Wide Bandgap Semiconductor in High-temperature Power Electronics

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Why high-temperature electronics?

• Operation of solid state devices closer to heat sources
  – Aircraft / Space Systems
  – Automotive Engines
  – Deep well logging and drilling
  – Energy production center

• Alternative solutions
  – Huge heat sinks and active water cooling system with thermal management
  – Long shielded wires
Semiconductor devices at high temperature

- Intrinsic carrier concentration
  \[ n_i = \sqrt{N_c N_v e^{-E_G/2kT}} \]

- Metal/semiconductor interdiffusion
- Lowering of Schottky barrier
- Degradation of Ohmic contact
- Mobility degradation

[Zolper1998]
Limits of silicon power devices

- Si-based CMOS technology expected to operate up to 200°C

- Silicon-on-insulator technology (lower leakage and attenuated threshold voltage shift) extending this to 300°C

[Cristolo1998]
Some desired properties

- Wide bandgap
  - Intrinsic carrier density

- High breakdown field
  - Reduce thickness of conduction region
  - Then lower conduction resistance

- High electron mobility

- Large saturation velocity
  - Good RF performance

- High thermal conductivity
  - Compact and high power density
## Physical Properties of semiconductors

<table>
<thead>
<tr>
<th></th>
<th>Bandgap (eV)</th>
<th>Electron saturation velocity ($10^7$ cm s$^{-1}$)</th>
<th>Dielectric constant</th>
<th>Breakdown field ($10^5$ V cm$^{-1}$)</th>
<th>Thermal conductivity (W cm$^{-1}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1</td>
<td>1.0</td>
<td>11.8</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>SiC</td>
<td>3.3</td>
<td>2.0</td>
<td>9.8</td>
<td>25</td>
<td>4.9</td>
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<tr>
<td>GaN</td>
<td>3.4</td>
<td>2.2</td>
<td>7.8</td>
<td>20</td>
<td>1.4</td>
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<tr>
<td>Diamond</td>
<td>5.5</td>
<td>2.7</td>
<td>5.5</td>
<td>100</td>
<td>10 - 20</td>
</tr>
<tr>
<td>AlN</td>
<td>6.2</td>
<td>1.8</td>
<td>8.5</td>
<td></td>
<td>3.0</td>
</tr>
</tbody>
</table>
SiC diodes

• Schottky Diodes
  (Commercialized)
  – Schottky barrier must be low to reduce power loss
  – Schottky barrier must be high enough to reduce leakage current, even at elevated temperature

  – Different combinations of transition metals form good Schottky contacts
  – Change to ohmic or degrade severely above 600°C

• Junction-Barrier Schottky Diodes

[Liu1998]
[Baliga1984]
[Zetterling 1998]
Vertical JFET in SiC

<table>
<thead>
<tr>
<th></th>
<th>Room T</th>
<th>325ºC</th>
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</thead>
<tbody>
<tr>
<td>Breakdown Voltage [V]</td>
<td>1644</td>
<td>1928</td>
</tr>
<tr>
<td>Leakage Current [A/cm²] at $V_D = 1600$V</td>
<td>1.2e-7</td>
<td>2.7e-4</td>
</tr>
<tr>
<td>Forward current density [A/cm²] at $V_D = 1.2$V</td>
<td>249</td>
<td>61</td>
</tr>
</tbody>
</table>

[Zhao2001]
SiC JFET and SBD with thermal stable package

- Ni-plated JEDEC TO-258 package
- The buck converter tested up to an ambient temperature of 400ºC

[Funaki2007]
SiC MOSFET

- Carrier mobility of SiC

- Effective channel mobility is even smaller because of trapping of field-induced carriers by the interface states

- No low threshold and high current carrying SiC power MOSFET found in literature

[Elasser2002]
[Chatty2001]
AlGaN/GaN HFET

- [Ueda2005] “confirmed that the GaN HEMTs operated at more than 300°C”

- No data on gate leakage and drain leakage current shown for high-temperature operation

- 2DEG mobility is sensitive to temperature, $T^{-2.3}$ dependence

Fig. 1 Cross-sectional GaN HEMT unit cell structure (unit: $\mu$m)

[Trew2002]
Keep your AlGaN/GaN HFET cool: via-holes

[Uemoto2009]
• Uniform power generation of 8W/mm in the channel

• Integration of the via-holes reduces the maximum channel temperature down to 150°C, while that without the via-holes is as high as 225°C

• The metal filling the via-holes greatly helps to reduce the temperature.

[Uemoto2009]
InAlN/GaN HEMT

- 0.25um gate length
- 100V breakdown with field plates
- 13nm/5nm/2.5nm barrier demonstrated

<table>
<thead>
<tr>
<th>AlInN barrier thickness</th>
<th>Pinch-off voltage</th>
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<tbody>
<tr>
<td>13nm</td>
<td>-9V</td>
</tr>
<tr>
<td>5nm</td>
<td>-2V</td>
</tr>
<tr>
<td>2.5nm</td>
<td>-0.8V</td>
</tr>
</tbody>
</table>

[Medj2006]
[Medj2007]
• 2A/mm at room temperature
• 0.85A/mm at 800°C in vacuum
• 0.6A/mm at 1000°C in vacuum
• Operation up to melting point of gold
• No published data on leakage current at elevated temperature

[Medj2006]
Challenges

• Reliable Schottky contact and ohmic contact
• Normally-off operation
• Reliable Package
Reference