SiC on outside of carbon die.

a

b

Fig. 4. Scanning electron micrographs of SiC crystals scraped from orifice of carbon die (a and b).

c

d

Fig. 4. Scanning electron micrographs of SiC crystals scraped from orifice of carbon die (c and d).

Fig. 5. X-ray topograph of seed-ribbon interface.

Fig. 6. Definition of ribbon surface orientation.

Ribbon Number	Seed Orientation		Sample Distance from Seed (cm)	Sample Orientation			Twin Axis a/b	Remarks
	Face	Growth Direction		Face	Growth Direction			
				Nearest Pole		Deviation (degrees)		
40404	(111)	$\langle \bar{1}\bar{1}2 \rangle$	>50	011	$\theta_R = 11.3$ $\theta_a = 3.5$ $\theta_g = 10.7$	$2\bar{1}\bar{1}$	$11\bar{1} \leftrightarrow \bar{1}\bar{1}1$	Twin boundaries in growth direction
40812	(1 $\bar{1}$ 0)	$\langle 111 \rangle$	50	011	$\theta_R = 9.7$ $\theta_a = 5$ $\theta_g = 8.3$	$21\bar{1}$	$1\bar{1}1 \leftrightarrow \bar{1}1\bar{1}$	Twin boundaries not in growth direction (10° off)
40820	(1 $\bar{1}$ 0)	$\langle 111 \rangle$	50	011	$\theta_R = \theta_a = 8.4$ $\theta_g = 0$	$21\bar{1}$	$1\bar{1}1 \leftrightarrow \bar{1}1\bar{1}$	Twin boundaries in growth direction
50520	(100)	$\langle 110 \rangle$	120	011	$\theta_R = 18$ $\theta_a = 14$ $\theta_g = 11$	$21\bar{1}$	$1\bar{1}1 \leftrightarrow \bar{1}1\bar{1}$	Twin boundaries in growth direction

Fig. 7. Summary of ribbon surface orientations.

a.

b

Fig. 8. Examples of ribbon surface quality.

a. Parallel twinning

b. Non-parallel twinning and grain boundary

c. Complex surface disorder

Type of Boundary	Surface Orientation	Twin Plane*	Nature of Boundary
A/B	$(01\bar{1})/(0\bar{1}1)$	$(111)_p$	Twin
A/N	$(01\bar{1})/(41\bar{1})$	$(11\bar{1})_i$	Twin
N/M	$(41\bar{1})/(\bar{4} \ 5 \ 11)$	$(111)_i$	Twin
M/A	$(\bar{4} \ 5 \ 11)/(01\bar{1})$		Grain boundary
Z/A	$(111)/(01\bar{1})$		Grain boundary
Z/p	$(111)/(111)$		Grain boundary
p/p ₁	$(111)/(511)$	$(\bar{1}11)_i$	Twin
B/R	$(0\bar{1}1)/(4\bar{1}1)$	$(1\bar{1}1)_i$	Twin

Fig. 9a. Surface orientation analysis of ribbon corresponding to Fig. 8c: summary.

Fig. 9b. Surface orientation analysis of ribbon corresponding to Fig. 8c: SEM analysis example.

a

b

Fig. 10. Lifetime distribution in ribbon samples

- a. Parallel twinning only
- b. Complex surface disorder

IBM SOLAR CELL(S)
CELL NO: 10-24.

EFFICIENCY, PCT: 5.83
VOC (VOLTS): 0.51
ISC (MA/SQ CM): 16.17

PMAX (MW/SQ CM): 5.47
AT (VOLTS): 0.39
AND (MA/SQ CM): 14.20

CURVE FACTOR: 0.66

INTSY(MW/SQ CM): 93.78
LIGHT SOURCE: SUN
TEST EQUIPMENT : PYRANOMETER

1 SIZE ·DIA·W×L: 2.4 5.9
RESTUTY(OHM-CM):
SHT RES(OHMS/D):
THICKNESS (MM):

DATA POINTS:
MA V

226.00	0.00
215.00	0.30
190.00	0.40
0.00	0.51

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Fig. 11. Solar cell data of ribbon samples corresponding to Fig. 10.

a. Parallel twinning only

IBM SOLAR CELL(S)
CELL NO: 213-43.

EFFICIENCY, PCT: 2.24
VOC (VOLTS): 0.46
ISC (MA/SQ CM): 12.33

PMAX (MW/SQ CM): 2.09
AT (VOLTS): 0.27
AND (MA/SQ CM): 7.69

CURVE FACTOR: 0.37

INTSY (MW/SQ CM): 93.29
LIGHT SOURCE: SUN
TEST EQUIPMENT: PYRANOMETER

1 SIZE ·DIA·W×L: 2.5 6.0
RESTUTY(OHM-CM):
SHT RES(OHMS/□):
THICKNESS (MM):

DATA POINTS:
MA U

186.00	0.00
138.00	0.20
106.00	0.30
0.00	0.46

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SOLAR_CELL_DATA

b. Complex surface disorder