## Low-Stress EFG Configurations

- **Stress, dislocation densities reduced only at expense of growth speed capacity:**
  - For interface gradients ≤ 1000°C, speed is limited to 1–1.5 cm/min.
  - $N_0 \leq 1 \times 10^5$/cm², Lüders strain occurrence eliminated, residual stress is reduced.

- **Horizontal gradient modeling shows some promise for stress manipulation below 1200°C to 900°C, where creep is still significant, but will not allow speed capacity increases.**

- **Inclined interface growth appears to be only alternative to overcome high temperature creep limitation.**
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**Growth Direction**

![Diagram showing stress distribution](image)

**High Stress, 2 cm/min, \( N_D \sim 10^6 \) to \( 10^7/cm^2 \)

**Low Stress, 1 cm/min, \( N_D \leq 1 \times 10^5/cm^2 \)**
New Interpretation of Stress-Strain Effects in High-Speed Sheet Growth
(J. W. Hutchinson, Harvard University)

\[ \varepsilon_{\text{tot}} = \varepsilon + \varepsilon^c + \varepsilon^m \]

![Velocity Profile Across Strip at \( x = 0 \)]

**Implications of Velocity Nonuniformity on Interface Shape, Structure Unknown.**

Stress Analysis with Horizontal Temperature Gradients

\[ \Delta x_{\text{max}} \]

**High Creep Condition:** \( v = 3 \) cm/min, width of 5 cm.

**Parabolic Horizontal Profile:**
- Horizontal Interface Profile.
- Peak difference \( \Delta T_{\text{max}} \) occurs at distance \( \Delta x_{\text{max}} \) from interface.
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Maximum Residual (Room Temperature) Stress (MPa) for Horizontal Temperature Field Variations

A) \( \Delta T = 500^\circ C/\text{cm}, \ SI = 60^\circ C/\text{cm} \)

\[
\begin{array}{c|cccc}
\Delta T_{\text{MAX}} & 0 & 50 & 100 & 150 & 200 \\
\hline
0.5 & 67.0 & 63.0 & & & \\
1.0 & 67.0 & 62.8 & 59.9 & & \\
2.0 & 67.0 & 69.6 & 77.4 & 85.6 & 84.0 \\
3.0 & 67.0 & 68.8 & 74.5 & & \\
\end{array}
\]

B) \( \Delta T = 1250^\circ C/\text{cm}, \ SI = 40^\circ C/\text{cm} \)

\[
\begin{array}{c|cccc}
\Delta T_{\text{MAX}} & 0 & 50 & 100 & 200 & 300 \\
\hline
0.5 & 474 & 466 & 501 & & \\
1.0 & 474 & 472 & 470 & & \\
2.0 & 474 & 460 & 446 & & \\
3.0 & 474 & 459 & 444 & 415 & 387 \\
4.0 & 474 & 463 & 453 & 433 & 414 \\
\end{array}
\]

EBIC Measurement Configurations

\* DESIRE HIGH RESOLUTION ON L MEASUREMENT.

\* RELATE SAMPLE INHOMOGENEITIES IN L TO BULK L (LARGE AREA MEASUREMENT).
High-Resolution EBIC Results

- Large differences found between surface and edge cross section measurements of diffusion length by EBIC.

- Difference attributed to ability to resolve diffusion length inhomogeneities in near-surface regions of stressed samples at ≥ 500x.

- Caution must be exercised in interpretation of edge cross section EBIC measurements due to geometrical effects in addition to material inhomogeneities.
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EBIC Characterization

- **Scope of the Present Study:**
  - CZ silicon of various carbon levels and FZ silicon stressed above 1200°C, and EFG sheet.
  - Crystal growth furnace 17 and sealed, evacuated quartz ampoule anneals.

- Dislocation density dependence of L with $N_D$ up to $\approx 1 \times 10^7$/cm$^2$.
- Effect of post-deformation one-hour anneals at 575°C and 850°C.

**FZ and Cz Silicon Wafer Description for Samples Stressed at 1370°C in Four-Point Bending**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$D_i$ (cm$^{-3}$)</th>
<th>$C_s$ (cm$^{-3}$)</th>
<th>$N_D$ (As-Grown) (cm$^{-2}$)</th>
<th>Stress (MPa)</th>
<th>$N_D^C$ (cm$^{-2}$)</th>
<th>$N_D^E$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(111) FZ (#15)</td>
<td>$&lt;10^{16}$</td>
<td>$&lt;10^{16}$</td>
<td>0</td>
<td>8</td>
<td>$1 \times 10^6$</td>
<td>$&lt;10^4$</td>
</tr>
<tr>
<td>(111) FZ (#17)</td>
<td>$&lt;10^{16}$</td>
<td>$&lt;10^{16}$</td>
<td>0</td>
<td>14</td>
<td>$1 \times 10^7$</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td>(100) CZ (#25)</td>
<td>$&lt;10^{18}$</td>
<td>$&lt;10^{16}$</td>
<td>0</td>
<td>14</td>
<td>$&lt;10^7$</td>
<td>$&lt;5 \times 10^4$</td>
</tr>
<tr>
<td>(111) CZ (#9,</td>
<td>$&lt;10^{18}$</td>
<td>$4 \times 10^{17}$</td>
<td>$&lt;10^4$</td>
<td>7</td>
<td>$&lt;10^6$</td>
<td>$2 \times 10^4$</td>
</tr>
</tbody>
</table>
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![EBIC line scans for stressed SiC sample #17C in central high dislocation density (\(-1 \times 10^9 / \text{cm}^2\)) region: (a) after four-point bending at 1370°C; (b) after one-hour anneal at 575°C; (c) after one-hour anneal at 850°C.]

**Observations**

- **Anneals above 1200°C in evacuated quartz ampule in quartz tube furnace and crystal growth furnace have similar effects in degrading L.**

- **L is 15-25 microns in dislocation-free regions; dislocations up to \(-1 \times 10^9 / \text{cm}^2\) degrade it to 10-15 microns.**

- **Subsequent one-hour anneals at 575°C and 850°C raise L by factor of two at best (much below starting L ~ 150 microns).**

- **L values are independent of oxygen and carbon concentrations, and similar to EFG as-grown material.**

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Conclusions

- L IS POINT DEFECT LIMITED TO RANGE OF ABOUT 20 MICRONS AND IS FIXED BY COOLING RATE FROM HIGH TEMPERATURES.

- IN-DIFFUSION OF SLOW DIFFUSING IMPURITIES RULED OUT -- NO GRADIENTS.

- IF IN-DIFFUSION BY IRON OCCURS, DISLOCATIONS, CARBON AND OXYGEN DO NOT PRODUCE SIGNIFICANT GETTERING WITH ANNEALING FOR ONE HOUR AT 575°C AND 850°C.

Comparison of Boron and Gallium-Doped EFG Material As-Grown Quality as a Function of Resistivity

<table>
<thead>
<tr>
<th>RESISTIVITY (OHM-CM)</th>
<th>DOPANT TYPE</th>
<th>SPV L (MICRONS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNDOPED (&gt; 15)</td>
<td></td>
<td>40-60</td>
</tr>
<tr>
<td></td>
<td>BORON</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>GALLIUM</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>BORON</td>
<td>40</td>
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<td>GALLIUM</td>
<td>55</td>
</tr>
<tr>
<td>1</td>
<td>BORON</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>GALLIUM</td>
<td>45</td>
</tr>
<tr>
<td>0.2</td>
<td>BORON</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GALLIUM</td>
<td></td>
</tr>
</tbody>
</table>
Future Work

- EBIC studies of FZ silicon stressed at 600-1000°C, cooled under load
  - Suggestion is that dislocation electrical activity may differ when cooled with and without stress.
  - Use information to help identify temperature of generation of dislocations in EFG sheet-stress conditions.
  - Phosphorus gettering (900°C) response.

- Continued characterization and comparison of low resistivity boron and gallium dopant effects.

- Modeling of horizontal temperature profiles in sheet growth.

- Examination of feasibility of inclined interface EFG for stress reduction.