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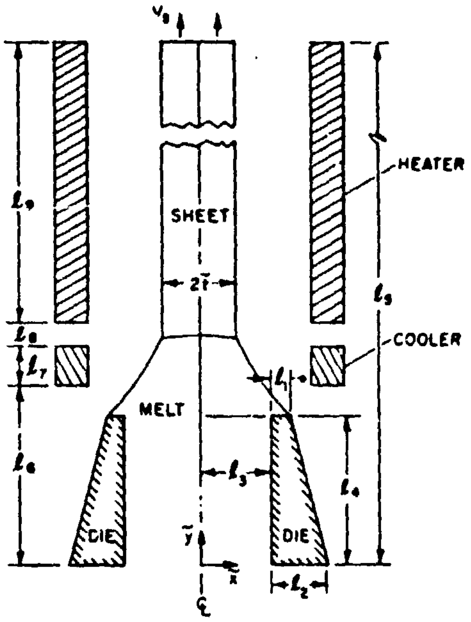
EDGE-DEFINED FILM-FED GROWTH OF THIN SILICON SHEETS

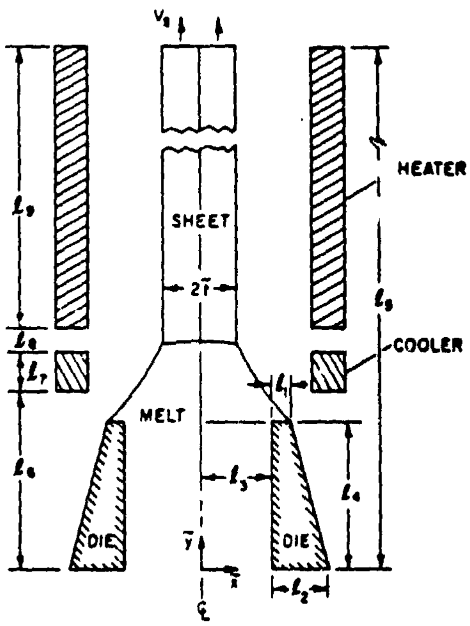
MOBIL SOLAR ENERGY CORP.

H.M. Ettouney and J.P. Kalejs



Thermal-Capillary Model

- TEMPERATURE FIELD DETERMINED CONDUCTION DOMINATED HEAT TRANSFER IN MELT AND CRYSTAL.
- MELT/SOLID INTERFACE SHAPE DETERMINED AS .. MELTING POINT ISOTHERM.
- MENISCUS SHAPE DETERMINED BY BALANCE OF SURFACE TENSION AND HYDROSTATIC FORCES.
- THICKNESS OF SHEET DETERMINED BY CONDITION FOR EQUILIBRIUM GROWTH ANGLE.
- DISTANCE FROM DIE TIP TO HEIGHT OF MELT POOL SETS REFERENCE PRESSURE IN MENISCUS REGION.



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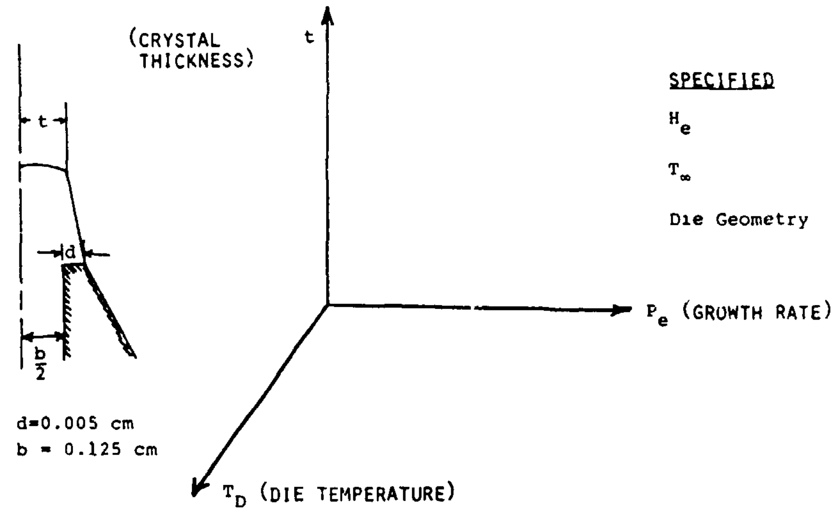
Model Description

- **Finite Element Analysis to Provide:**
  - **Coupled Solutions for Heat Transfer and Capillarity in Three-Phase Domain of EFG Die/Melt/Crystal.**
  - **Three Unknown Boundaries for Crystal Thickness, Melt/Solid, Melt/Gas Interfaces.**
- **Two-Dimensional Navier-Stokes Flow Field in Die Top and Meniscus (Interface) Melts**
- **Diffusion Equation Solutions for Segregated Aluminum Dopant**

Physics Is Best Explained for Growth Into Ambient at Uniform Surrounding Temperature



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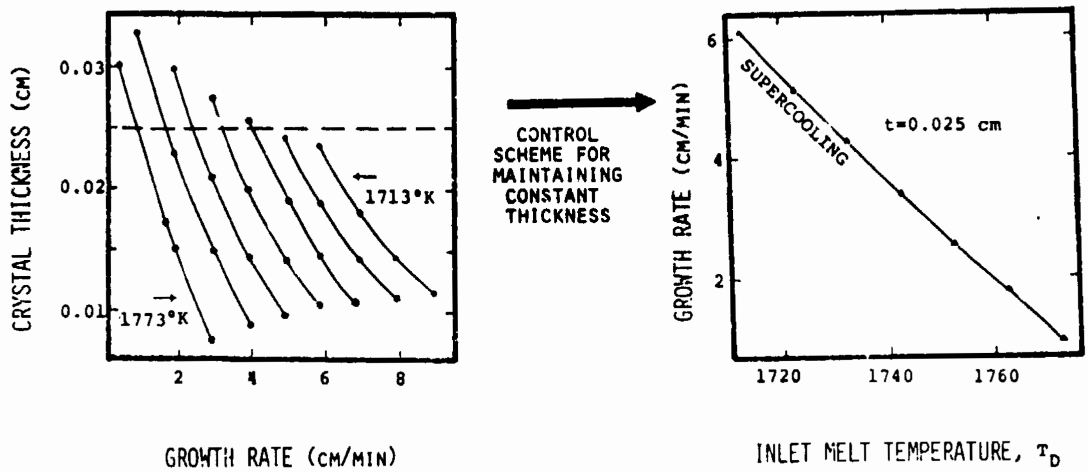
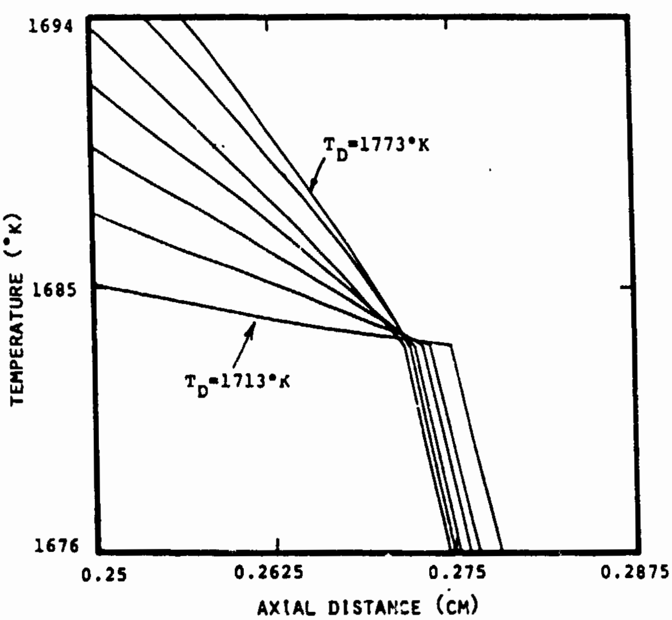
Operating Diagram for EFG



- MELT BECOMES SUPERCOOLED FOR LOW DIE TEMPERATURES

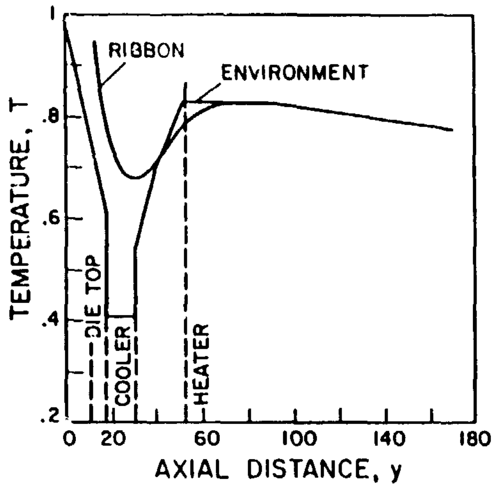
Crystal Thickness Is Maintained Constant by Simultaneously Changing v and T_D



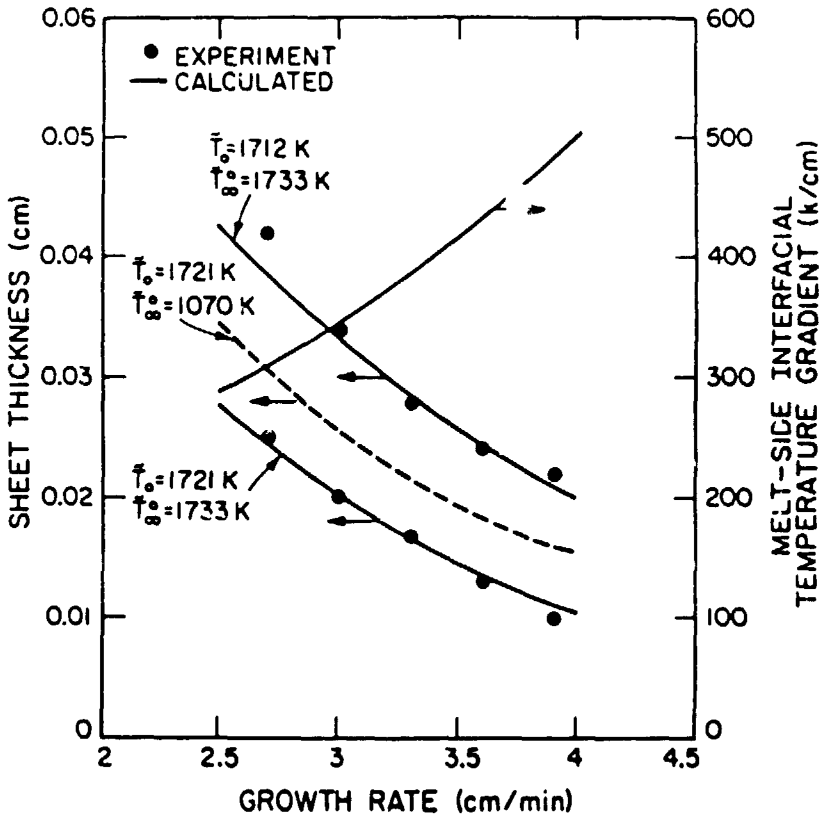
T_D(°K)	V(cm/min)	$\frac{dT_L}{dy}(\frac{°C}{cm})$
1773	0.96	875
1763	1.81	743
1753	2.57	612
1743	3.41	475
[illegible]	4.28	333
1723	5.15	186
1713	6.11	31

- A MAXIMUM GROWTH RATE EXISTS WHERE TEMPERATURE GRADIENT AT INTERFACE DROPS TO ZERO. ONSET OF SUPERCOOLING.

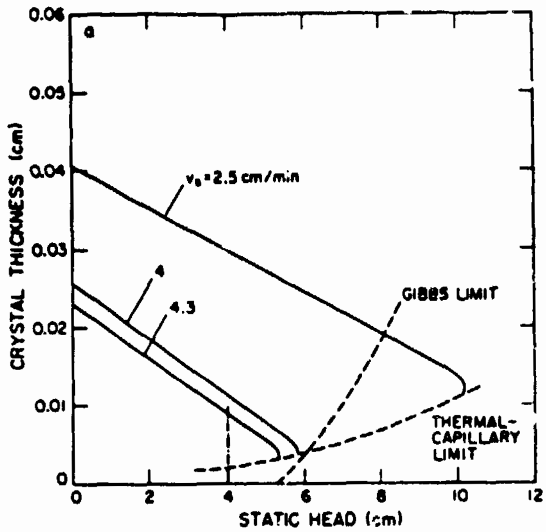
Ambient Temperature Distribution Used for Comparison With Experiments



Comparison of Calculations and Measurements for Prediction of Thickness Variation With Pull Rate



Operating Region Predicted by Finite Element Analysis



Dopant Segregation Effects

Distribution of Dopant Through Ribbon Thickness Depends on:

(1) Interface Shape – Heat Transfer Solution

(2) Solidification Flow Field – Navier Stokes Solutions Parameterized by Die Geometry, Meniscus Configuration

(3) Surface Tension-Driven Flow

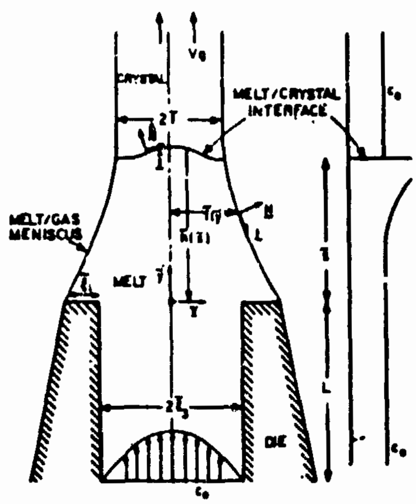
Accurate Calculation of Dopant Segregation

- FINITE ELEMENT ANALYSIS OF THERMAL-CAPILLARY MODEL SETS SHAPE OF MELT.
- VELOCITY FIELD IN MELT COMPUTED BY FINITE ELEMENT SOLUTION FULL NAVIER-STOKES EQUATIONS IN MELT.
- DOPANT CONCENTRATION FIELD CALCULATED BY SOLVING SPECIES CONSERVATION EQUATION

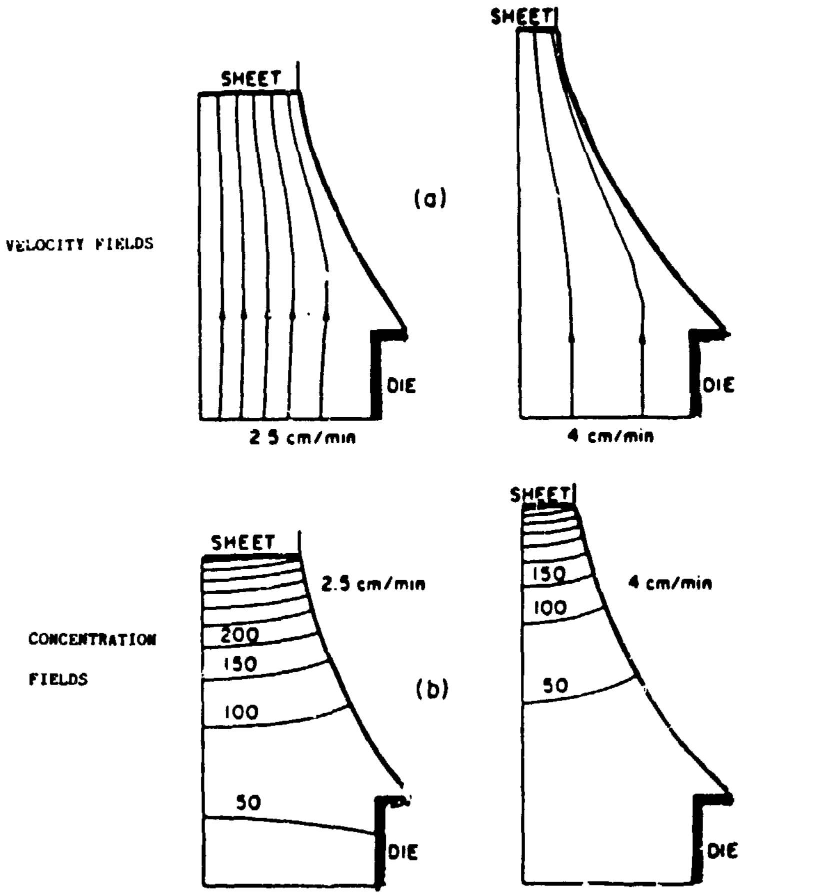
$$\nabla^2 c - Pe_m \nabla \cdot (c\, v) = 0$$

$$Pe_m = 2l_3 V^* / D$$

- NO ADJUSTABLE PARAMETERS IN CALCULATION !

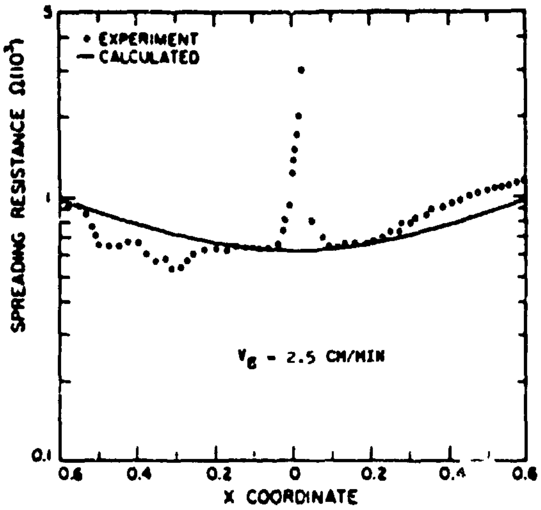


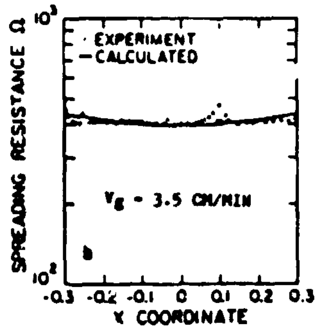
Lateral Dopant Segregation



LATERAL DOPANT SPEGREGATION PREDICTED BY CALCULATION OF DETAILED VELOCITY AND CONCENTRATION FIELDS IN THE MELT USING HEAT TRANSFER ANALYSIS.

Aluminum Distribution Across Thickness of Si Sheet





Surface-Tension-Driven Flow

$$V = \frac{d\sigma}{d\tilde{T}} \frac{\Delta T^*}{\mu}$$

For silicon sheet EFG:

$\Delta\tilde{T}^* \sim$ 5-20^{0}K (model)

$\frac{d\sigma}{d\tilde{T}}$ = -0.2 dynes/cm-K (Hardy)

μ = 0.0088 poise

V = 120 cm/sec $\gg V_g$ (0.04 cm/sec)

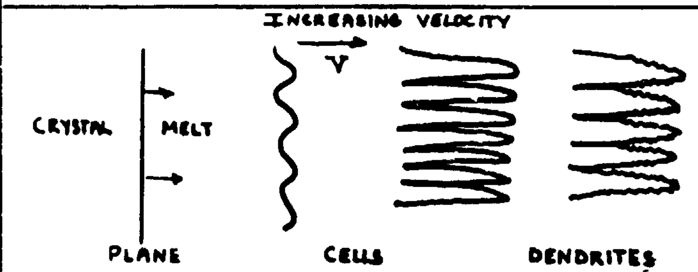
Summary

- **Fit of Finite Element Model Predictions to Experimental Data Achieved For:**
  - **t-V_s Relationship**
  - **Growth Rate Limits**
  - **Aluminum Dopant Segregation Dependence on t, V_s**

  With One Adjustable Parameter τ_0.

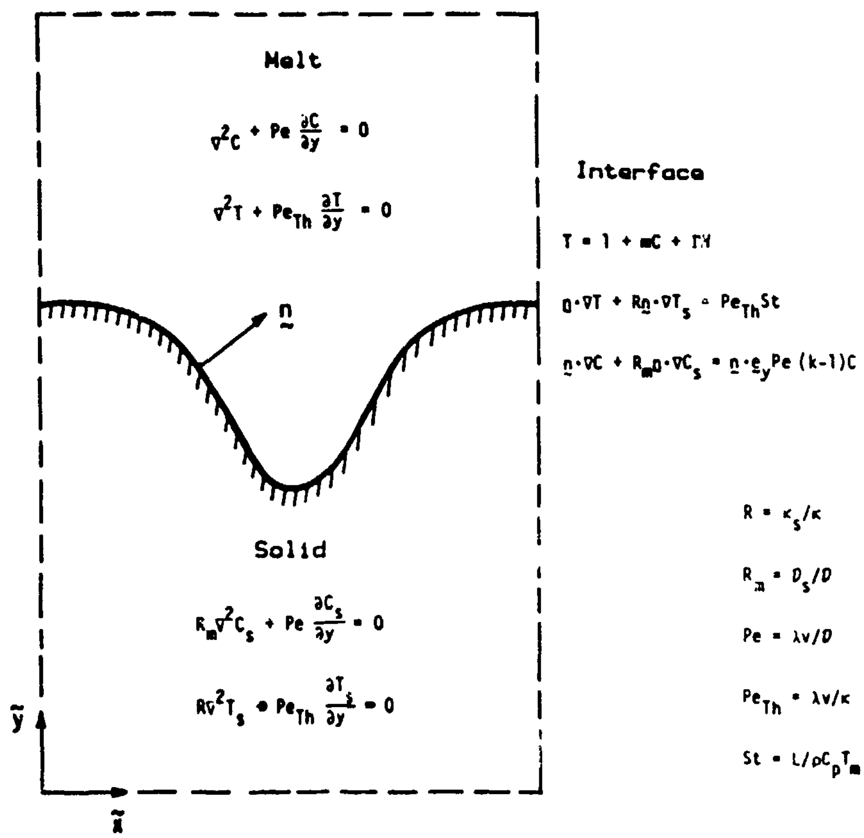
- **Comprehensive Nature of Finite Element Model Demonstrated for Predicting Process Variable Relationships, Interface Configuration and Dopant Segregation**

NONLINEAR ANALYSIS OF MORPHOLOGICAL TRANSITIONS DURING DIRECTIONAL SOLIDIFICATION TRACES EVOLUTION OF PLANAR INTERFACE INTO HIGHLY STRUCTURED CELLULAR AND DENDRITIC FORMS.



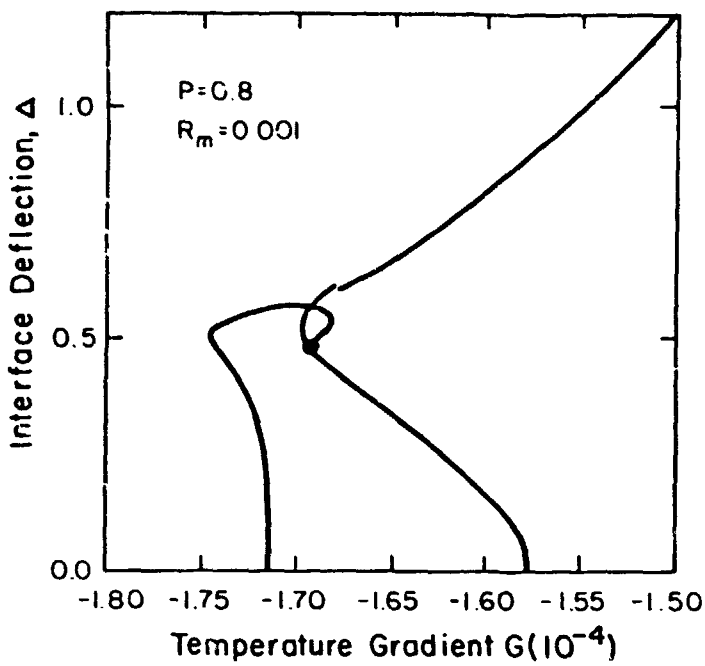
- ANALYSIS COMBINED FINITE-ELEMENT-METHODS FOR SOLVING EQUATION-SET FOR TRANSPORT AND MORPHOLOGY WITH NEW METHODS IN NONLINEAR ANALYSIS
- FIRST TO PREDICT TRANSITION TO DEEP CELLS
- SHOW FUNDAMENTAL MODE FOR REDUCTION OF CELL WAVELENGTH
- FIRST TO EXPLAIN ROLE OF GRAIN BOUNDARIES IN ONSET OF CELLULAR STRUCTURE
- ANALYSIS CAPABLE OF PREDICTION OF ONSET OF DENDRITIC GROWTH

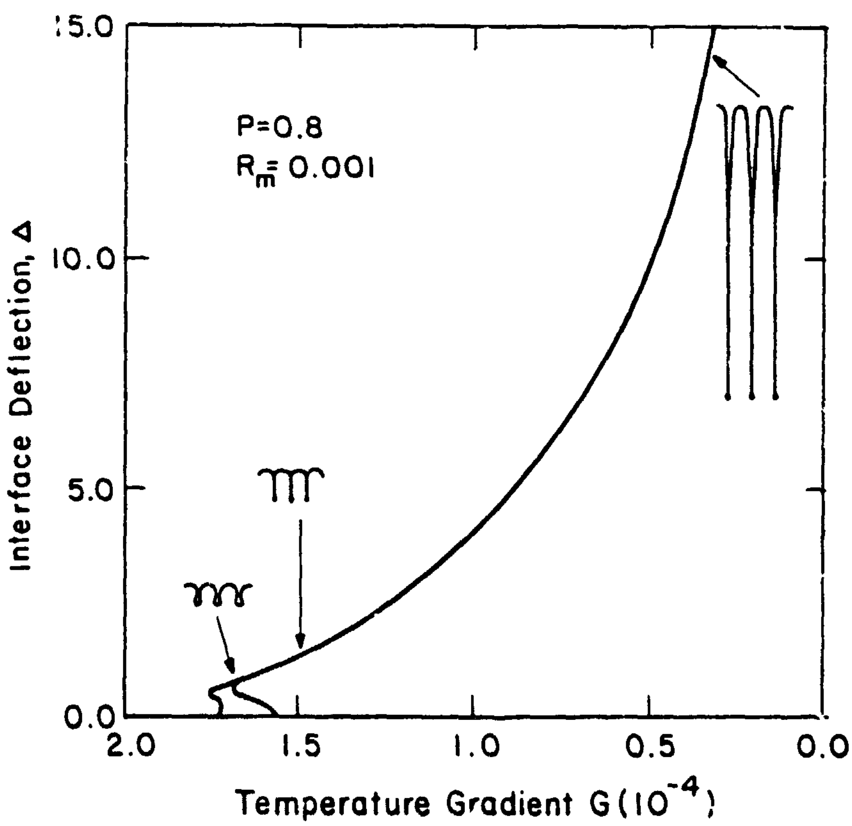
Two-Dimensional Model of Interface Morphology

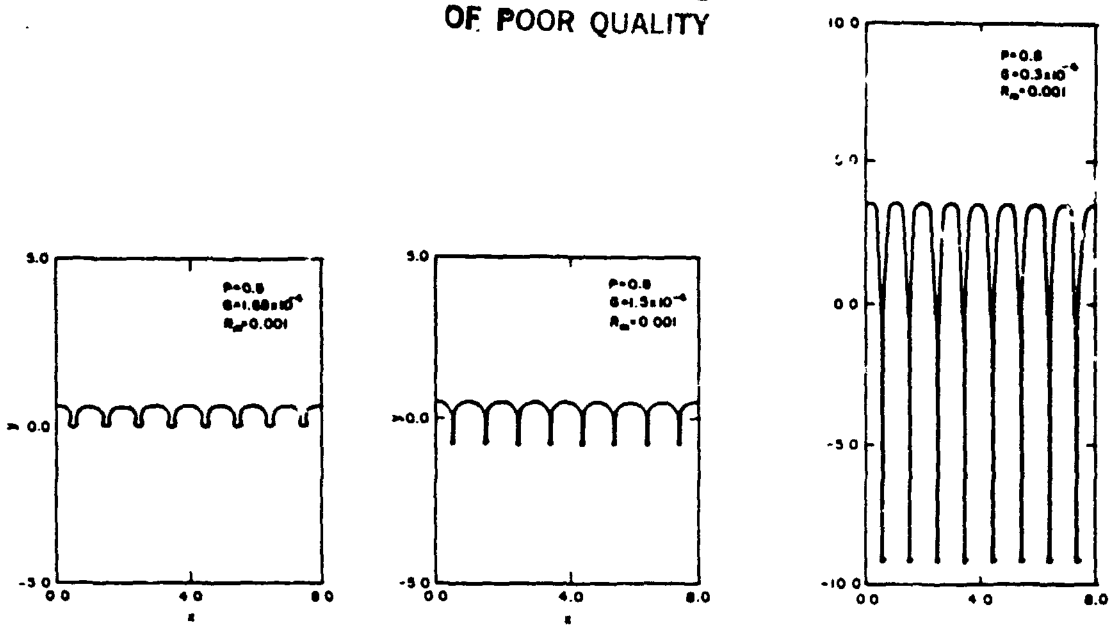


Models for Studying Morphological Structure

MODEL	LATENT HEAT	THERMAL CONDUCTIVITIES	CONVECTIVE HEAT TRANSPORT	SOLID DIFFUSION	REFERENCE
THERMAL-SOLUTAL (TSM)	YES	NOT EQUAL	YES	YES	UNGAR ET AL. (1984)
ONE-SIDED TSM	YES	NOT EQUAL	YES	NO	MULLINS AND SEKERKA J. Appl. Phys. 34 323 (1963)
EQUAL CONDUCTIVITY	YES	EQUAL	YES	NO	MC FADDEN AND CORIELL Physica D in press (1984)
SOLUTAL MODEL (SM)	NO	EQUAL	NO	YES	UNGAR AND BROWN, Phys. Rev. B. (1984)
SYMMETRIC SM	NO	EQUAL	NO	YES ($\mathcal{D}_L = \mathcal{D}_s$)	LANGER, Rev. Mod. Phys. 52, 1 (1980)
ONE-SIDED SM	NO	EQUAL	NO	NO	UNGAR AND BROWN Phys. Rev. B. 29, 1367 (1984)


P=0.8
R_m=0.001
Interface Deflection, Δ
1.0
0.5
0.0
-1.80
-1.75
-1.70
-1.65
-1.60
-1.55
-1.50
Temperature Gradient G(10^{-4})


P=0.8
R_m= 0.001
Interface Deflection, Δ
15.0
10.0
5.0
0.0
2.0
1.5
1.0
0.5
0.0
Temperature Gradient G(10^{-4})



Progress Report

1. FINITE ELEMENT PROGRAM FOR IDEALIZED GROWTH INCLINED GROWTH SYSTEM HAS JUST BEEN COMPLETED. RADIATIVE COUPLING BETWEEN MELT AND CRYSTAL SURFACES IN UNDERWAY.

2. PROGRAM WILL BE READY FOR COMPARISON WITH EXPERIMENTS BY 01/01/1985.

3. COUPLING OF THERMAL STRESS ANALYSIS TO THERMAL-CAPILLARY MODEL WILL BEGIN THIS FALL AND BE COMPLETED IN LATE SPRING.

4. FINITE ELEMENT ANALYSIS OF MICROSCOPIC INTERFACE MORPHOLOGY BEYOND THE POINT OF LINEAR INSTABILITY HAS BEEN DEVELOPED. CALCULATIONS FOR SILICON UNDER SHEET GROWTH CONDITIONS WILL BE COMPLETED BY EARLY SPRING.

Summary

FINITE ELEMENT ANALYSIS IS BEING USED ON TWO LENGTH SCALES TO UNDERSTAND CRYSTAL GROWTH OF THIN SILICON SHEETS.

1. THERMAL-CAPILLARY MODELS OF ENTIRE RIBBON-GROWTH SYSTEMS. DEMONSTRATED FOR EFG; MODEL PRESENTED FOR INCLINED-MENISCUS SYSTEM.
2. MICROSCOPIC MODELING OF MORPHOLOGICAL STRUCTURE OF MELT/SOLID INTERFACES BEYOND THE POINT OF LINEAR INSTABILITY. THE FORMATION OF DEEP CELLS AND DENDRITES. APPLICATION TO SILICON SYSTEM IS UNDERWAY.