## ADVANCED SILICON SHEET

**N87-16406**

**STRESS AND EFFICIENCY STUDIES IN EDGE-DEFINED FILM-FED GROWTH**

MOBIL SOLAR ENERGY CORPORATION

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### Technology

**Advanced Materials Research Task**

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<th>CONTRACTOR</th>
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<td>Mobil Solar Energy Corporation, Contract Number 956312</td>
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- Stress analysis shows potential for reducing sheet stress at lower growth speeds (<2 cm/min for EFG) exists:
  - When sheet edges are cooler than centerline.
  - Reductions sensitive to creep below 1200°C.
- Quantitative relationships established between L and N_d for FZ silicon stressed above 900°C:
  - L \( \propto \) \( N_d^{-1/4} \).
  - Point defect contributions to degradation defined.
- Dopants in EFG material shown to influence dislocation activity, point defect recombination.

### Topics of Presentation

- Brief summary of work 1982-86.
- Developments since 25th PIM.
Stress Studies, 1982-1986: Accomplishments

• Developed finite element analysis for calculating residual stress with plastic deformation in high speed sheet growth (with Prof. J. Hutchinson, Harvard U.).

• Verified quantitative finite element model for EFG control variable relationships/temperature profile calculations (with Prof. R.A. Brown, MIT).

• Developed residual stress measurement technique for EFG material using shadow Moire interferometry (with Prof. S. Danyluk, U. of Illinois at Chicago).

• Transient creep investigated in silicon for 800-1400°C in strain (10^-3) and strain rate (10^-4 s^-1) regimes of sheet growth.

Defect Electrical Activity Studies, 1984-1986: Accomplishments

• Developed quantitative minority carrier diffusion length measurements for dislocated, inhomogeneous material using EBIC.

• Obtained quantitative data on dopant (B, Ga) influence on defect densities and electrical activity in EFG material.

Dislocation Electrical Activity

• L vs. N_d relationships established for FZ silicon stressed in temperature range 900-1400°C
  - Microdefect recombination limits in N_d ≤ 10^4 cm^-2 regions.
  - Dislocation effects give L ~ N_d^-1/4 above N_d threshold that depends on microdefect recombination level.

• Contrast to as-grown dislocation activity for which L ~ N_d^-1/2 (τ ~ N_d^-1).
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Diffusion Length Dependence on Heat Treatment and Dislocation Density

\[ \tau = \frac{L^2}{D} \]

\[ \frac{1}{\tau_e} = \frac{1}{\tau_0} + \frac{1}{\tau_d} \]

\[ \frac{1}{\tau_d} = 2\pi S_d N_d \]

\[ Z_e(1000^\circ C, 105 s) = 3.0 \mu m (40 \mu m) \]

\[ Z_e(1000^\circ C, 105 s) = 2.7 \mu m (40 \mu m) \]

1000^\circ C

105 s stress, \( N_d = 0 \)

900^\circ C, 1 hr.

1000^\circ C, 105 s

>1200^\circ C, 1-10 s

Dislocation density \( (\text{cm}^{-2}) \)

Starting diffusion length, \( L_0 = 0 \)

78 s stress, \( N_d = 0 \)

II stressed in four-point bending

Dislocation length (microns)

\( S_d Z_e = 0.13 \)

\( S_d L_e = 0.072 \)

\( S_d L_e = 0.41 \)

ORIGINAL PAGE 2
OF POOR QUALITY
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EBIC Line Scans of Dislocations in High and Low Resistivity EFG Silicon Ribbon

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- 0.2Ω-cm Gallium
- 3.0Ω-cm Boron

EBIC Signal vs. Scan distance x

1.0 μm
Dislocation Versus Point Defect Limitations on Lifetime

- RESULTS SUGGEST ELECTRICAL ACTIVITY OF GROWN-IN DISLOCATIONS DIFFERS FROM CREEP-RELATED DISLOCATIONS.

- $L \sim N_d^{-1/4}$ ($\tau \sim N_d^{-1/2}$; dependence may be related to dislocation "debris" or total area swept out by dislocations, requires point defect-dislocation interaction dynamics to be included.

- $L$ IS NOT EQUAL TO MEAN DISLOCATION SEPARATION $\ell = N_d^{-1/2}$ FOR ANY SITUATION, INDICATING ONLY SMALL FRACTION OF CORE SITES ARE ACTIVE.
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Future Directions for Electrical Activity Studies

DEVELOPMENT OF PASSIVATION SCHEMES FOR DEFECTS AND PROCESSING/PASSIVATION OPTIMIZATION CRUCIAL TO VIABILITY OF CURRENT SHEET MATERIAL FOR LOW-COST PHOTOVOLTAIC INDUSTRY.

CURRENT EFG STATUS:
L: 100-200 MICRONS
\( \eta \): 13-15% (45 cm\(^2\) AREAS)

FUTURE REQUIREMENTS:
L: 200-300 MICRONS
\( \eta \): \( \geq 16\% \)

FUNDAMENTAL NEED IS FOR DEVELOPMENT OF MODELS FOR AND IDENTIFICATION OF RELATIVE CONTRIBUTIONS OF POINT DEFECTS AND DISLOCATIONS TO LIFETIME LIMITATIONS, PARTICULARLY IN LOW RESISTIVITY SILICON.

- **FINITE ELEMENT MODELING OF EFFECTS OF TRANSVERSE ISOTHERM NONUNIFORMITY ON STRESS**

- **STRESS REDISTRIBUTION IN FINITE SIZE BLANKS**
  - L. Bucciarelli (MIT).

- **STRESS RELAXATION MEASUREMENT IN SILICON BETWEEN 800°C AND 1200°C**
  - PLANS FOR EXPERIMENTS.
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$\Delta T_T = 0$

$\Delta T_T = -100^\circ C$

$\dot{\varepsilon}_{xX}, CENTER$

$\dot{\varepsilon}_{xX}, EDGE, \Delta T_T = -100^\circ C$

$\dot{\varepsilon}_{xX}, EDGE, \Delta T_T = 0$

$\dot{\varepsilon}_{xX}, CENTER$

$\Delta T_T = 0, -100^\circ C$

$\dot{\varepsilon}_{yy}, CENTER$

$\dot{\varepsilon}_{yy}, CENTRE$

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$\dot{\varepsilon}_{yy}, CENTRE$
Transverse Isotherm Effects: Conclusions

- Nonuniformity leads to higher maximum stress in the sheet
  - Increases tendency for buckling.
  - Increases defect density.
  - Only edge cooling reduces residual stress.

- Significant compensation for high axial temperature profile nonuniformity cannot be produced for moderate (100-300°C) edge cooling.

- Residual stress distribution is fundamentally altered
  - Possible there are temperature distributions which reduce stress to zero.
  - Creep behavior between 800°C and 1200°C needs to be studied.
Coordination of Frame and Stress Components
Sign Convention

FIGURE 1.
COORDINATE FRAME & STRESS COMPONENTS
SIGN CONVENTION
Residual Stress Distribution in Semi-Infinite Ribbon

Note: y = 0 is ribbon center line
Note: $\sigma_{xx}$ is plotted; other stress components are zero.

Stress Component Variation with "x" at y = 0.0

Note: Half length of ribbon $L = 4*(\text{the half width})$
Note: For $x$ negative:
- $\sigma_{xx}$ is symmetrical
- $\sigma_{yy}$ is symmetrical
- $\sigma_{xy}$ is asymmetrical
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Stress Component Variation with ‘‘x’’ at y = 0.5

![Graph showing stress components at y = 0.5]

Stress Redistribution in Finite Size Blanks: Summary

- Method for calculating shear flow developed
  - Can be obtained for any size blank.
  - Can be related to grown-in thermoelastic stress in semi-infinite sheet.

- Significant stress redistribution at blank end produces large tensile non-zero \( \sigma_{yy} \) component.

Stress Relaxation Measurements in Silicon (800°C - 1200°C)

- Previous creep measurements obtain
  \[ \frac{\partial \varepsilon}{\partial t} , \sigma \text{ constant} \]
  Constitutive law: \( \dot{\varepsilon} \sim f(T) \sigma^N \)

- Relaxation measurements will obtain
  \[ \frac{\partial \sigma}{\partial t} , \varepsilon \text{ constant} \]