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STRESS AND EFFICIENCY STUDIES IN EFG

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TECHNOLOGY

ADVANCED MATERIALS RESEARCH TASK

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APPROACH

STRESS AND EFFICIENCY STUDIES IN EFG

CONTRACTOR

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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.

STATUS

- 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.

Work in Progress

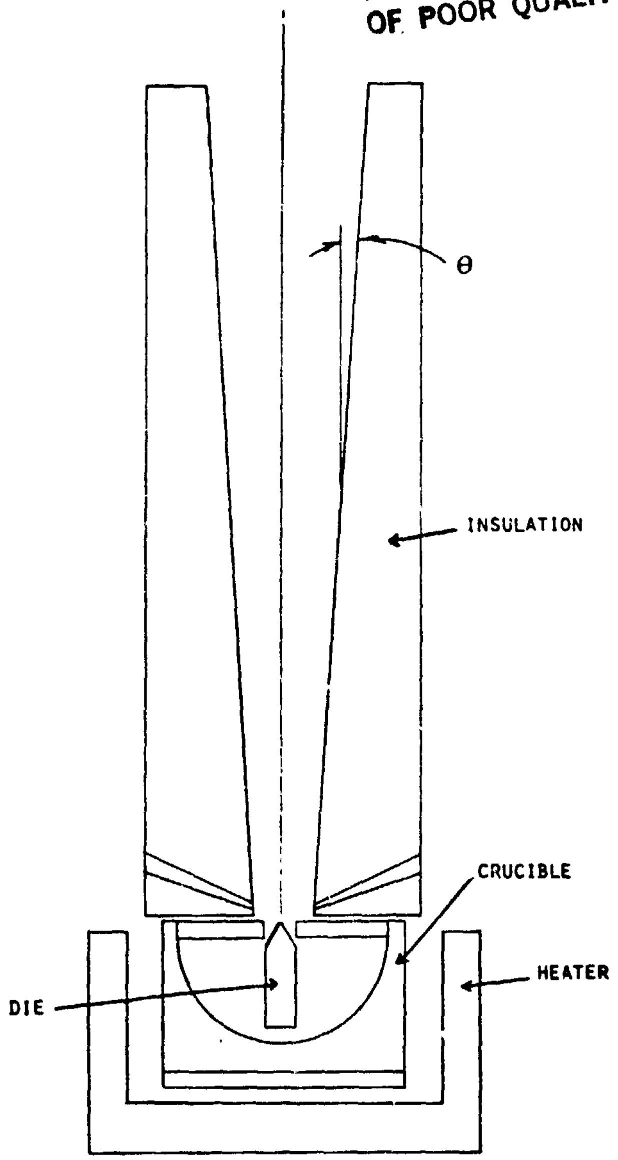
- DEFINITION OF MINIMUM STRESS SHEET GROWTH CONFIGURATIONS:
  - MODELING OF NEW EFG TEST SYSTEM GROWTH AND STRESS/DEFECT CHARACTERIZATION OF RIBBON.
  - EVALUATION OF NEW CREEP DATA FOR PREDICTING STRESS RELIEF.
- EBIC CHARACTERIZATION OF DEFECTS:
  - DEVELOPMENT OF HIGH RESOLUTION QUANTITATIVE MEASUREMENTS 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, & 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.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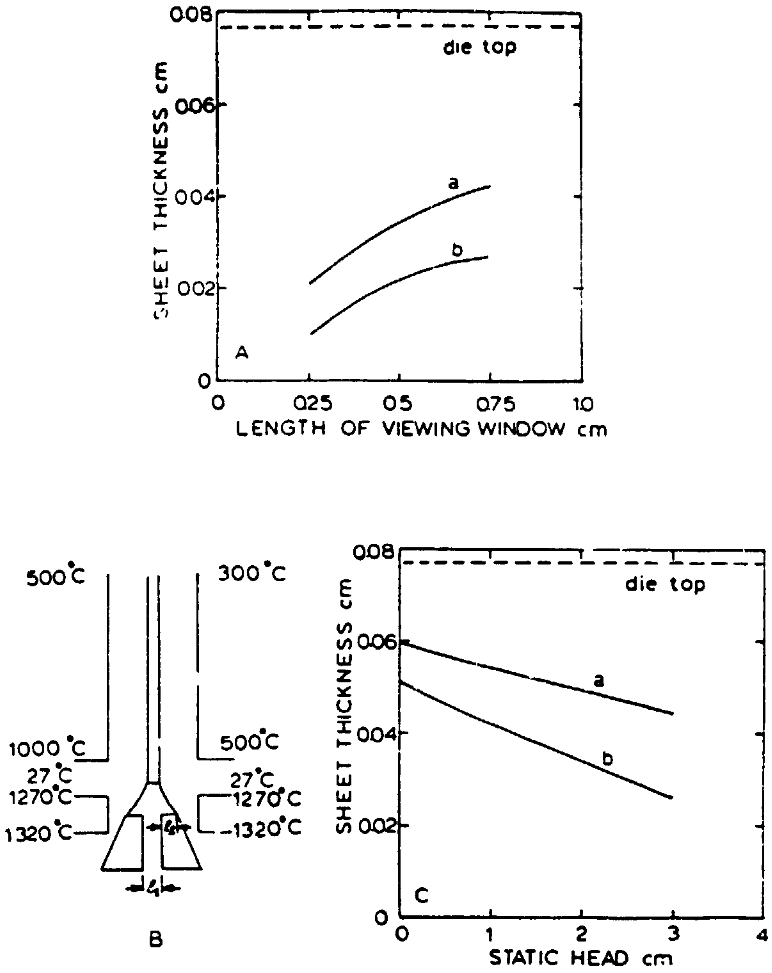
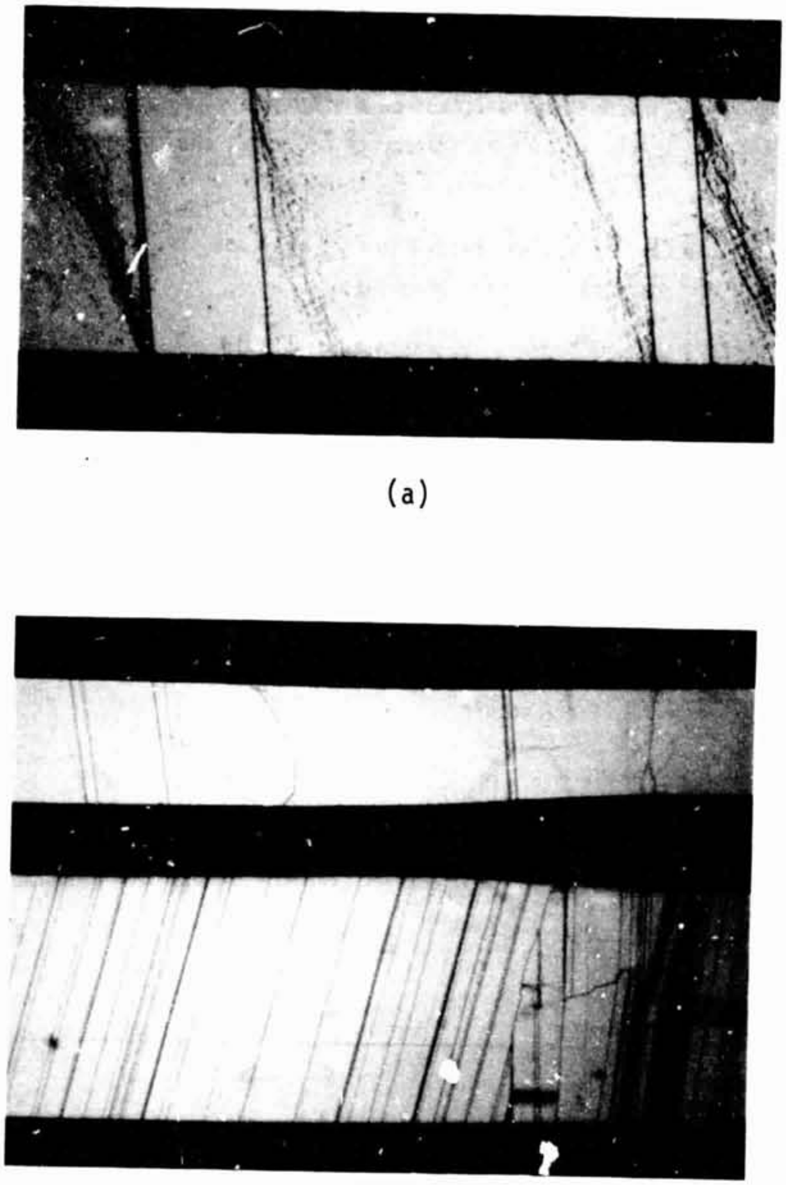


(A) Effect of dimensions of the capillary spacing and die flats and length of the viewing slot on the sheet thickness for new system at capillary spacing (ℓ_1) of: (a) 0.0254 cm and (b) 0.0662 cm. (B) Asymmetric environment temperature distribution. (C) Dependence of the sheet thickness on the static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



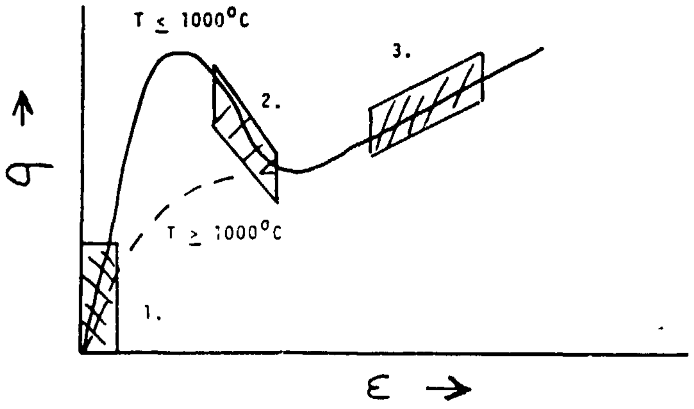
(a)

(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 $1 \times 10^7/\mathrm{CM}^2$.
  - TWIN BOUNDARIES, IMPURITIES PROVIDE ADDITIONAL CONSTRAINTS.
- AT HIGH STRESS LEVELS (≥ 10 MPA) STRESS RELIEF IN EFG SHEET OCCURS BY LÜDERS OR SHEAR BAND FORMATION.



1. Primary Creep - Present Work

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

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

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

   Observed for $T \leq 1000°\mathrm{C}$

3. Secondary Creep - Steady-State

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

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

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*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 $T_O < T_M$.

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

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

New Creep Presentation

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

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

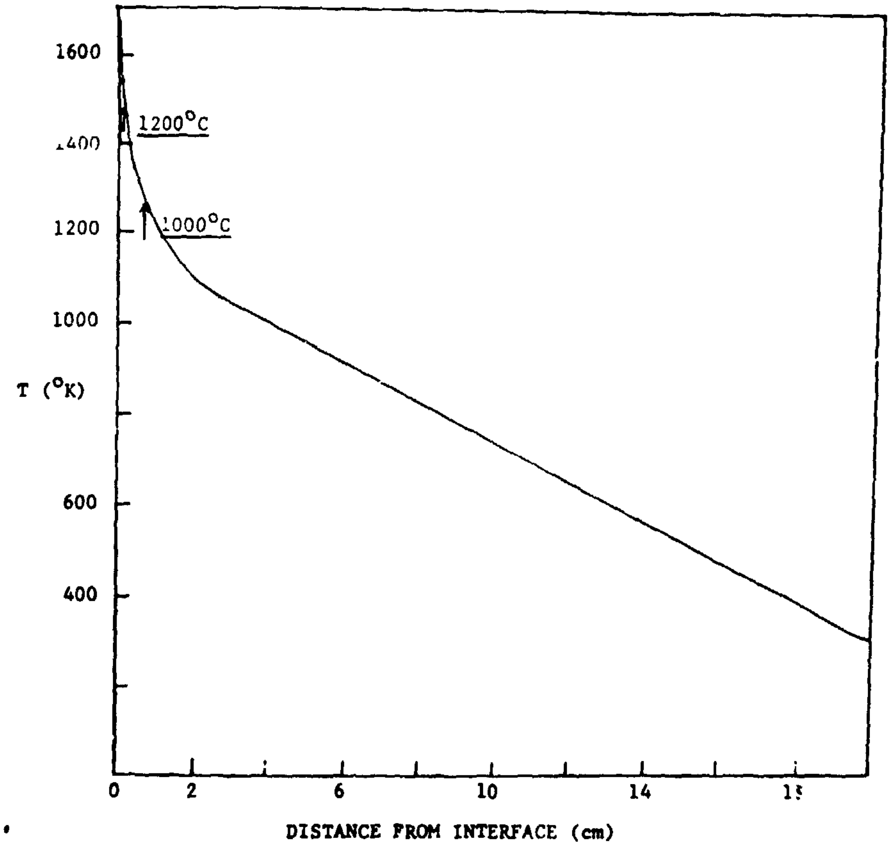
<u>MODEL CASES</u>

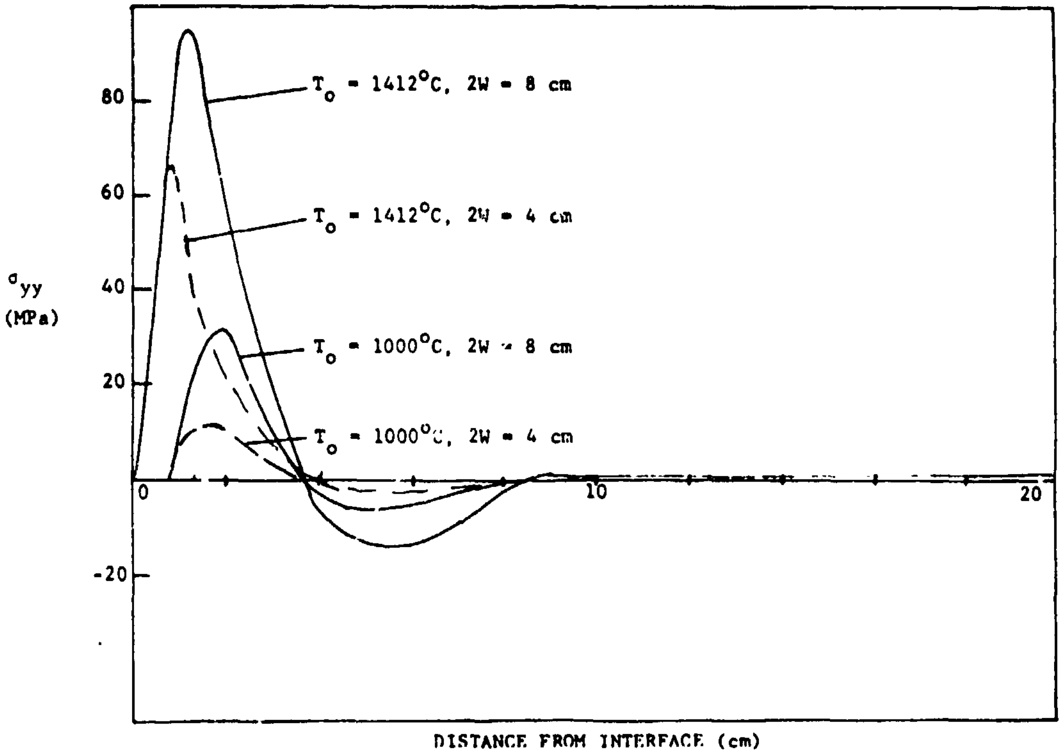
$T_0 = 1200^\circ C,\ 1000^\circ C$

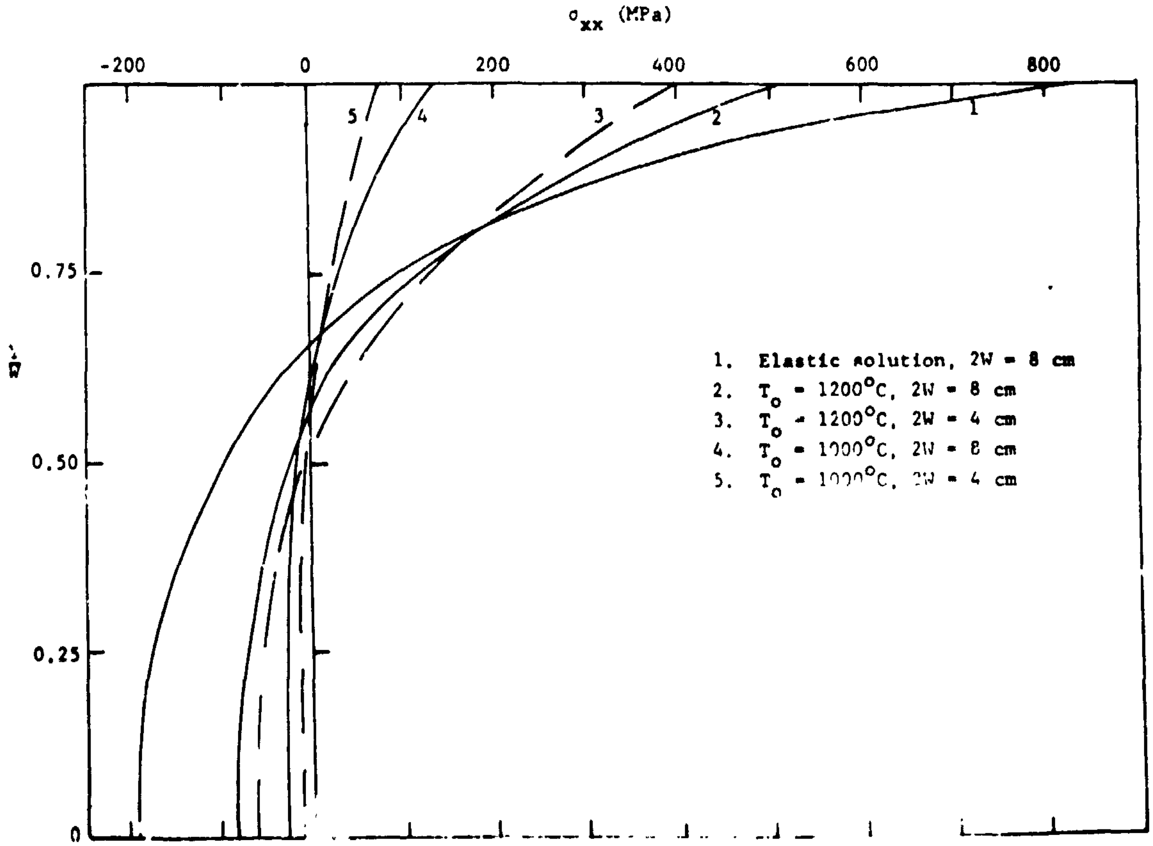
WIDTH = 8 CM, 4 CM

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)

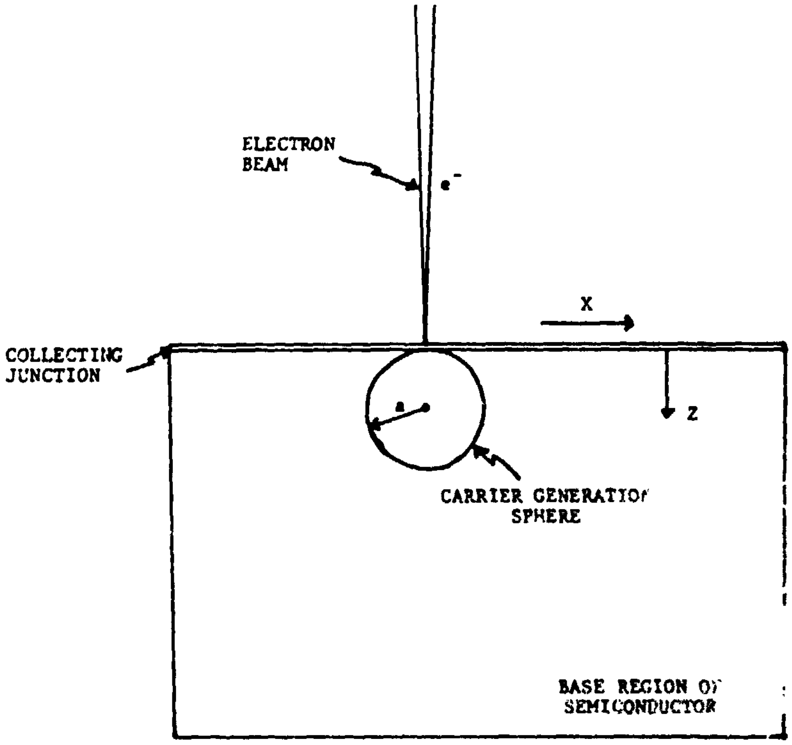

σ_{xx} (MPa)
-200
0
200
400
600
800
0.75
0.50
0.25
0
y/W
5
4
3
2
1
1. Elastic solution, 2W = 8 cm
2. T_o = 1200°C, 2W = 8 cm
3. T_o = 1200°C, 2W = 4 cm
4. T_o = 1000°C, 2W = 8 cm
5. T_o = 1000°C, 2W = 4 cm

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.

<u>WORK IN PROGRESS</u> - COMPARISON OF STRESSED FZ, CZ AND EFG RIBBON.



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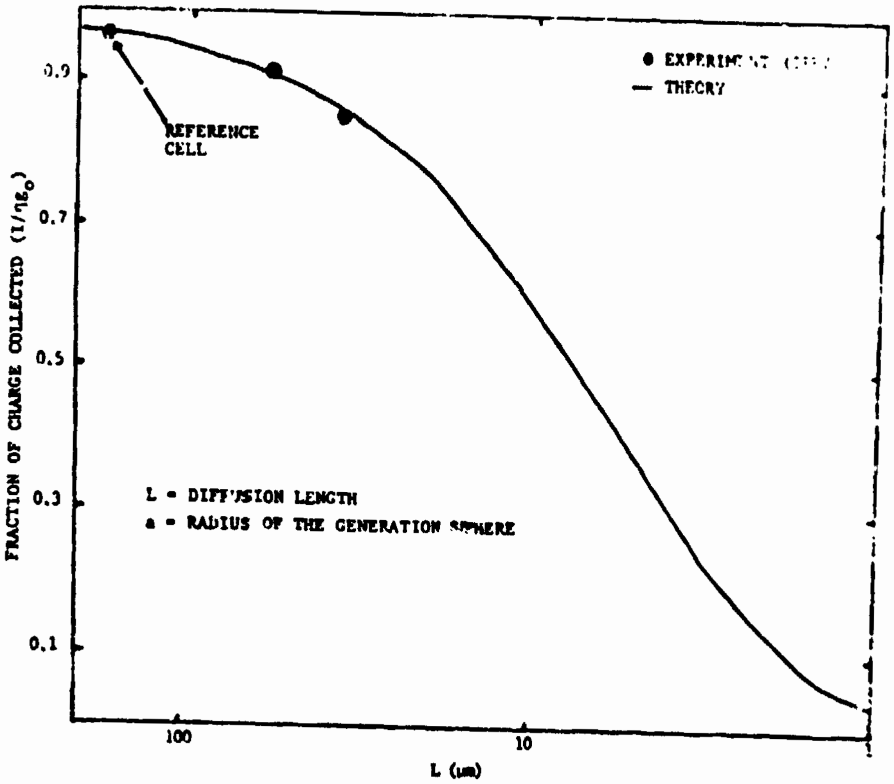
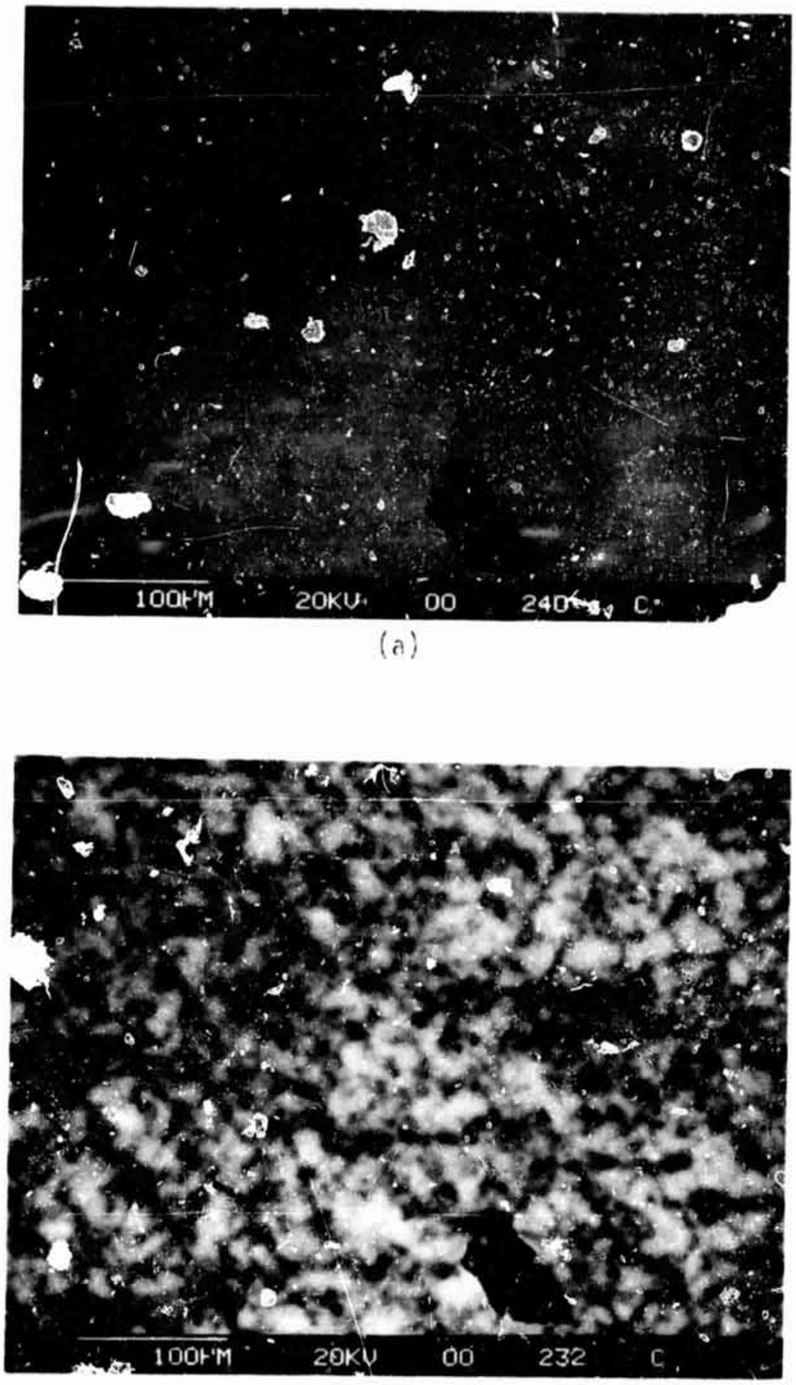
$I = 3qg_0\,(L/a)^3\,e^{-a/L}\,[a/L \cosh a/L - \sinh a/L]$

C. Donolato, Optik, 52 19 (1979)

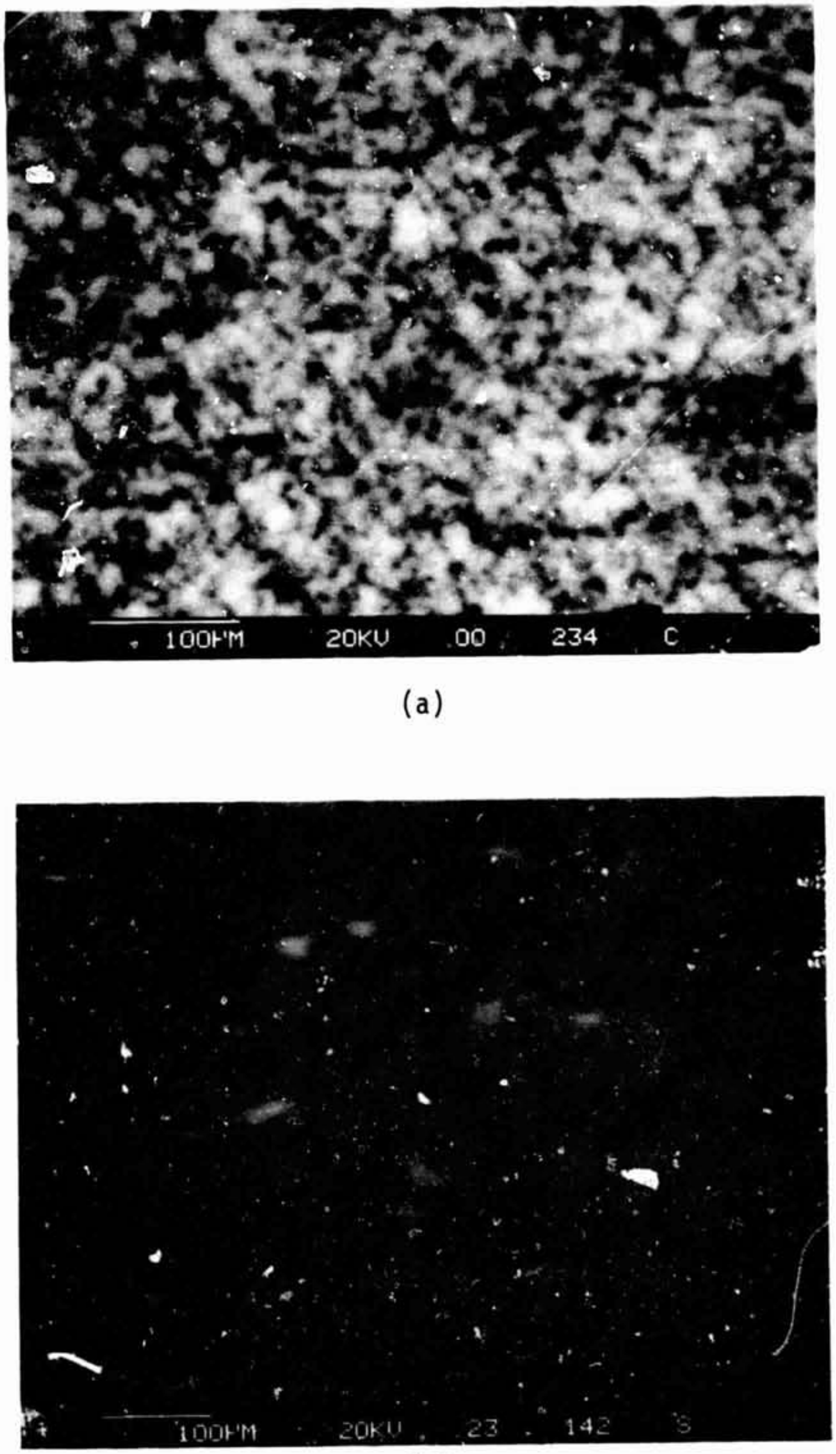




(a)

(b)

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



(a)

(b)

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

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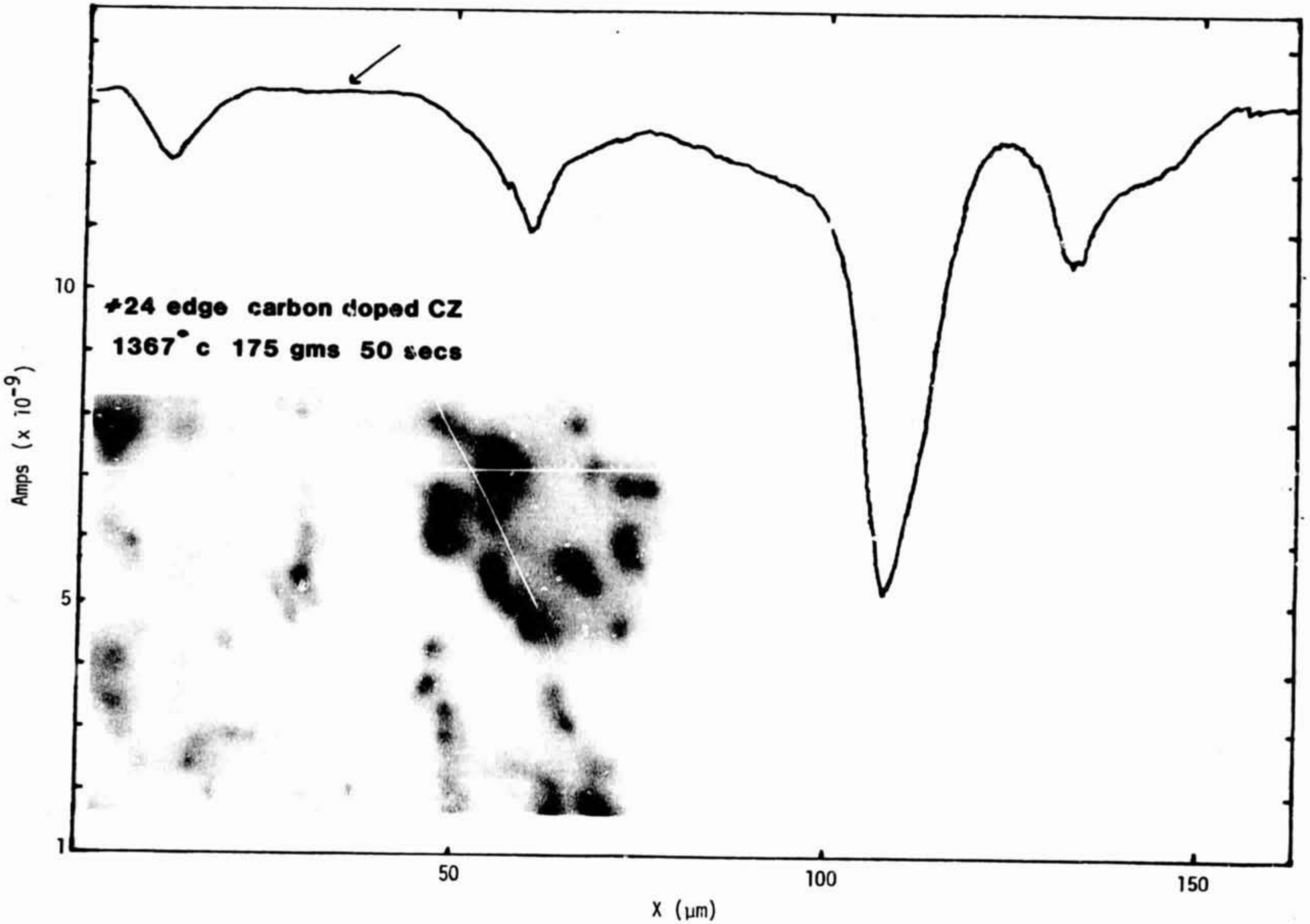


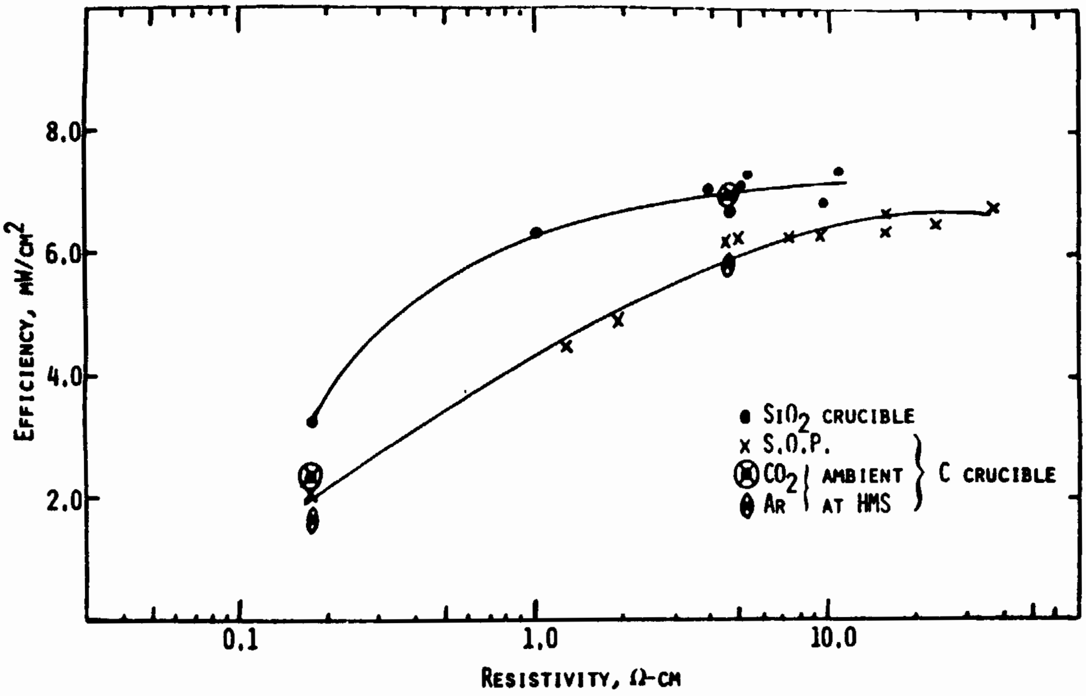
Fig. 8. High magnification (500X) low temperature EBIC line scan of stressed carbon-doped CZ.

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.