N86-29392

ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

WESTINGHOUSE ELECTRIC CORP.

R. H. Hopkins

Advanced Silicon Sheet Task

Technology Single Crystal Ribbon Growth	Report Date 6/19/85
Approach Silicon Dendritic Web Growth Contractor Westinghouse Electric Corporation Advanced Energy Systems Division JPL Contract 955843 Goals For 1985 Demonstrate • Area Growth Rate of 13 cm²/min (2 m Length) • Area Growth Rate of 16 cm²/min (2 m Length) • Closed Loop Growth Control System	Status • Model-Driven Low Stress Design Led to Record Web Width - 6.7 cm • New Length Record with Continuous Replenishment - 7.5 m (4.1 cm Width) • Area Rates - 8 cm²/min (1.5 m) - 13 cm²/min Short Lengths • 5 cm Wide Webs Grown Regularly • Sensor for Closed Loop Control Based on Dendrite Thickness Demonstrated • Software and Hardware Elements for Closed Loop Control Completed • Plastic Flow Modeling Initiated for Stress Reduction

Outline

Introduction — — — — — — — — — — — — — — R. H. Hopkins

- Goals
- Organization

Closed Loop Web Growth System Development

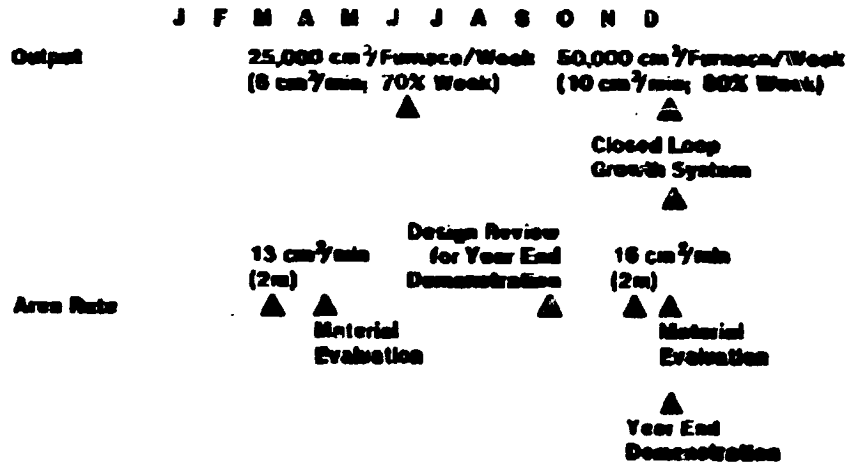
- Dendrite Thickness Monitor
- Closed Loop Control System
- System Monitoring

Stress Reduction for High Area Rate Growth

- Far Stress
- Near Stress

Plastic Deformation — — — — — — — — — — — — J. Spitznagel

Web Technology Development
1985 Milestones



Web Technology Development

Output Team - C.S. Duncan

- System Performance Task — P.A. Piotrowski
- Continuous Replenishment Task — F.A. Pryzwarty
- Instrumentation and Control Task — J.R. Easoz

Goals	Date
25,000 cm²/Furnace/Week	6/30/85
50,000 cm²/Furnace/Week	12/31/85
Closed-Loop Growth Control	12/31/85

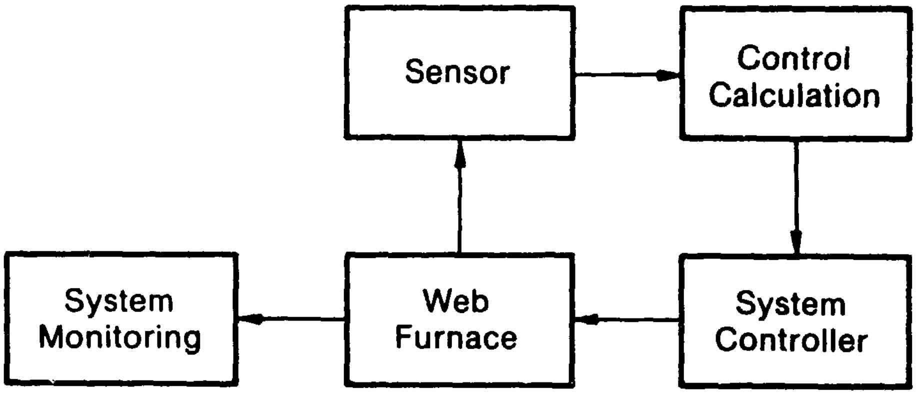
Area Rate Team - R.H. Hopkins

- Modeling and Analysis Task — R.G. Seidensticker
- Experiment Concept and Evaluation Task — J.P. McHugh
- Component Design and Implementation Task — R.P. Sprecace
- Characterization Task — J. Spitznagel

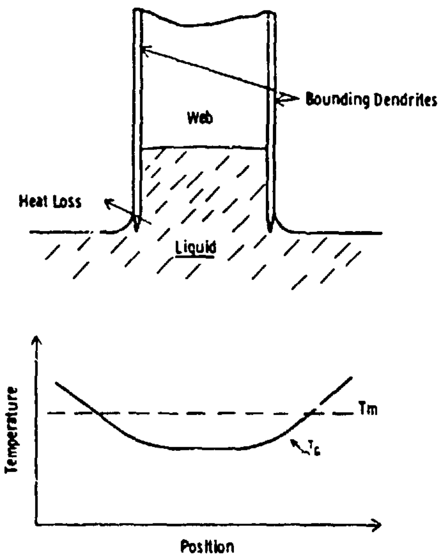
Goals	Date
13 cm²/min (2m)	3/31/85
16 cm²/min (2m)	12/31/85

Information Management - E.L. Kochka

Closed Loop Web Growth System

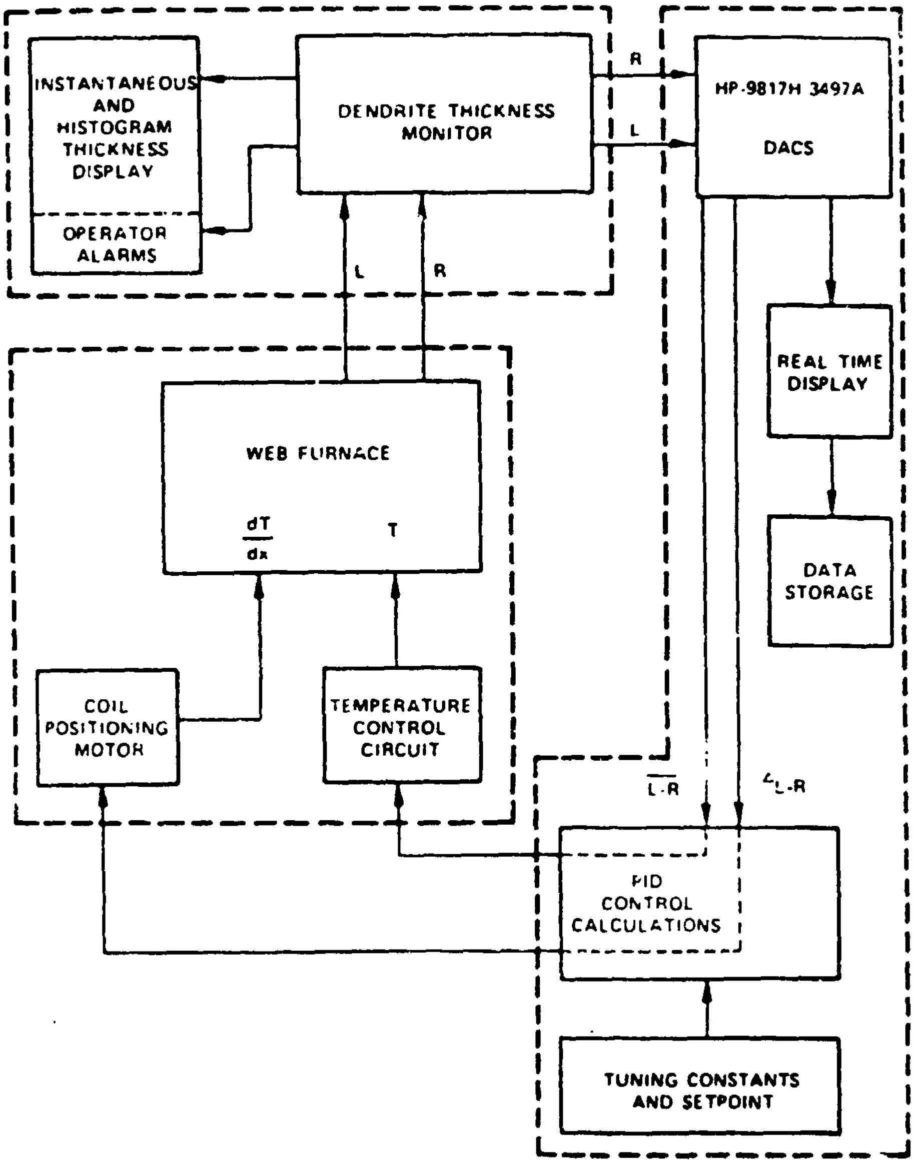


Web Growth Control



- Growth Temperature, T_G - Control Furnace Temperature
- Lateral Symmetry - Control Coil Position

Closed-Loop Control System

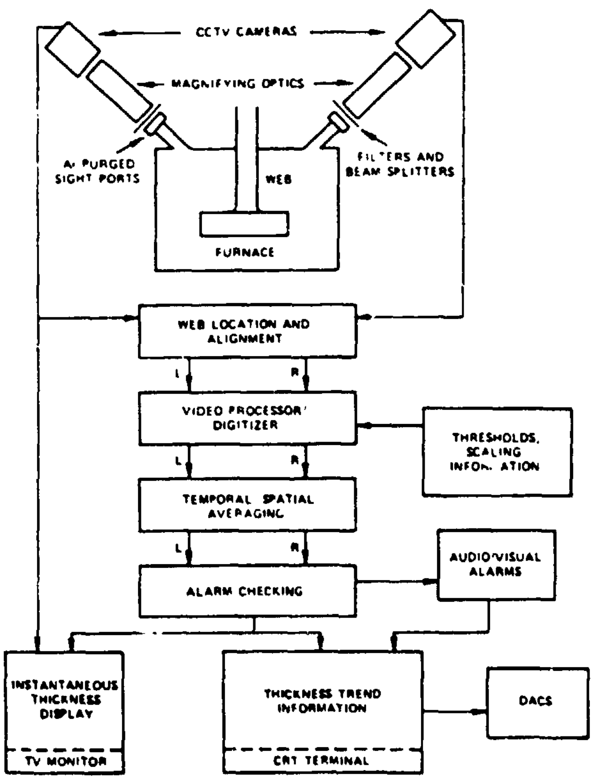


Basis for Web Closed-Loop Control

Dendrite Thickness Controlled Through Digital Feedback Loop

- DTM Provides Input to Two Uncoupled P-I-D Control Equations
  - — Average L-R Thickness Controls Temperature
  - — Thickness Difference Controls Spatial Temperature Distribution
- RF Coil Position (Left-Right) Adjusted Through PID Output to Motorized Stage for dT/dx Changes
- Temperature (RF Power) Adjusted By Biasing Light Pipe Input to Analog Temperature Controller (Based on PID Control Output)

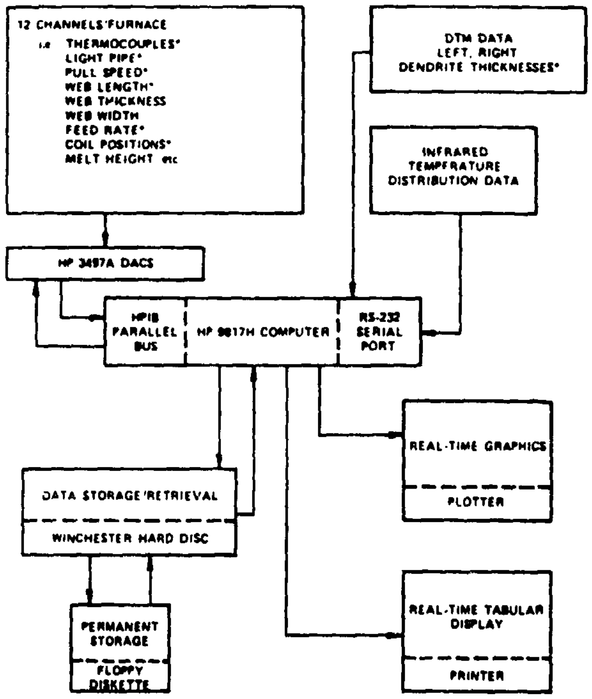
Dendrite Thickness Monitor



Dendrite Thickness Monitor (DTM)

- View-719 VidiconType Dimension Inspection System
- (W) Developed Application Software
  - — Visual Display for Operator in Manual Mode
  - — Input to Control System in Automatic Mode
- Automatic Calibration and Dendrite Tracking
- Gas Purged Viewport System on Furnace Provides Clean Sightpath
- 50 Microns (1 PIXEL) Resolution; with Software Averaging, Repeatability ~10 Microns

Data Acquisition System

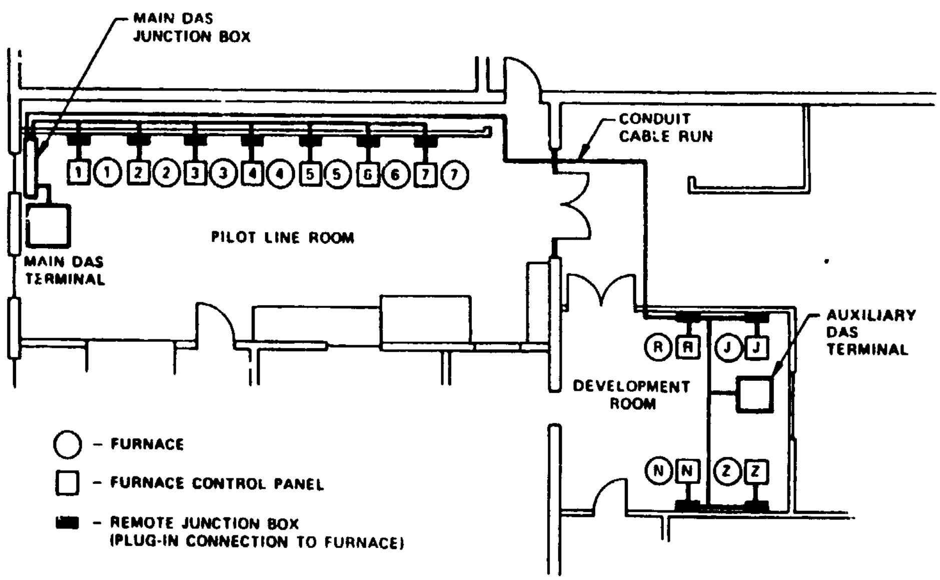


*CURRENTLY AVAILABLE

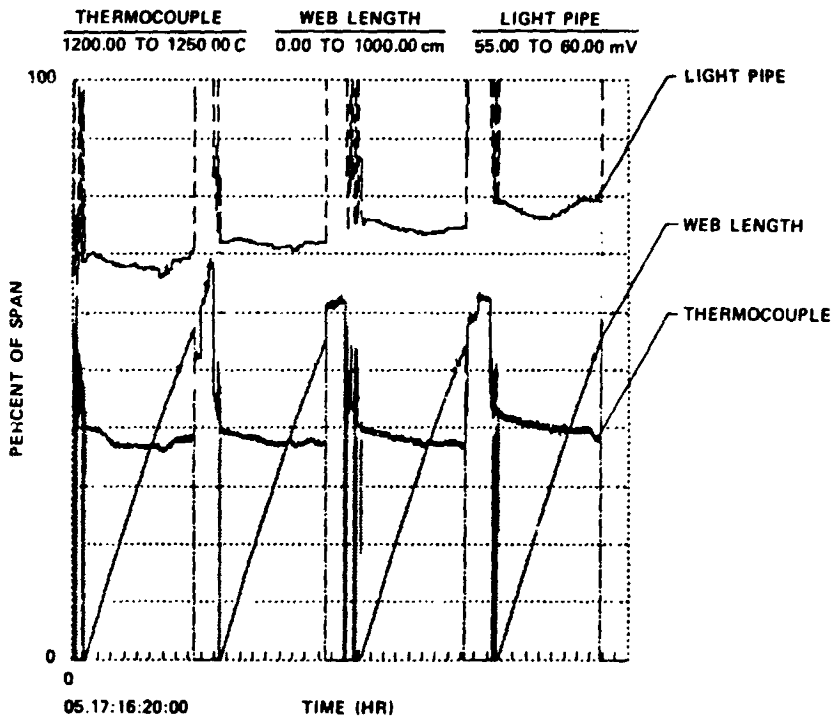
Data Acquisition System (DAS)

- Based on HP-9817H Computer with HP-3497A Data Acquisition System
- Hardware Configuration Allows Maximum of 12 Data Channels Per Furnace
- Anticipated Storage Capacity ~1 Week of Data for 11 Furnaces
- Real-Time Graphics or Tabular Display
- Variable Sampling Rate Data Storage with Time Compression/ Expansion Capability on Recalled Graphics Display

Data Acquisition Cabling Plan



Monitoring with Real-Time Data Acquisition System



Closed-Loop Development Status

- DTM Tests Successful
  - Operator Acceptance for Manual Operation
  - Adequate Resolution
  - Reduced Terminations/Longer Webs
- Dendrite Thickness Data Compatible with Control Function
- Software for P.I.D. Control Algorithm Complete
- Computer Controlled Coil Positioner and Temperature Control Demonstrated
- Software for Dual Furnace Operation of DTM Complete
- Cabling of Furnaces for Data Acquisition and Monitoring Complete

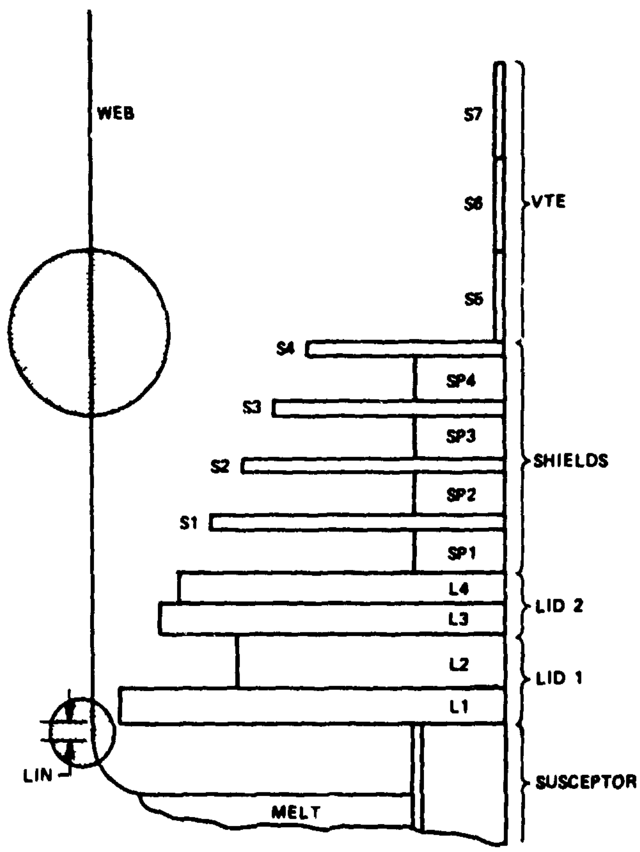
Area Rate

TECHNICAL ISSUES

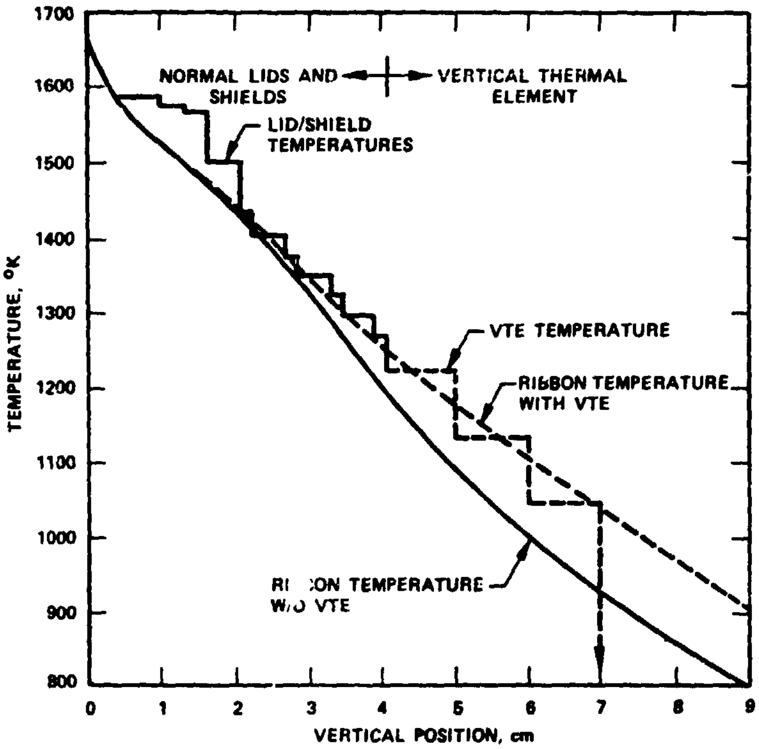
1. Low Stresses ⟶ Wide Crystals
   - Far Stress
   - Near Stress

2. Maximum Interface Heat Loss ⟶ High Speed
   - Growth Stability with Deep Melts
   - Stress Trade-Offs

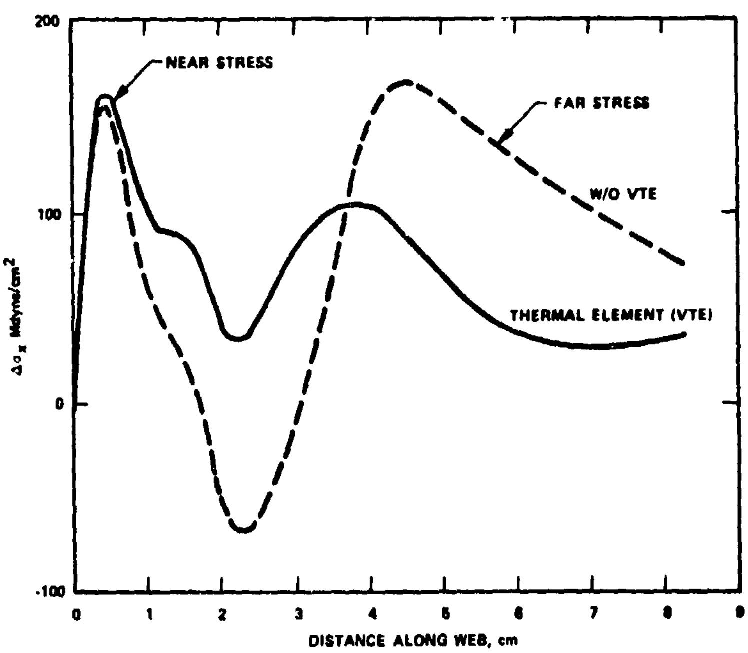
Schematic Growth Configuration (for modeling)



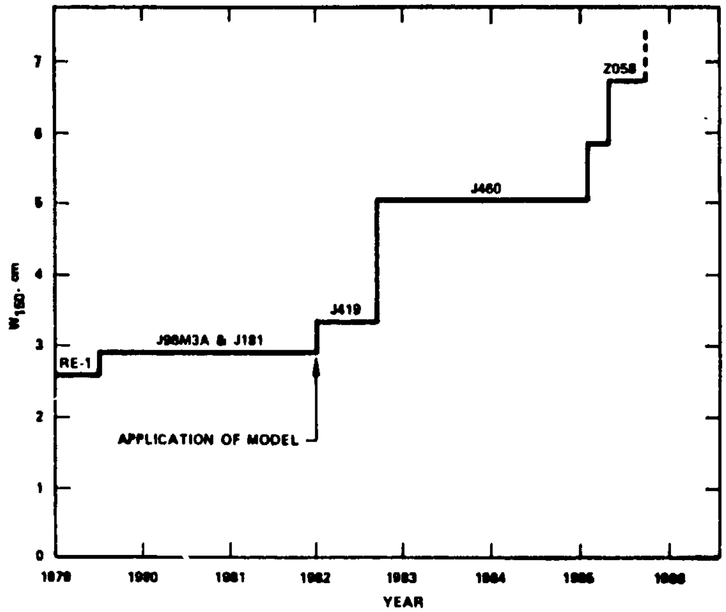
Calculated Web Thermal Profiles



Far Stress Reduction by Thermal Element Above Shield Stack



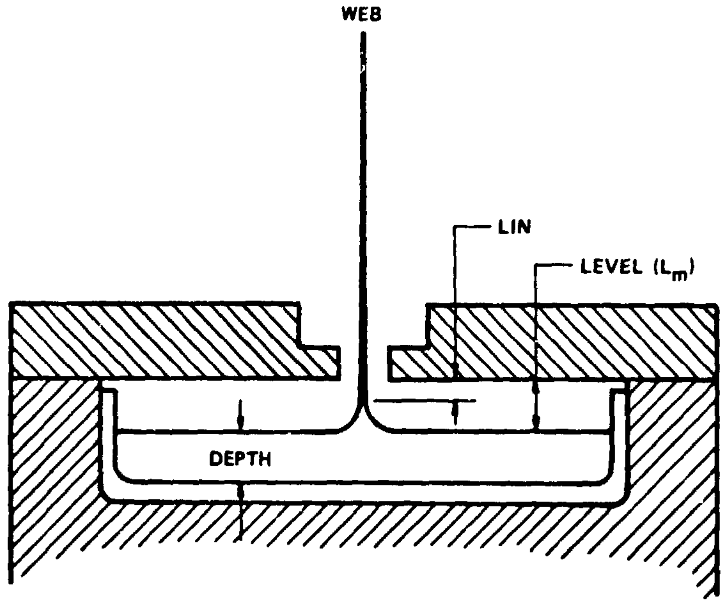
Undeformed Web Width



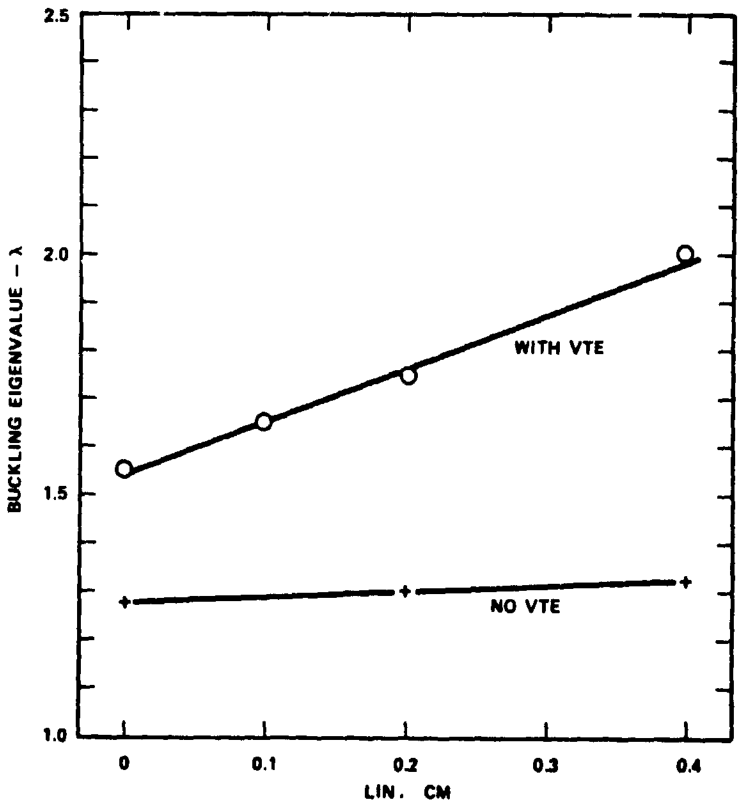
Recent Wide Web Crystals

CRYSTAL	W (cm)	t (μm)	V (cm/min)	Area Rate (cm^2/min)
N126-14	5.0	210	1 13	5.6
N127-3	5.6	170	1.13	6.3
N127-4	5.0	140	1 43	7.1
Z058-4	5.8	160	1.05	6.1
Z059-2	5 0	135	1 13	5.6
N128-15	4 9	75	1.88	9 2
N128-16	5.2	95	1.65	8.6
N128-19	5.2	130	1.43	7.4
Z060-14	4.5	135	1.57	7.1
R483-10	4 8	145	1.38	6.6
N130-11	5.4	140	1.28	6.9
R485-7	4.8	105	2.04	9.8
N132-2	4.7	145	1.28	6.0
R486-12	5 0	210	1.38	6.9
R486-13	4 8	150	1.38	6 6
N132-2	4.7	145	1.28	6.0
Z063-2	5 5	130	1.35	7.4
			2.10	11.5
J55-13	5.2	125	1.29	6.7
J551-15	5.5	150	1.02	5.6
J552 1	6.7	. . .	1.29	8.1
J554-1	5 4	170	1.15	6.2
J554 2	5 3	165	1.15	6.1
J555-1	5 0	205	1 15	5.8
		65	2.65	13.3
J55-6	5.2	150	1.15	6.0
J557-2	5 3	170	1.29	
J557-5	6 4	190	1 15	7 4
J557-6	5 0	160	1 15	5.8
J557-7	5 3	165	1 15	6 1
J559-8	5 0	170	1 15	5 8
J560-2	6 0	155	1 15	6 9
N141-1	5 2	150	1 28	6 7
Z066-7	5 0	140	1.22	6 1
Z069-1	4 8	170	1.31	6 3
Z069-8	4 8	165	1.22	5 9
Z070-17	4 8	135	1 31	6 3
N142-3	4 8	120	1 28	6 1
R492	5 1	155	1.11	5.7

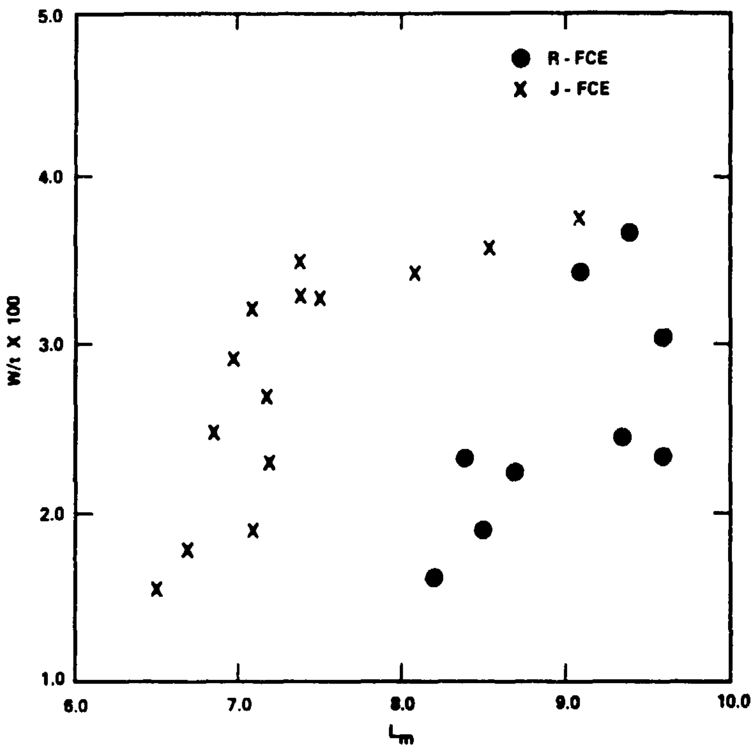
Melt Geometric Parameters

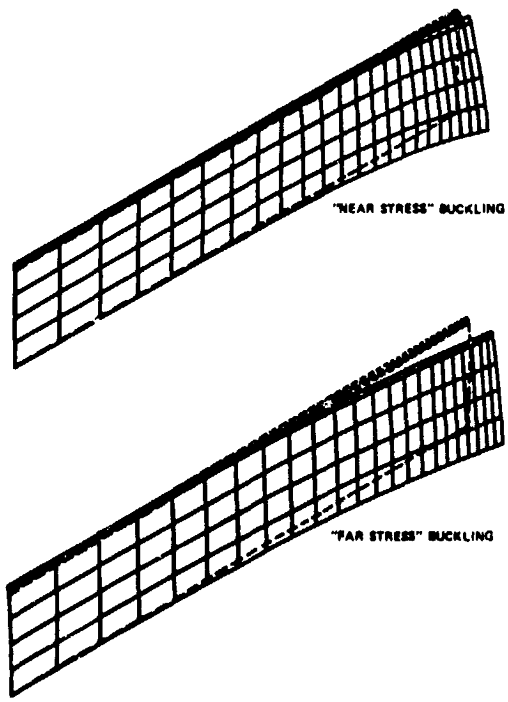


Variation in Web Buckling Eigenvalue with Crystal-Liquid Interface Position



Normalized Buckling Width Versus Melt Level





Near Stress Reduction

APPROACHES

Model

- **Direct Stress Calculation from Hypothetical Lid Design**
- **General Analysis from Synthetic Temperature Profiles**
- **Guidance from Effective Ambient Temperature Calculation**

Fabricate and Test Lids

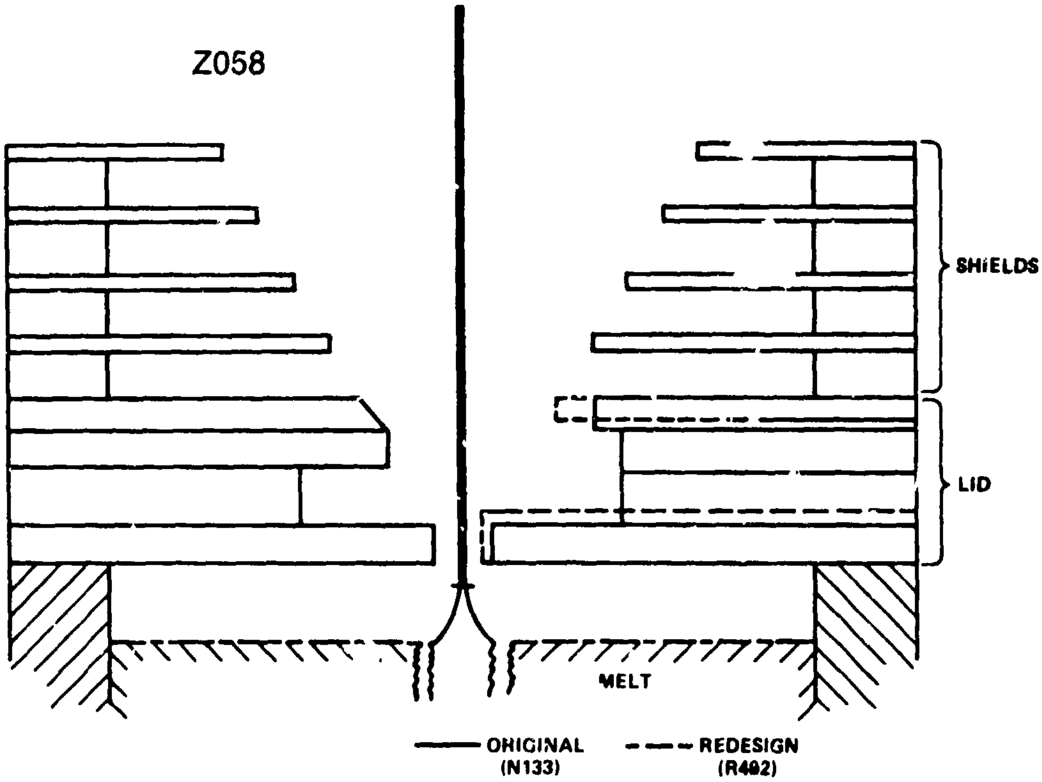
Evaluate Parametric Effects on Crystal Quality

Modeling New Lids for Interface Stress Reduction

(LIN = 0)

Model Case	Remarks	V Web (cm/min)	σ_y (0) (Md/cm^2)	$\Delta\sigma_x$ (near) (Md/cm^2)
J460	Baseline	1.53	-645	155
New 1 (N-133)	Std. T's	1.53	-612	145
New 1 (N-133)	Hotter Cavity	1.52	-591	139
New 1 (N-133)	Hot/Deeper Cavity	1.48	-581	140

Lid Designs for Interface Stress Reduction



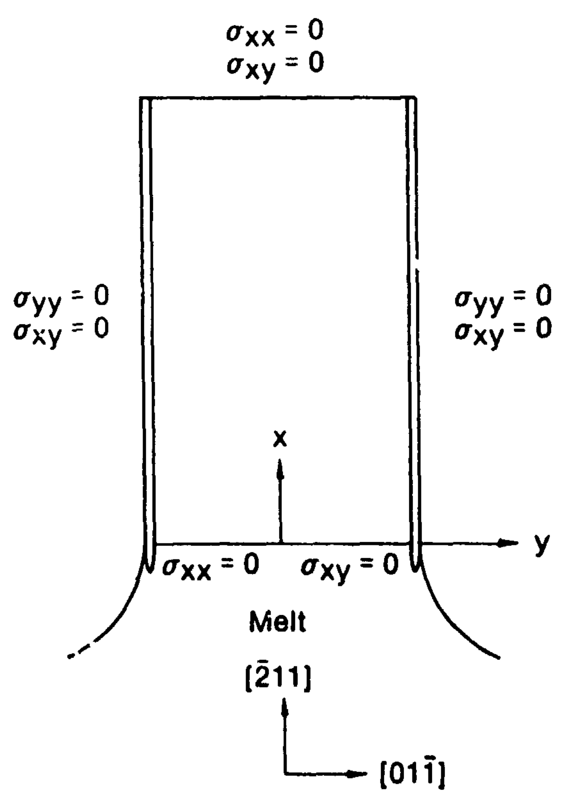
Typical Web Etch Pit and Stress Data

Growth Configuration	J435	Z058 (Far Stress Control)	R492 (Near Stress Control)
Residual Stress (Mdyn/cm^2)	20-40 (Tensile)	<10 (T and C)	<10 (Compressive)
Etch Pit Density (cm^{-2})	20-30K	~3K	<5K

Plasticity Effects in Web Growth

- Finite Element Calculation of σ_{xx}, σ_{yy}, σ_{xy} from Thermoelastic Strains
- Resolved Shear Stresses on Nine Possible Slip Systems
- Calculation of Position (Temperature) Dependent CRSS
- Estimate Dimensions of Plastic Zone
- Compare Dislocation Etch Pit Patterns and Calculated Slip System Activity
- Determine Necessity of Incorporating Constitutive Equation for Si Into Finite Element Model

Web Geometry



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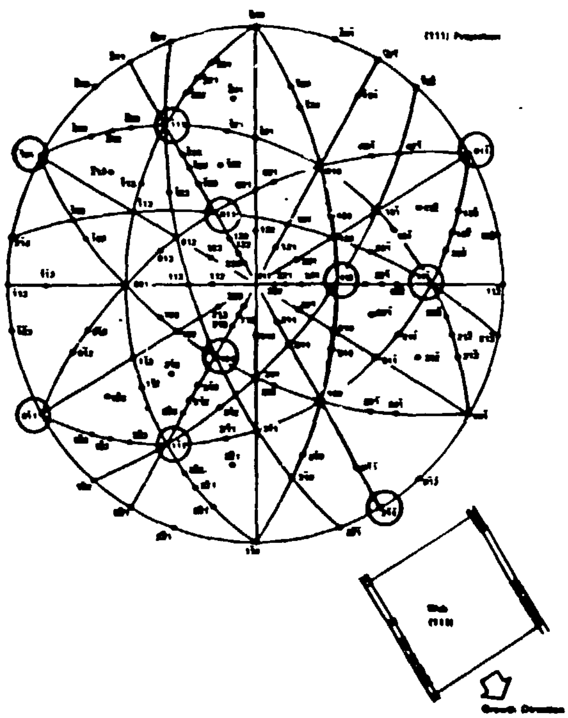
Web Slip Systems



Calculation of Resolved Shear Stresses

$$\sigma_{ij} = a_{ix}\, a_{jx}\, \sigma_{xx} + [a_{ix}\, a_{jy} + a_{iy}\, a_{jx}]\, \sigma_{xy} + a_{iy}\, a_{jy}\, \sigma_{yy}$$

Where

a_{ix} = Cosine of Angle Between Normal to Slip Plane and $[2\bar{1}\bar{1}]$

a_{jx} = Cosine of Angle Between Slip Direction and $[2\bar{1}\bar{1}]$

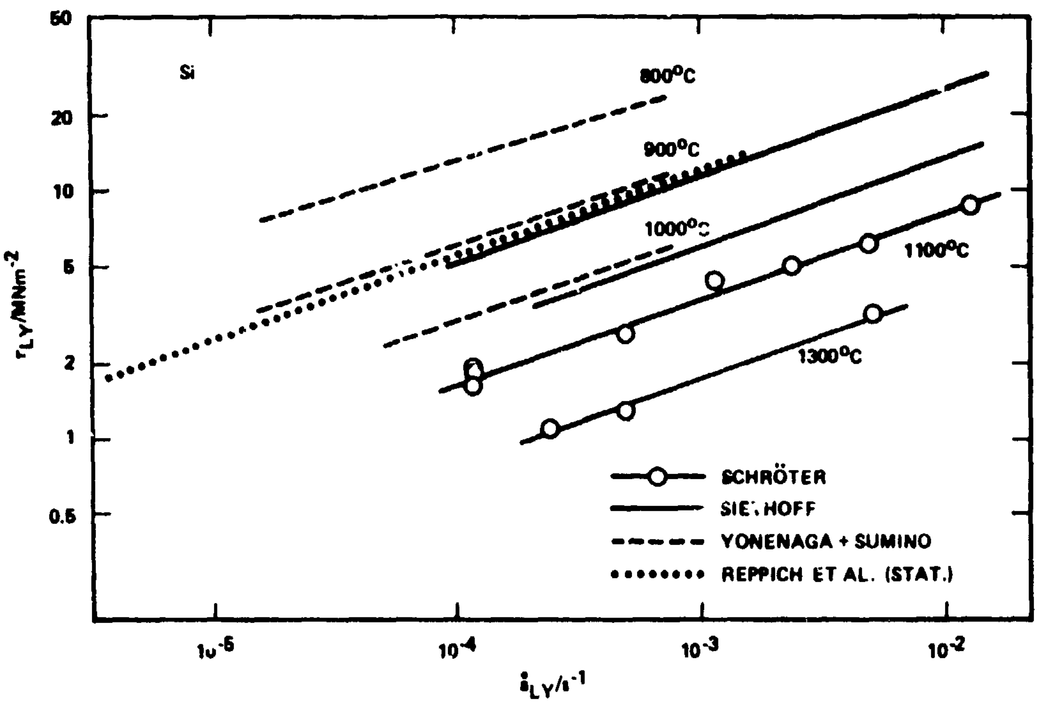
a_{iy} = Cosine of Angle Between Normal to Slip Plane and $[01\bar{1}]$

a_{jy} = Cosine of Angle Between Slip Direction and $[01\bar{1}]$

Resolved Shear Stresses for Single Crystal (111) Web Silicon

Plane	Direction	Resolved Shear Stress
$(1\bar{1}1)$	[011]	$-0.272\,\sigma_{xx} + 0.470\,\tau_{xy}$
$(1\bar{1}1)$	[110]	$0.136\,\sigma_{xx} - 0.408\,\sigma_{yy}$
$(1\bar{1}1)$	$[\bar{1}01]$	$-0.408\,\sigma_{xx} + 0.471\,\tau_{xy} + 0.408\,\sigma_{yy}$
$(11\bar{1})$	[011]	$-0.272\,\sigma_{xx} - 0.470\,\tau_{xy}$
$(11\bar{1})$	[101]	$0.136\,\sigma_{xx} - 0.943\,\tau_{xy} - 0.408\,\sigma_{yy}$
$(11\bar{1})$	$[\bar{1}10]$	$-0.408\,\sigma_{xx} - 0.471\,\tau_{xy} + 0.816\,\sigma_{yy}$
$(\bar{1}11)$	[110]	$-0.272\,\sigma_{xx} - 0.471\,\tau_{xy}$
$(\bar{1}11)$	[101]	$-0.272\,\sigma_{xx} + 0.471\,\tau_{xy}$
$(\bar{1}11)$	$[0\bar{1}1]$	$0.943\,\tau_{xy}$

Lower Yield Stress as a Function of Strain Rate in FZ and Cz Silicon



Critical Resolved Shear Stress Criterion for First !.eration

$$\dot{\epsilon}_{avg} = \frac{\partial(\alpha T)}{\partial t}$$

$$\simeq 5 \times 10^{-5}\ s^{-1}$$

$\tau_{LY} = 1.505 \times 10^{-3}$ EXP $[^{9283}/T]$

τ_{LY} = Shear Stress at Lower Yield Point in MPa

T = Web Temperature, °K (T $\gtrsim$ 1000K)

T°K	τ_{LY} (MPa)
1073 (800°C)	8.6
1173 (900°C)	4.1
1273 (1000°C)	2.2
1373 (1100°C)	1.3
1573 (1300°C)	0.55

Problems/Concerns

(1) Reduction in Interface Stress for High Speed Gro equires Analytical and Experimental Effort: Calendar Year edule is Ambitious

(2) Uncertainties in High Temperature Properties of Silicon Impact Stress Modeling