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STRESS AND EFFICIENCY STUDIES IN EFG

MOBIL SOLAR ENERGY CORP.

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TECHNOLOGY	REPORT DATE
ADVANCED MATERIALS RESEARCH TASK	OCTOBER 2, 1984

APPROACH	STATUS
STRESS AND EFFICIENCY STUDIES IN EFG **CONTRACTOR** MOBIL SOLAR ENERGY CORPORATION, CONTRACT NUMBER 956312 **GOALS** • TO DEFINE MINIMUM STRESS CONFIGURATION FOR SILICON SHEET GROWTH. • TO QUANTIFY DISLOCATION ELECTRICAL ACTIVITY AND LIMITS ON CELL EFFICIENCY. • TO STUDY BULK LIFETIME DEGRADATION DUE TO INCREASE IN DOPING LEVELS.	• DEVELOPMENT OF INTEGRATED STRESS AND THERMAL MODELS FOR EFG GROWTH PROCESS IS COMPLETED - EFG TEST SYSTEM OPERATIVE. - NEW CREEP DATA FOR STRESS ANALYSIS AVAILABLE. • EBIC ANALYSIS IS UNDERWAY TO QUANTIFY RELATIONSHIPS BETWEEN ELECTRICAL ACTIVITY AT DISLOCATIONS AND BULK L_N. • LOW RESISTIVITY SHEET DEFECTS CHARACTERIZATION HAS BEEN STARTED.

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Work in Progress

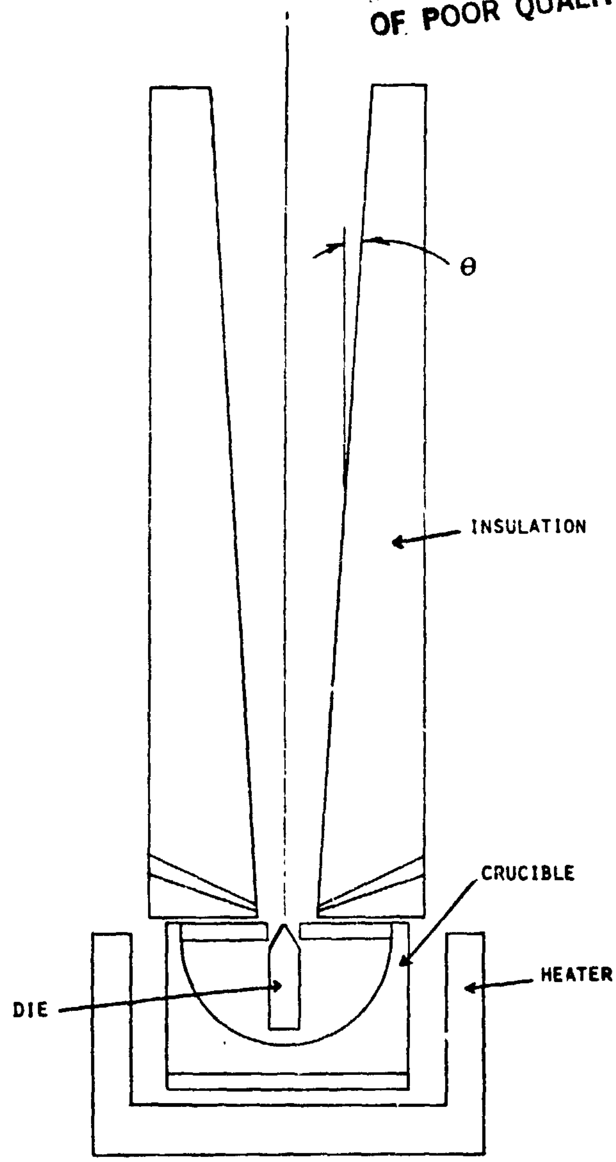
- DEFINITION OF MINIMUM STRESS SHEET GROWTH CONFIGURATIONS:
  - MODELING OF NEW EFG TEST SYSTEM GROWTH AND STRESS/DEFECT CHARACTERIZATION OF RIBBON.
  - EVALUATION OF NEW CREEP DATA FOR PREDICTING STRESS RELIEF.
- EBIC CHARACTERIZATION OF DEFECTS:
  - DEVELOPMENT OF HIGH RESOLUTION QUANTITATIVE MEASUREMENTS OF LOCAL L_N VARIATIONS.
  - ROOM AND LOW TEMPERATURE COMPARISON OF DISLOCATIONS.
- OPTICAL AND HREM STUDY OF DEFECTS IN HIGHLY DOPED ($\leq$ 1 Ω-CM) SHEET:
  - EFG RIBBON COMPARISON OF B, P GA DOPING EFFECTS.

Combined Thermal-Stress Analysis

- THERMAL ANALYSIS DEFINES OPERATING SPACE FOR GIVEN SYSTEM BOUNDARY CONDITIONS.

- SHEET TEMPERATURE PROFILES ARE GENERATED FOR GROWTH CONDITIONS.

- SHEET STRESS STATE IS RELATED TO OPERATING POINT; FIND:
  - STRESS LEVEL CHANGE WITH T, V_S DEPENDENT ON OPERATING POINT LOCATION.


θ
INSULATION
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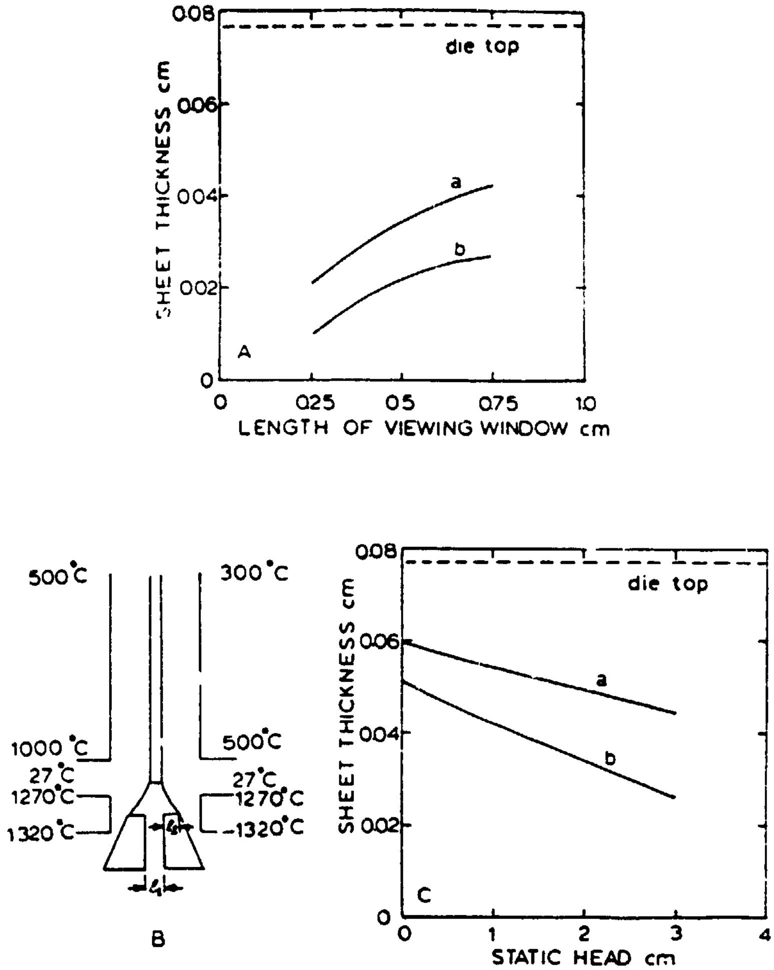
HEATER
DIE



(A) Effect of dimensions of the capillary spacing and die flats and length of the viewing slot on the sheet thickness for new system at capillary spacing (ℓ_1) of: (a) 0.0254 cm and (b) 0.0662 cm. (B) Asymmetric environment temperature distribution. (C) Dependence of the sheet thickness on the static head for (a) symmetric and (b) asymmetric heat transfer surroundings.

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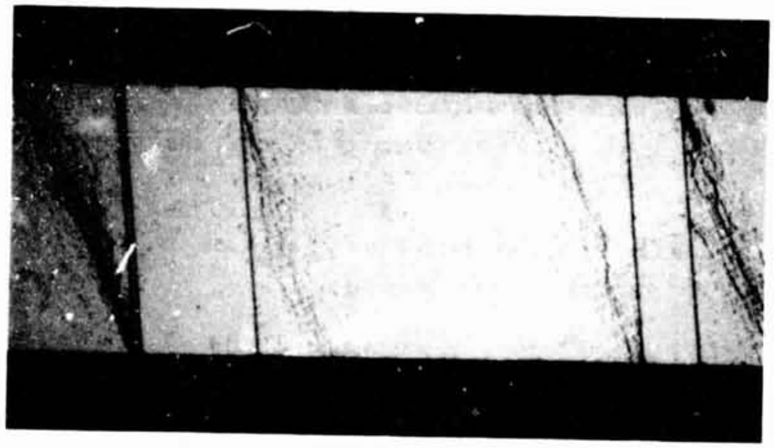
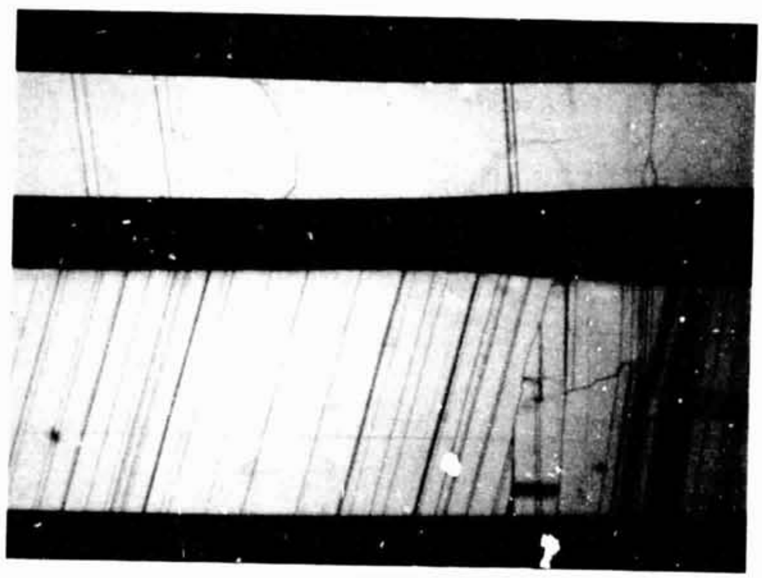


(a)

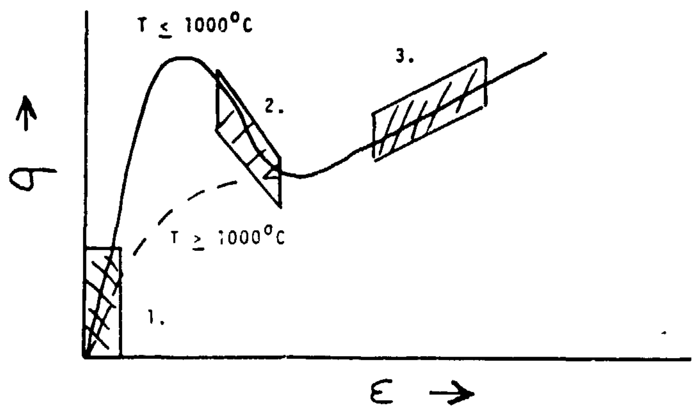


(b)

Fig. 2. EFG ribbon grown at 0.8-0.9 cm/min: (a) high magnification dislocated region of Lüders bands (thickness 0.23 mm); (b) low magnification dislocation-free regions of thin (0.36 mm) and thick (0.75 mm) ribbon.

New Creep Law Formulation

- SILICON SHEET RESPONDS AS A PLASTIC SOLID DURING STRESS TRANSIENTS TYPICAL OF EFG SHEET GROWTH ABOVE 1200°C.
- LIMITATIONS AT LOW STRESS ($\lesssim$ 5 MPA) ARE IMPOSED BY DISLOCATION/DEFECT DENSITIES:
  - CREEP RATE IS REDUCED ESSENTIALLY TO ZERO WITH N_D APPROACHING $1 \times 10^7/\text{CM}^2$.
  - TWIN BOUNDARIES, IMPURITIES PROVIDE ADDITIONAL CONSTRAINTS.
- AT HIGH STRESS LEVELS ($\geq$ 10 MPA) STRESS RELIEF IN EFG SHEET OCCURS BY LÜDERS OR SHEAR BAND FORMATION.



1. Primary Creep - Present Work

   $0 \leq \varepsilon \leq 10^{-2}$, $0 \leq \dot{\varepsilon} \leq 10^{-3}\ s^{-1}$

   $N_D \leq 5 \times 10^7/cm^2$

2. Lüders Bands (Mahajan et al., Acta Met. 27(1979) 1165.)

   Observed for T $\leq$ 1000°C

3. Secondary Creep - Steady-State

   $\varepsilon \geq 1 - 10\%$, $N_D \geq 10^8/cm^2$

Comparison of Secondary and Primary Creep Laws for Silicon Above 1200°C

Secondary (Steady-State) $\dot{\varepsilon}_{ij} = C[\exp(-\beta/T)/T]\ (\tau/\mu)^{n-1}\ S_{ij}$

Reference	C (°K/GPa-s)	β (°K)	n	$\dot{\varepsilon}$(s^{-1})*
"High Creep" Condition	1.05×10^{31}	59,760	5	1×10^{-4}
Siethoff and Shröter (1983)	5.85×10^{22}	41,800	3.6	41×10^{-4}

Primary (Transient) $\dot{\varepsilon}_{ij} = C\ (\sigma_e/\mu)^{n-1}\ S_{ij}$

Reference	C (GPa-s)$^{-1}$	n	$\dot{\varepsilon}$(s^{-1})**
Present Work (111) FZ	7.45×10^{31}	10	4.7×10^{3}

*Calculated strain rate for $\tau/\mu = 10^{-3}$ and T = 1300°K.

**Calculated strain rate for $\sigma_e/\mu = 10^{-3}$

$\sigma_e = \sqrt{(3/2)\ S_{ij}\ S_{ij}}$

$S_{ij} = \sigma_{ij} - 1/3\ \sigma_{kk}\ \delta_{ij}$

Stress Analysis

- INCORPORATION OF <u>VERY</u> HIGH CREEP RELAXATION ABOVE 1200°C:

  - $\sigma \simeq 0$ DOWN TO SOME $T_0 < T_M$.

- NEW THERMAL EXPANSION COEFFICIENT (Y. OKADA AND Y. TOKUMARA, J. APPL. PHYS., 56, 314 (1984)):

  $\alpha = 3.725 \times 10^{-6} \{1 - \exp[-5.88 \times 10^{-3} (T - 124)]\} + 5.548 \times 10^{-10}\ T\ (K^{-1})$.

New Creep Presentation

$\dot{\epsilon} \sim \infty,\ \sigma_{YY},\ \sigma_{XX} \simeq 0 \qquad T_M > T > T_0$

$\dot{\epsilon} = (C/T)\ [\exp(-\beta/T)]\ \sigma^5 \qquad T_0 > T > 300^{\circ}K$

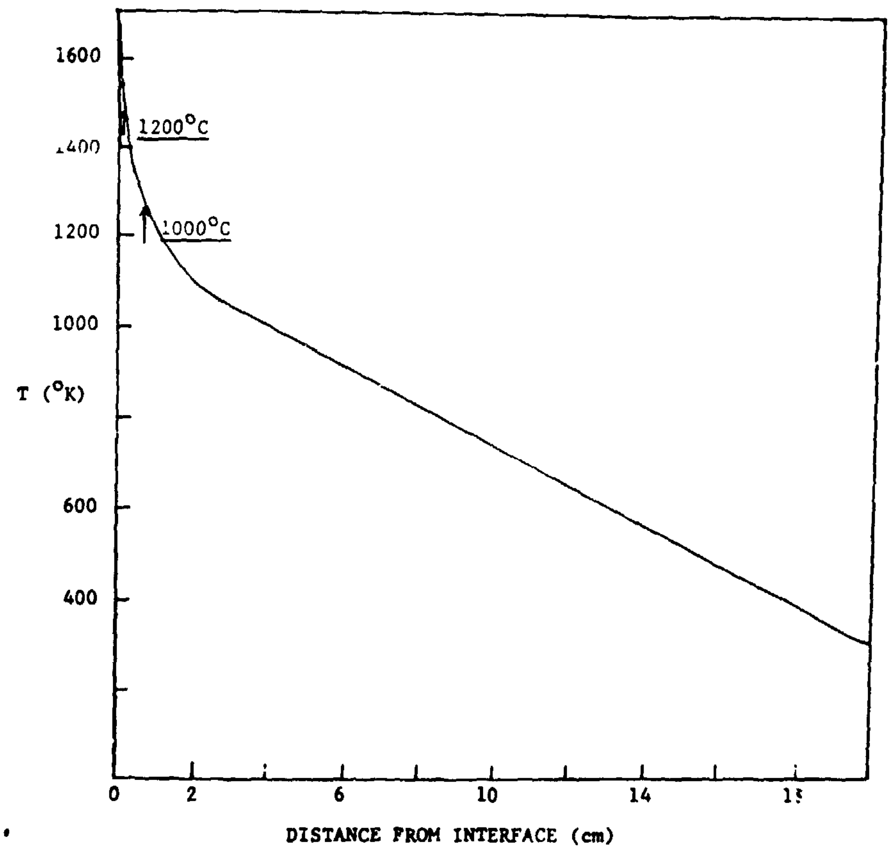
MODEL CASES

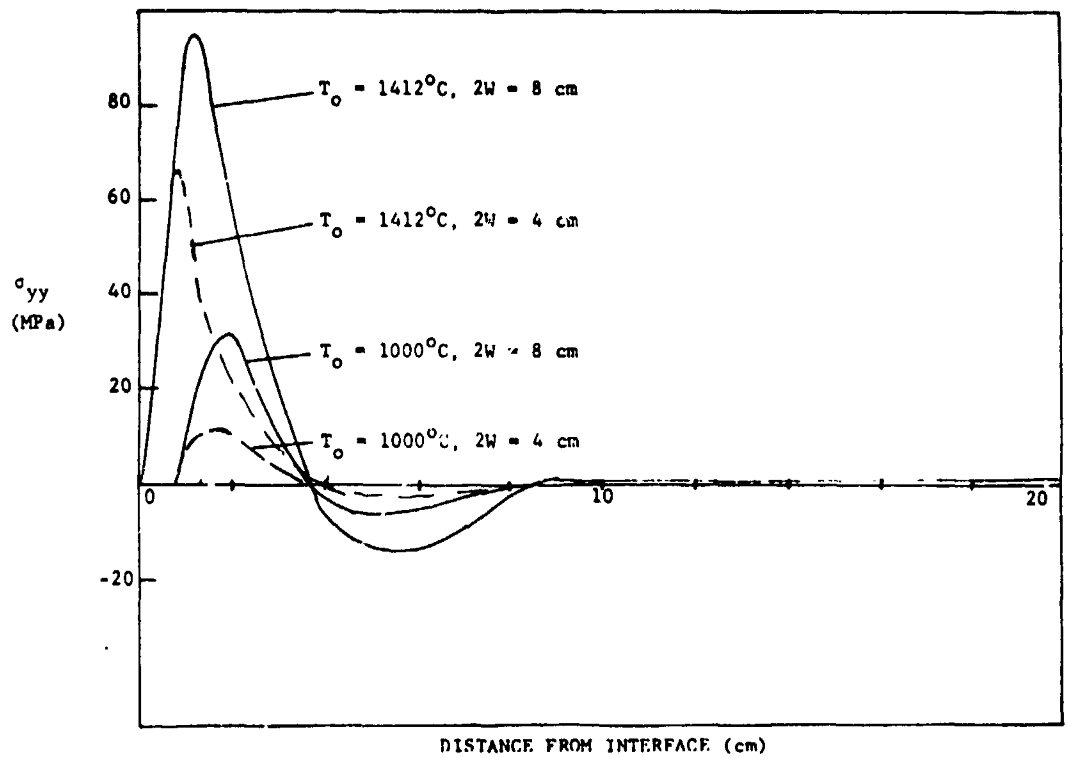
$T_0 = 1200^{\circ}C,\ 1000^{\circ}C$

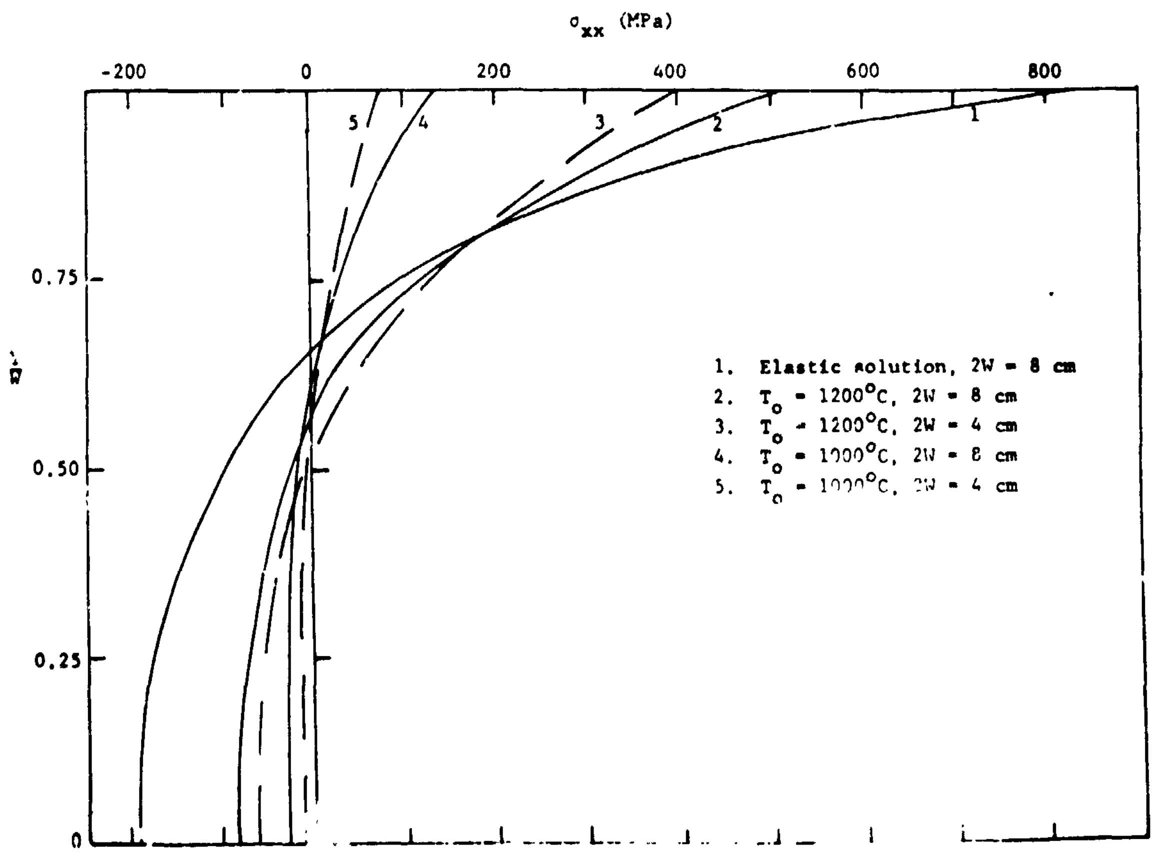
WIDTH = 8 CM, 4 CM

GROWTH SPEED = 3 CM/MIN

HIGH CREEP CONDITION




σ_{yy} (MPa)
80
60
40
20
-20
0
10
20
T_o = 1412°C, 2W = 8 cm
T_o = 1412°C, 2W = 4 cm
T_o = 1000°C, 2W = 8 cm
T_o = 1000°C, 2W = 4 cm
DISTANCE FROM INTERFACE (cm)

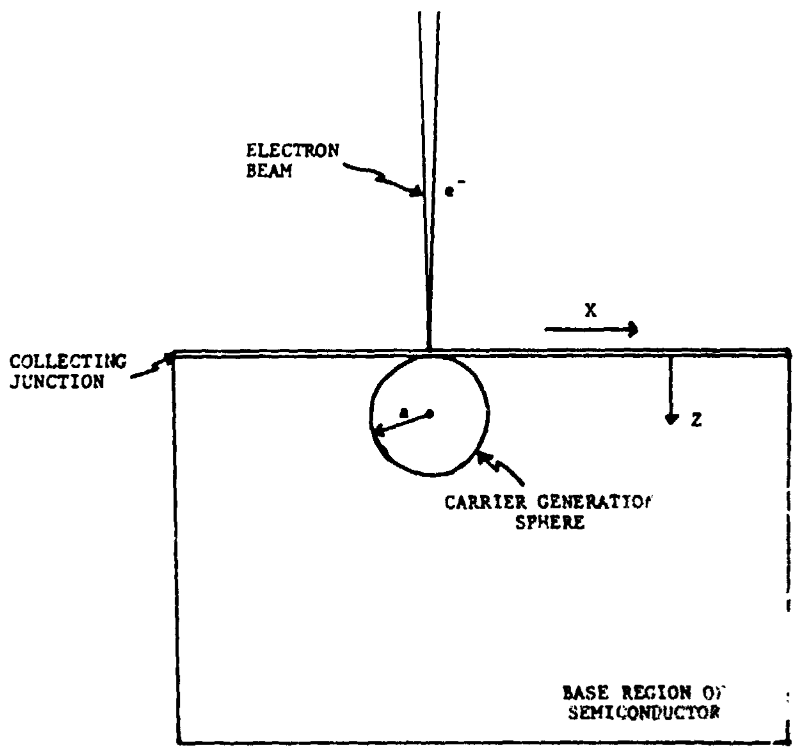

σ_{xx} (MPa)
-200
0
200
400
600
800
0.75
0.50
0.25
0
1. Elastic solution, 2W = 8 cm
2. T_o = 1200°C, 2W = 8 cm
3. T_o = 1200°C, 2W = 4 cm
4. T_o = 1000°C, 2W = 8 cm
5. T_o = 1000°C, 2W = 4 cm

Dislocation-Efficiency Studies

- DEVELOP METHODS TO QUANTIFY INFLUENCE OF DISLOCATION ELECTRICAL ACTIVITY ON BULK LIFETIME WITH ROOM AND LOW TEMPERATURE EBIC.

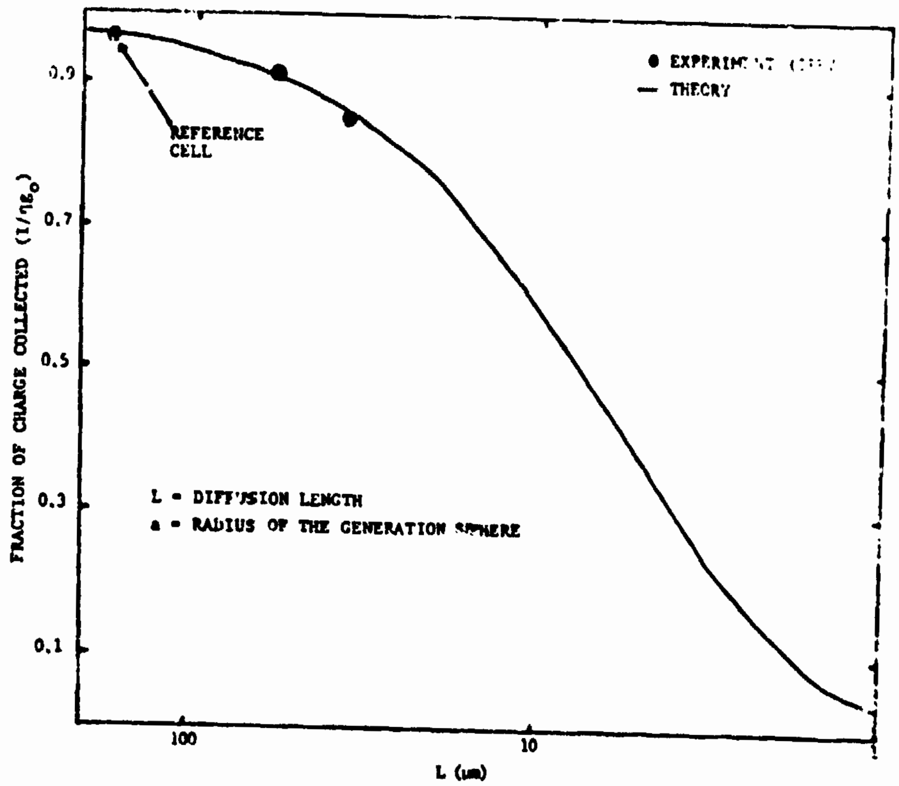
- STUDY EFFECTS OF DISLOCATION DENSITY, STRESS LEVEL AND TEMPERATURE OF GENERATION OF DISLOCATIONS ON BULK LIFETIME.

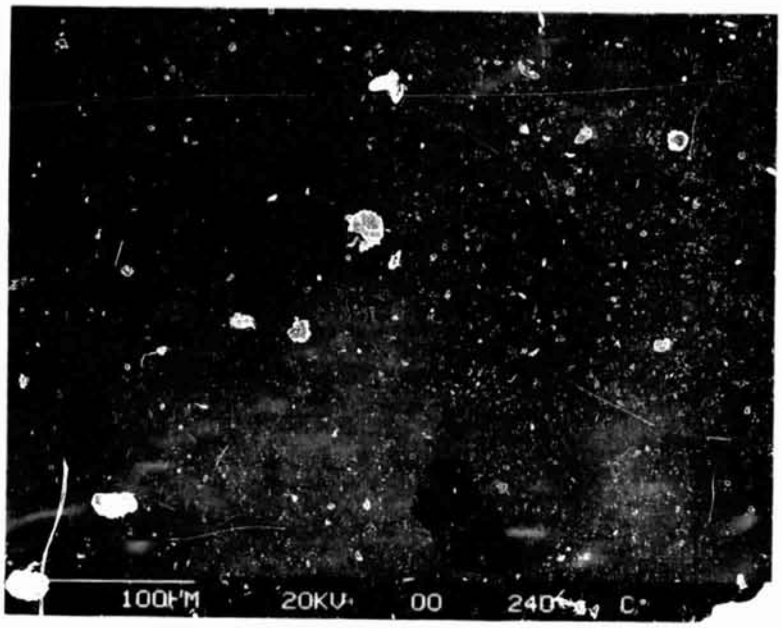
WORK IN PROGRESS - COMPARISON OF STRESSED FZ, CZ AND EFG RIBBON.



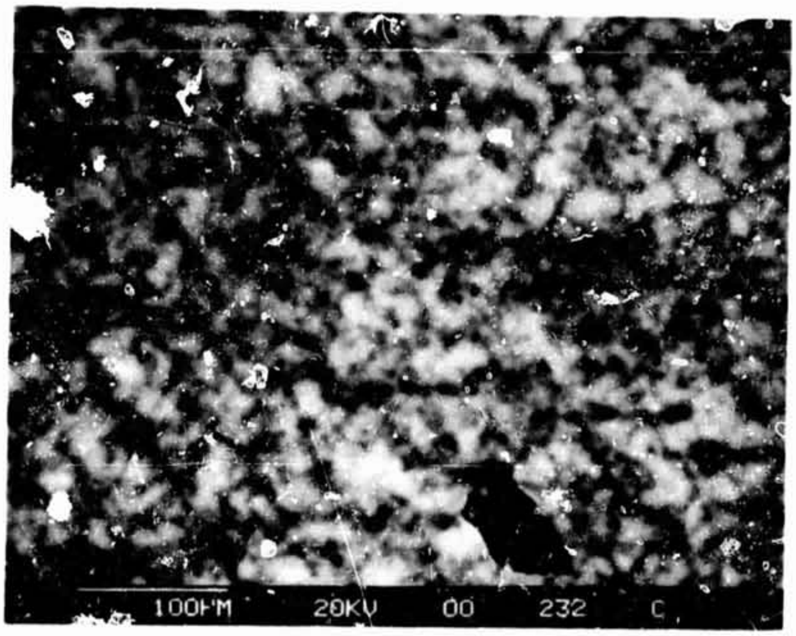
$I = 3qg_o\ (L/a)^3\ e^{-a/L}\ [a/L \cosh a/L - \sinh a/L]$

C. Donolato, Optik, 52, 19 (1979)





(a)



(b)

Fig. 12. (a) Room temperature, and (b) low temperature EBIC of same region for stressed carbon-rich CZ.

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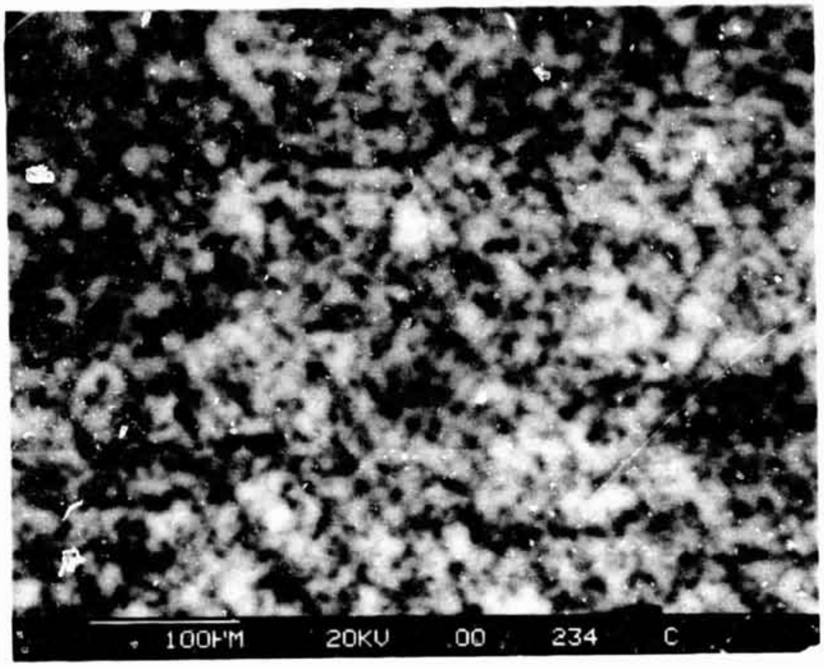
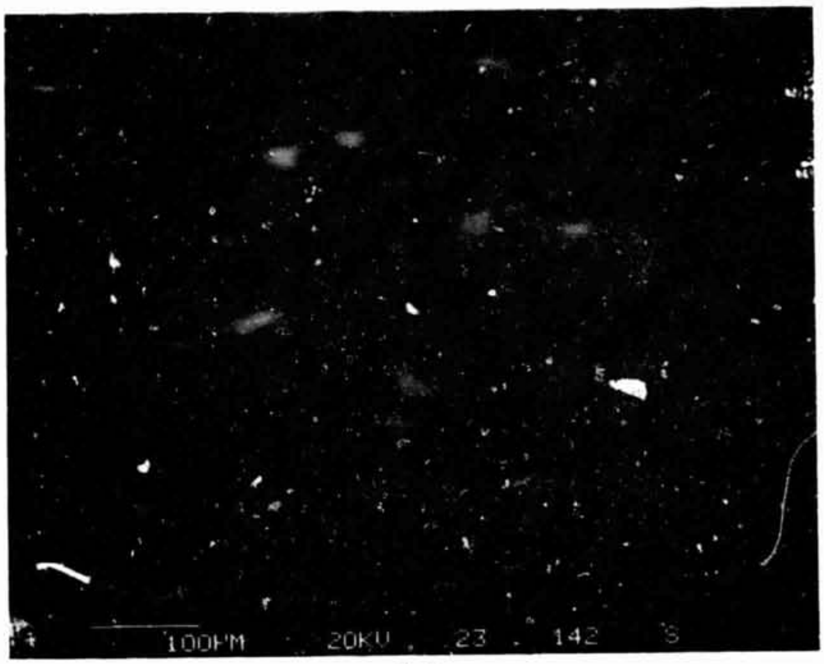


(a)



(b)

Fig. 11. Low temperature EBIC micrographs of (a) center and (b) edge of stressed carbon-doped CZ wafer.

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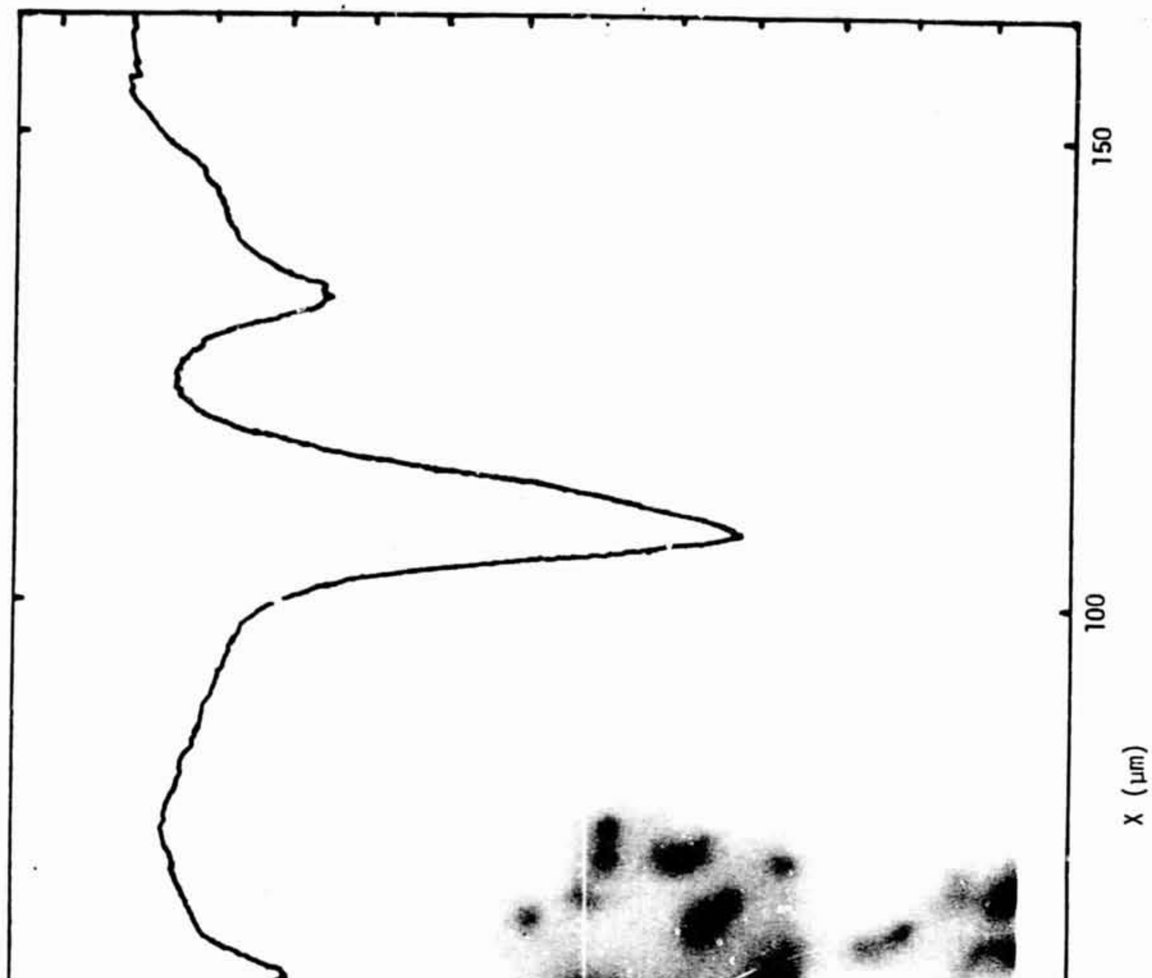


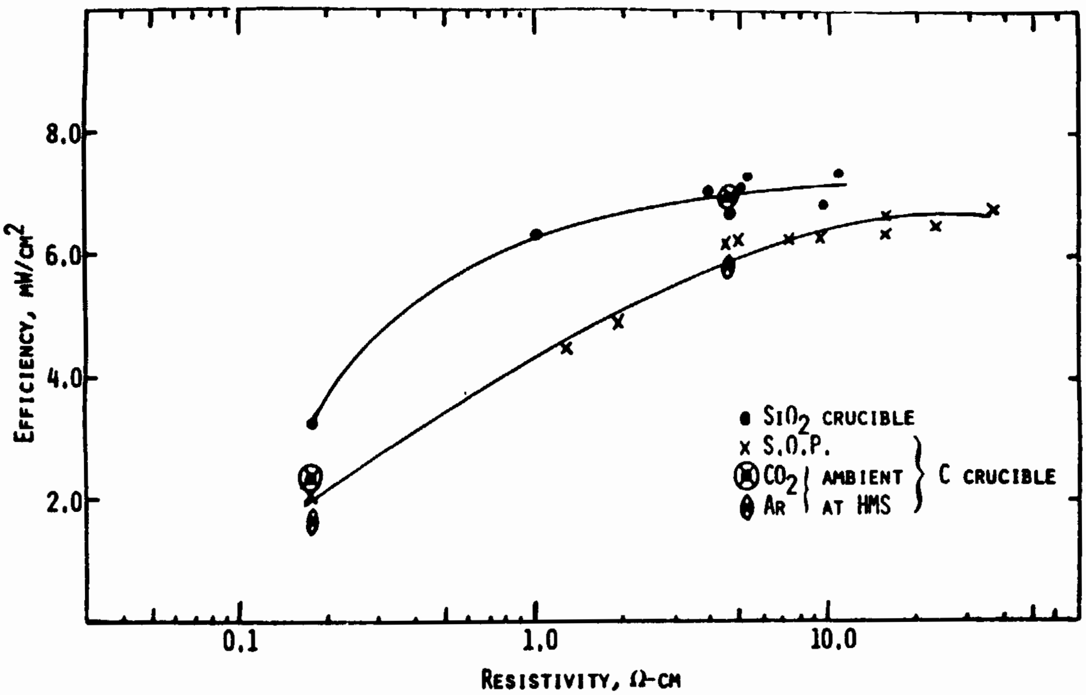
Fig. 8. High magnification (500X) low temperature EBIC line scan of stressed carbon-doped CZ.

Low Resistivity Studies

- POWER OUTPUT OF SILICON SOLAR CELLS MAXIMIZED BELOW 1 Ω-CM, BUT SEVERE DEGRADATION OF I_{SC}, V_{OC} OCCURS IN MORE DEFECTED SILICON BELOW 1 Ω-CM.

- BORON-IMPURITY-DEFECT INTERACTIONS LEADING TO DEFECTS RESPONSIBLE FOR DEGRADATION HAVE NOT BEEN STUDIED.

- PURPOSE IS TO CHARACTERIZE LOW RESISTIVITY MATERIAL DEFECT STRUCTURE AND ATTEMPT TO RELATE IT TO DEGRADATION.



EFFICIENCY AS A FUNCTION OF RESISTIVITY IN EFG MATERIAL, B-DOPING, GROWTH FROM FUSED SILICA AND GRAPHITE CRUCIBLES. AMBIENT EFFECTS WITH GRAPHITE CRUCIBLE GROWTH ARE NOTED IN THE FIGURE.

Problems and Concerns

- RESIDUAL STRESS MEASUREMENTS NEED TO BE RELATED TO GROWTH VARIABLES.
- DISLOCATION ELECTRICAL ACTIVITY DEPENDENCE ON:
  - TEMPERATURE AT WHICH THEY WERE FORMED.
  - CARBON, OXYGEN IMPURITY AVAILABILITY.
  - CELL PROCESSING VARIABLES.
- LOW RESISTIVITY DEGRADATION MECHANISMS IN MORE HIGHLY DEFECTED SILICON MUST BE AVOIDED.

Future Work

- ANALYSIS TO DEFINE MINIMUM STRESS CONFIGURATIONS:
  - STUDY EFFECTS OF NEW CREEP LAW AND PREDICTIONS FOR EFG TEST SYSTEM.
  - TEMPERATURE FIELD CHARACTERIZATION.
  - RESIDUAL STRESS-DEFECT EVALUATION OF RIBBON (U. OF ILLINOIS).
- ROOM AND LOW TEMPERATURE EBIC CORRELATION OF DISLOCATION STRUCTURE AND ELECTRICAL ACTIVITY WITH BULK L_N.
- CHARACTERIZE LOW RESISTIVITY SILICON MATERIAL:
  - DISLOCATION STRUCTURE WITH VARYING LEVELS OF DOPING, (B, B-GA).
  - HREM (CORNELL) STUDY OF MICRODEFECTS.