Epitaxial 3C- and 6H-SiC PN Junction Diodes

OBJECTIVE OF DEVICE RESEARCH:

To advance and improve 3C- and 6H-SiC fundamental device processing and epitaxial growth techniques for use in all SiC-based electrical device structures (e.g., SiC Diodes, MESFET's, JFET's, MOSFET's, SIT's, Thyristors, BJT's, etc.).

APPROACH:

Focus on fundamental pn junction

Fabricate epitaxial 3C- and 6H-SiC pn junction diodes on same 6H-SiC substrate.

Characterize electrical capabilities and identify performance limiting factors

STATUS:

Best 3C-SiC pn diodes ever reported
- Rectification demonstrated to -200 V (4-fold improvement in 3C blocking voltage)
- Green-yellow light emission
- Stacking faults not yet completely eliminated

Excellent 6H-SiC pn diodes
- Reverse leakage of 200 µm x 200 µm diode at -1100 V < 20 nA (< 50 µA/cm²)
- Forward current perimeter dominated
Electrical Characterization of 3C- and 6H-SiC PN Junction Diodes Grown by CVD on Low-Tilt-Angle 6H-SiC Wafers

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3C PN Diode

- 1 µm P+ 3C-SiC N_A > 10^{18} cm^{-3}
- 5 µm N^+ 3C-SiC Epilayer
  N_D = 1 \times 10^{16} cm^{-3}
- N^+ 3C-SiC Epilayer
  N_D > 10^{18} cm^{-3}
- N^+ 6H-SiC Epilayer
- N^+ 6H-SiC Substrate

6H PN Diode

- 1 µm P+ 6H-SiC N_A > 10^{18} cm^{-3}
- 5 µm N^+ 6H-SiC Epilayer
  N_D = 1 \times 10^{16} cm^{-3}
- N^+ 6H-SiC Epilayer
  N_D > 10^{18} cm^{-3}
- N^+ 6H-SiC Substrate

Unannealed Al Contact

Thermal SiO_2

Unannealed Ni Backside Contact
Epitaxial 3C-SiC PN Diode Grown on 6H-SiC Wafer

100 µm x 100 µm Device

T = 25 °C

P. Neudeck et. al. Unpublished Data 1992
Improvement in 3C-SiC PN Diode Characteristics

T = 25 °C

NASA Lewis Research Center, Unpublished Data 1992
Temperature Performance of Epitaxial 3C-SiC PN Junction Diode

NASA Lewis Research Center, Unpublished Data 1992
3C PN Diode Characteristics on a Logarithmic Scale

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>J₀ (A/cm²)</th>
<th>n</th>
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</thead>
<tbody>
<tr>
<td>24</td>
<td>3.8 x 10⁻¹¹</td>
<td>3.07</td>
</tr>
<tr>
<td>95</td>
<td>2.1 x 10⁻¹⁰</td>
<td>2.56</td>
</tr>
<tr>
<td>200</td>
<td>4.9 x 10⁻⁸</td>
<td>2.42</td>
</tr>
<tr>
<td>300</td>
<td>1.1 x 10⁻⁶</td>
<td>2.08</td>
</tr>
</tbody>
</table>

NASA Lewis Research Center, Unpublished Data 1992
Though Vastly Improved, NASA 3C-SiC PN Diodes Are Far From Ideal

- DBP's eliminated. Stacking faults significantly reduced, but not eliminated.

- Leakages significantly reduced, but still excessive for wide band gap semiconductor.

- Record 200 V rectification demonstrated, but breakdown remains "soft".

- 3C on 6H epilayer growth is not as well-developed as 6H on 6H epilayer growth, but considerable progress has been made.
On-Axis 6H-SiC PN Diode

T = 24 °C in Fluorinert
200 µm x 200 µm Device

Leakage Current at -1100 V < 20 nA

NASA Lewis Research Center, Unpublished Data 1992
200 µm Diameter NASA 6H-SiC On-Axis PN Junction Diode

(Measured in Air)

Milliamp Scale

Microamp Scale

NASA Lewis Research Center, Unpublished Data 1992
On-Axis 6H-SiC PN Diode Forward Characteristics

- T = 24 °C
- 200 µm Diameter Device
- $J_0 = 5 \times 10^{-22} \text{ A/cm}^2$
- Ideality Factor = 2.04
- Exponential Forward Current
- Resistance Due To Unannealed Contacts
- Background Measurement Noise

NASA Lewis Research Center, Unpublished Data 1992
Perimeter Recombination Current:

\[ I_{\text{Perim. Rec.}} = qP \int_{-x_p}^{x_n} R_S(y)dy \approx qn_is_0L_sW_{\text{eff}} P \left( e^{qV/n_s kT} - 1 \right) \]
\[ = J_{0\text{Perim.}} P \left( e^{qV/n_s kT} - 1 \right) \]

Bulk Recombination Current:

\[ I_{\text{Bulk Rec.}} = qA \int_{-x_p}^{x_n} R_B(y)dy \approx \frac{qn_iW_{\text{eff}}}{\tau_0} A \left( e^{qV/n_b kT} - 1 \right) \]
\[ = J_{0\text{Bulk}} A \left( e^{qV/n_b kT} - 1 \right) \]

Typically:

1.) Temperature dependence dominated by \( n_i = \sqrt{N_C N_V} e^{-E_G/2kT} \)
\[ \Rightarrow \text{Activation Energy of } J_0 \approx \frac{E_G}{2} \]

2.) \( n_S, n_b \approx 2 \Rightarrow \text{Ideality Factor} \approx 2 \)
Saturation Current Density $J_0$ (A/cm$^2$)

Temperature (°C)

$E_A = 1.45$ eV $\approx \frac{E_G}{2}$

NASA 6H-SiC Epitaxial PN Junction Diodes

NASA Lewis Research Center, Unpublished Data 1992
Current = \( I_{Diode} = I_{Bulk} + I_{Perimeter} \)

\[ = (J_{Bulk} \cdot A) + (J_{Perimeter} \cdot P) \]

Current Density = \( \frac{I_{Diode}}{A} = J_{Bulk} + J_{Perimeter} \cdot \left( \frac{P}{A} \right) \)

Plot of Current Density (J) vs. Perimeter-to-Area Ratio (P/A)

Y intercept ⇒ Bulk Current Component
Slope ⇒ Perimeter Current Component
Zero Y-intercept indicates that bulk recombination current is unmeasurably small compared to surface recombination current at room temperature.

First-Order Calculations:
- Bulk lifetime $\tau_0 > 5 \times 10^{-8}$ s (limit of measurement scatter error)
- Surface recombination velocity $s_0 \approx 5 \times 10^5$ cm/s
Summary

Best 3C-SiC pn junction diodes ever reported

- Rectification demonstrated to -200 V (4-fold improvement in 3C blocking voltage)
- Green-yellow light emission
- Much room for improvement remains
  - Stacking faults not yet completely eliminated

Excellent 6H-SiC pn junction diodes

- Reverse leakages of less than 50 µA/cm² at -1100 V demonstrated
- Bulk recombination insignificant compared to perimeter recombination
- Half band gap activation energy observed