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SILICON STRESS/STRAIN ACTIVITIES AT JPL

JET PROPULSION LABORATORY

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Contents

- Highlight the important accomplishments of in-house efforts including:
  - Fracture Mechanics of Si
  - Stress/Strain Analysis
  - Thermal analysis
  - High Temperature Testing
- Recommend future work

Rationale: Fracture Mechanics of Silicon

- THE CRACKING CELL IS ONE OF THE MAJOR SOURCES OF SOLAR PANEL REJECTION AND FAILURE THAT CONTROL THE COST.
- F.M. DATA OF Si ARE CRITICALLY IMPORTANT FOR THE DESIGN OF RELIABLE SOLAR CELLS. NO DATA WAS AVAILABLE.

Objectives I: Fracture Mechanics

- DEVELOP FRACTURE MECHANICS (F.M.) METHODOLOGY
- GENERATE F.M. DATA
- CHARACTERIZE CRACK PROPAGATION IN Si

Key Accomplishments of Fracture Mechanics of Silicon

- Developed a "Standard test method for silicon solar cell strength" by a four-point twisting method. This method has been implemented in many PV manufacturers.
- Developed test methodology and generated FM data of Si. Results of this pioneering effort have enhanced production yields; improved cell reliability and durability and established mechanical design criteria which has reduced cell cost.
- FM technique has been utilized to modelling the silicon ingot wafering and to predict the limits and to improve the wafering conditions.
- FM technology has been recently extended to other semiconductors (e.g. GaAs).
- Published more than 30 papers in the area of FM of Si. Established a technology base at JPL on the fracture mechanics of Si.

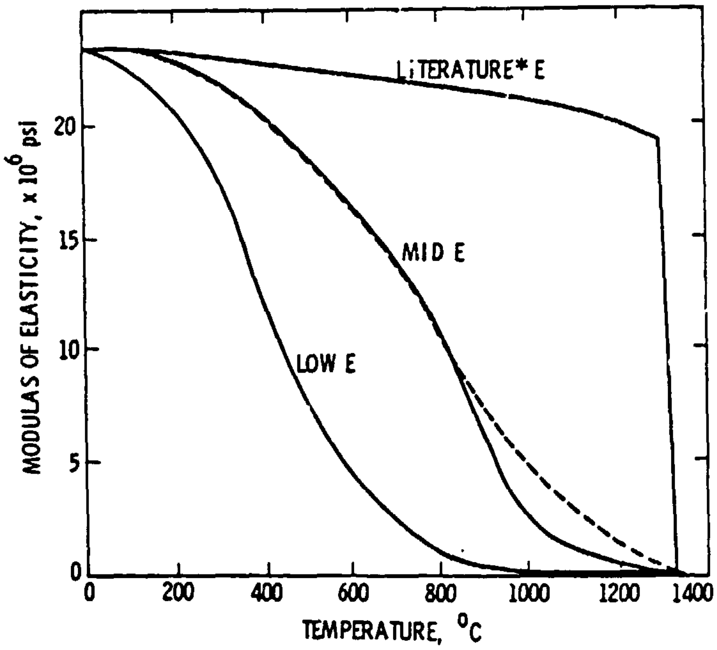
Future Work — I: Fracture Mechanics of Silicon

1. The effect of plastic zone propagation on the crack extension silicon at several temperatures.
2. Creep deformation of Si sheet at high temperature.
3. Fracture mechanics properties of other semiconductor materials (e.g., GaAs, Cd Te, InP).

Objective II: Nonlinear Stresses Analysis of Silicon Web

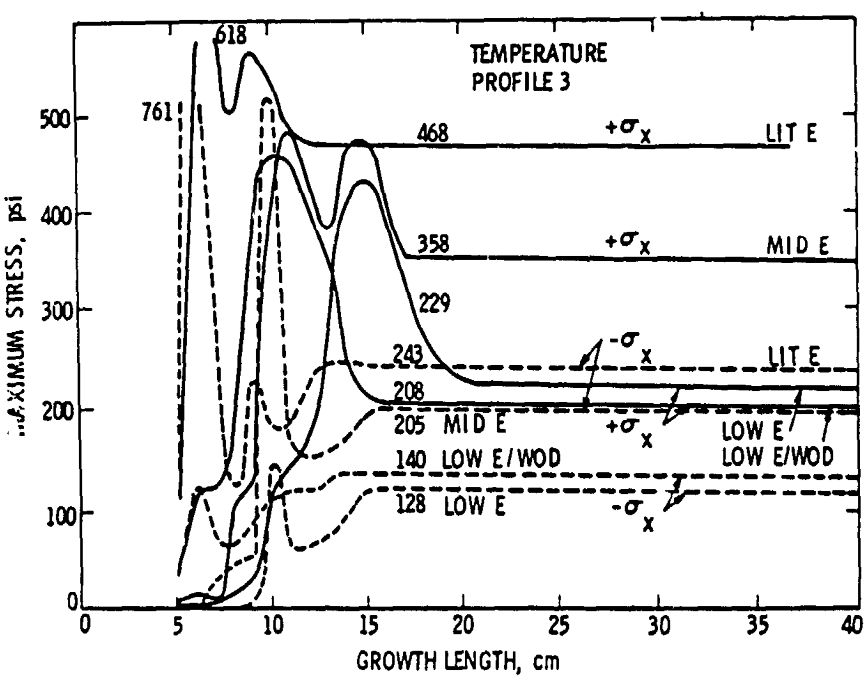
TO DETERMINE AN OPTIMAL TEMPERATURE PROFILE IN A WEB SUCH THAT THE DETRIMENTAL STRESSES ARE MINIMAL.

Modulus of Elasticity



* TEMPERATURE DEPENDANCE OF ELASTIC CONSTANTS OF SILICON, BY Yu A. BARENKOV AND S. P. NIKANOROV SOV. PHYS. SOLID STATE, VOL 16, No. 5, NOV 1974

Maximum Stresses



Steady State Maximum Stresses Versus Temperature Profile

(LOW E CASE)

MAX STRESS / TEMP PROFILE	σx psi		σy	
	TENSION	COMPRESSION	TENSION	COMPRESSION
4	251	82	332	400
1	295	165	487	575
2	435	154	512	618
3	229	128	522	604

(LITERATURE E)

MAX STRESS / TEMP PROFILE	σx		σy	
	TENSION	COMPRESSION	TENSION	COMPRESSION
3	468	243	911	1027
4	1747	775	2913	2114

Conclusion

- DETRIMENTAL STRESS ARE HIGHLY DEPENDENT UPON MATERIAL PROPERTIES
- STEADY STATE MAXIMUM σ_x (IN WIDTH WISE) IS ALWAYS LESS THAN TRANSIT STATE MAXIMUM AND MAXIMUM σ_y (IN LENGTH WISE) IS GRADUALLY INCREASED TO STEADY STATE MAXIMUM WITH GROWTH
- THE OPTIMAL TEMPERATURE PROFILE IS DEPENDENT UPON MATERIAL PROPERTIES (E, σ_y, α etc.)

Future Work Planned — II

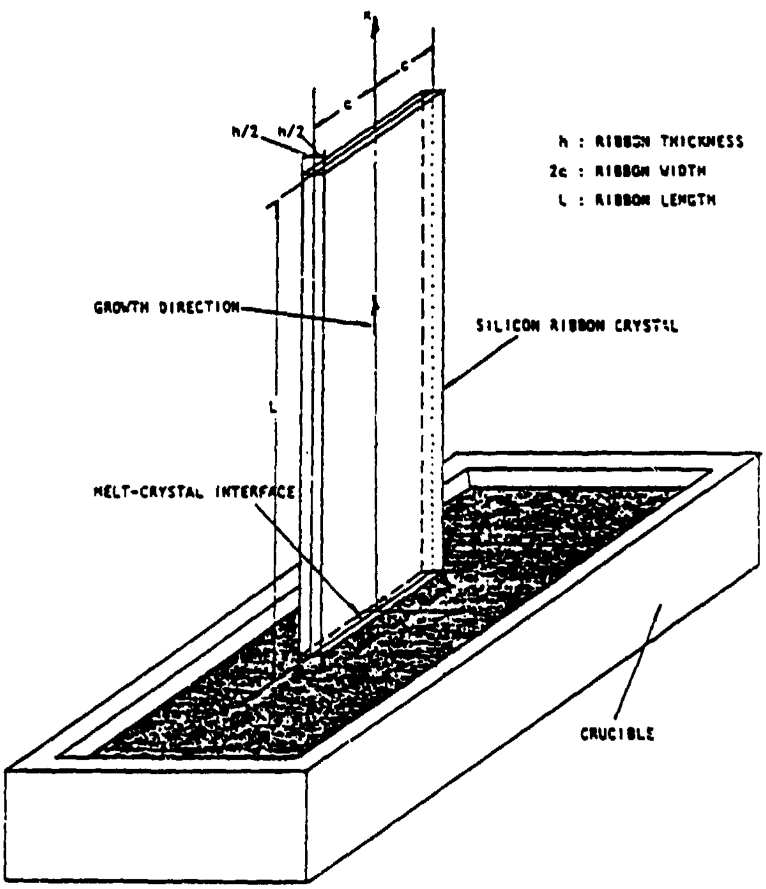
1) MORE MATERIAL PROPERTIES IN $20^{0}C - 800^{0}C$
2) LOCAL BUCKLING BEHAVIOR, STRESS STIFFNESS AND ITS EFFECTS IN BUCKLING MODES.
3) EFFECT OF WEB SIZE, PULL-UP SPEED

Objective III: Thermal Analysis

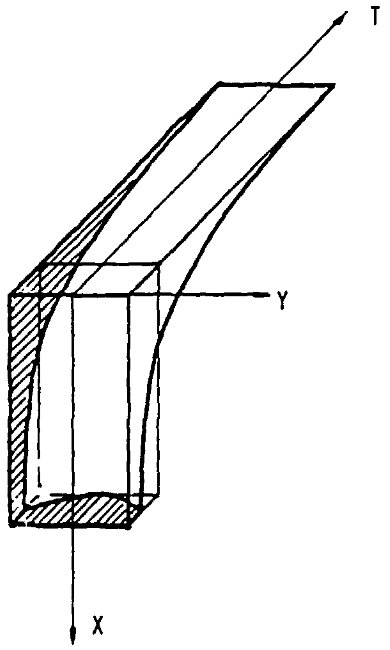
Analytical simulation of thermal stresses distribution in WEB during growth process.

Geometry of Ribbon and the Reference Coordinate System

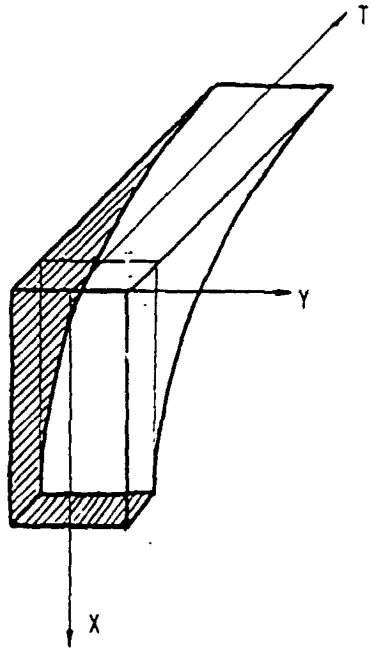
PLANE STRESS PROBLEM



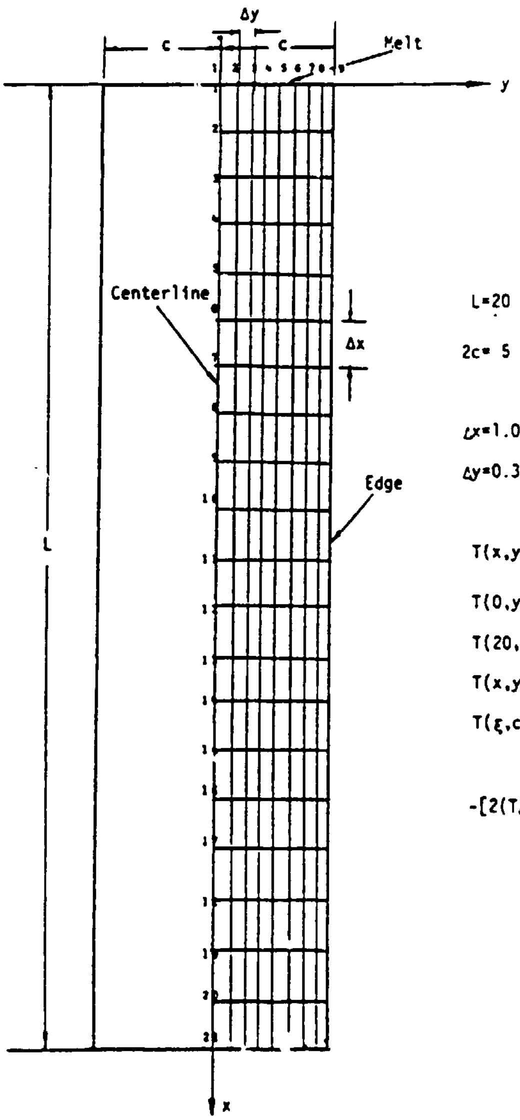
Frowning Temperature Distribution
No Thermal Stresses Develop



Uniform Temperature Distribution
Thermal Stresses Develop



Keysketch for Determining Temperature Distribution Satisfying $\Delta^2 T = 0$



L=20 cm

2c= 5 cm

$\Delta x = 1.0$ cm

$\Delta y = 0.3125$ cm

T(x,y) Temperatures

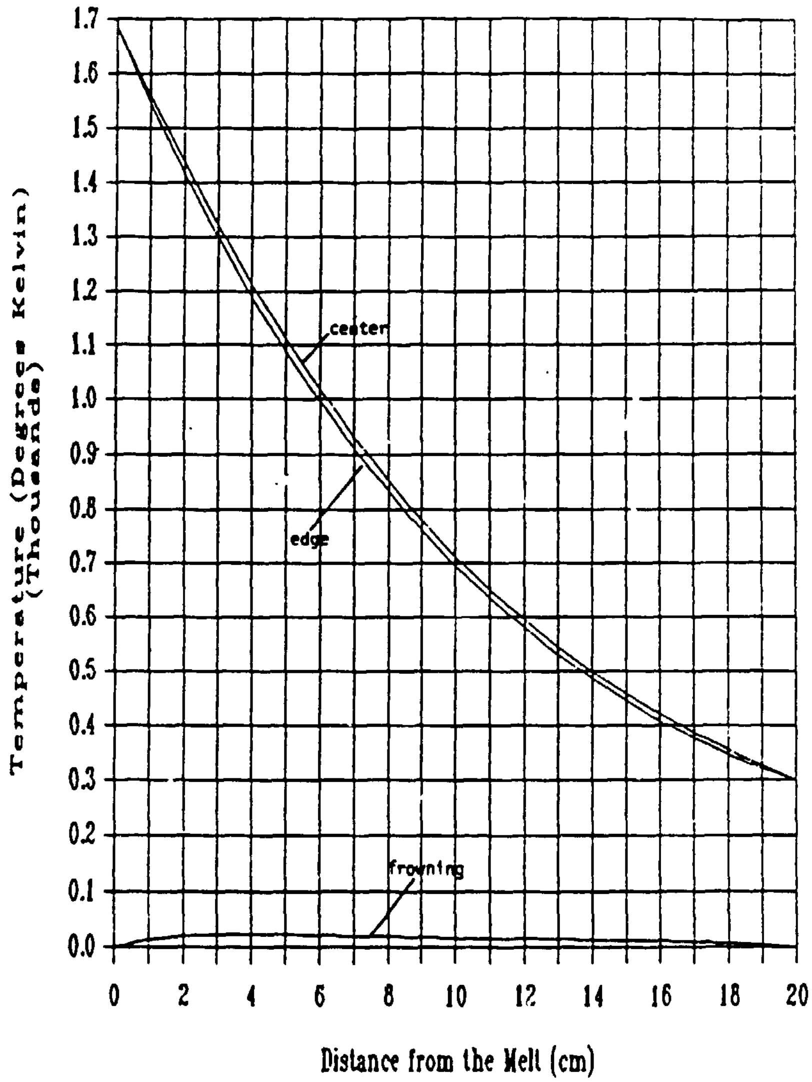
$T(0,y) = 1685°K$

$T(20,y) = 300°K$; $T_\infty = 700°K$

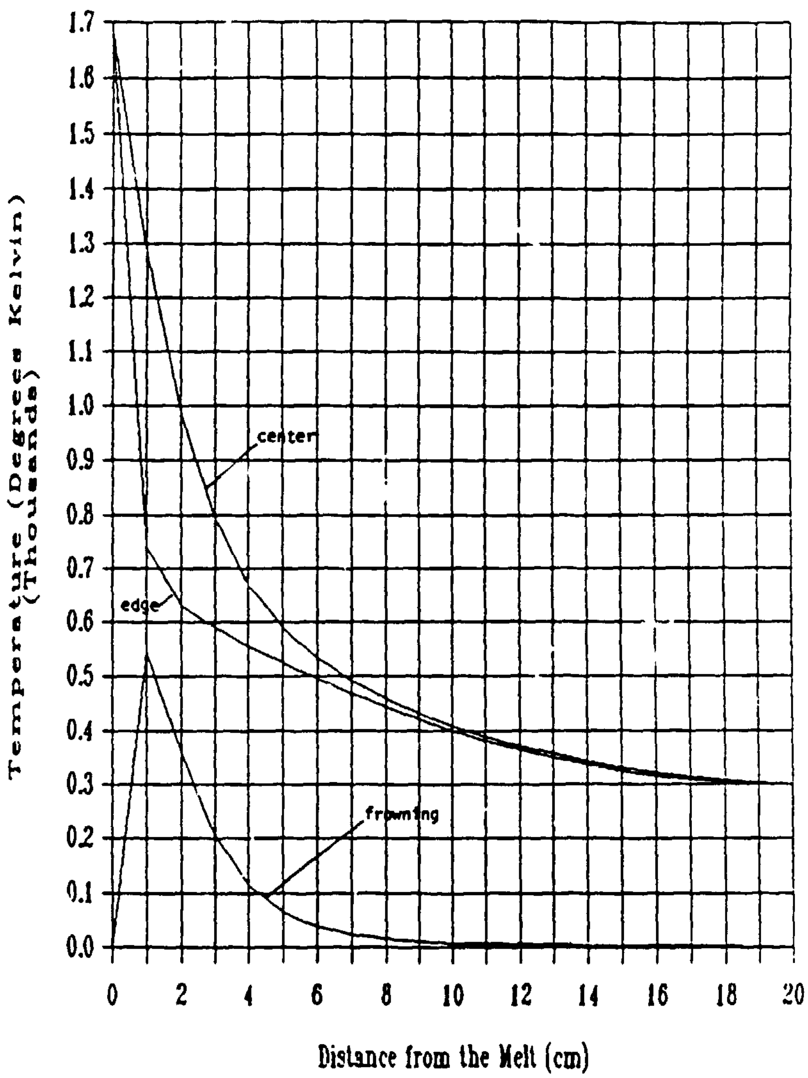
$T(x,y) = T(x,-y)$; $\xi = x/L$

$$T(\xi,c) = [T(0,c) - T_\infty]\, e^{-\beta\xi} + [T_\infty - T(L,c)]\, \xi^2 - [2(T_\infty - T(L,c)) + (T(0,c) - T_\infty)e^{-\beta}]\xi + T_\infty$$

Center, Edge, and Frowning Temperatures for Beta = 2



Center, Edge, and Frowning Temperatures for Beta = 50



Conclusions

- TEMPERATURE PROFILES MAY BE SLIGHTLY FROWNED TO ELIMINATE THE THERMAL STRESSES
- IN THE NUMERICAL COMPUTATION OF THERMAL STRESSES NUMERICAL CONVERGENCE ANALYSIS IS VERY IMPORTANT
- A SIMULATOR IS BEING DEVELOPED FOR THE ELASTO-THERMO-VISCO-PLASTIC BEHAVIOR OF THE SILICON RIBBON FOR ANY THERMAL LOADING. ELASTIC PORTION OF THE SIMULATOR IS COMPLETE, INCLUDING THE BUCKLING TENDENCY ANALYSIS
- THERMO - VISCO - PLASTIC PART OF THE SIMULATOR IS BEING DEVELOPED.
- IN ORDER TO MINIMIZE THE EXECUTION COST OF THE SIMULATOR, PARTITIONING OF THE MATRICES IS NECESSARY WHICH WILL BE IMPLEMENTED LATER.

Silicon High-Temperature Test Program: Objectives

- PERFORM UNIAXIAL, TENSILE, STRESS-STRAIN AND STRESS RELAXATION TESTS ON SILICON SHEET MATERIALS AT TEMPERATURES ABOVE 1000°C IN ORDER TO MEASURE THE LOW STRAIN (LESS THAN 1%) RESPONSE OF THESE MATERIALS.
- QUANTIFY THE EFFECT OF LOW STRAIN AND STRESS ON THE GENERATION OF RIBBON STRUCTURAL DEFECTS, PRIMARILY DISLOCATIONS.
- PROVIDE NEW HIGH TEMPERATURE MATERIAL PROPERTY DATA, SUCH AS CREEP CHARACTERISTICS, SO THAT SILICON STRESS-STRAIN MODELING COULD BE IMPROVED.

Silicon High-Temperature Test Program: Status

- BASED ON COMMENTS BY DR. SUMINO AND SCATTERED TEST DATA FROM DOZENS OF TESTS CONDUCTED IN 1985 THE TEST COUPON DESIGN/ PROCESSING WAS MODIFIED IN EARLY 1986.
- NO NEW TEST DATA YET.
- SOME CALIBRATION TESTS, SUCH AS MEASUREMENT OF EXTENSOMETER FRICTIONAL LOAD CONTRIBUTION AND LOW TEMPERATURE SPRING CONSTANT OF THE LOAD TRAIN HAVE BEEN COMPLETED.
- MEASUREMENT OF +1000°C LOAD TRAIN STIFFNESS HAS BEEN DIFFICULT.
- NEW TEST COUPONS OF ZERO DISLOCATION [211] ORIENTED CZ AND WEB RIBBON HAVE BEEN PRODUCED BY ULTRASONIC MACHINING AND SUBSEQUENT CHEMICAL EDGE-ONLY ETCHING.
- VACUUM CAPABILITY HAS BEEN ADDED TO THE TEST FURNACE.

Silicon High-Temperature Test Program: Future

- COMPLETE ELEVATED TEMPERATURE LOAD TRAIN STIFFNESS MEASUREMENTS.
- CONDUCT STRESS RELAXATION TESTS (CONSTANT TOTAL STRAIN) AT 1000^{o}C AND 1200^{o}C. INITIAL STRESS LEVELS WILL BE IN THE RANGE 3-20 MPA DEPENDING ON TEST TEMPERATURE. TOTAL STRAIN $\leq$1%. MEASURE TIME CONSTANT OF LOAD DECAY AND DEVELOP CONSTITUTIVE CREEP EXPRESSION BASED ON EXPERIMENTAL BEHAVIOR.
- USE X-RAY TOPOGRAPHY AND ETCH PIT STUDY TO CHARACTERIZED EXTENT OF LOW STRAIN STRUCTURE FORMATION.