Towards Medium Voltage (3.3 – 15kV) SiC Devices

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## Why MV Silicon Carbide Power Devices?

<table>
<thead>
<tr>
<th>Property - Silicon Carbide vs Silicon</th>
<th>Performance of MV SiC Devices</th>
<th>Impact on Power Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown Field (10X)</td>
<td>Lower On-state Voltage drop for 5-20 kV Devices (2-3X)</td>
<td>Higher Efficiency of circuits</td>
</tr>
<tr>
<td>Thinner Epitaxial Layers (10-20X)</td>
<td>Faster Switching speeds (100-1000X)</td>
<td>Compact circuits</td>
</tr>
<tr>
<td>Higher Thermal Conductivity (3.3-4.5 W/cmK vs 1.5 W/cmK)</td>
<td>Higher Chip Temperatures (250-300°C instead of 125°C)</td>
<td>Higher pulsed power Higher continuous current densities,</td>
</tr>
<tr>
<td>Melting Point (2X)</td>
<td>High Temperature Operation (3X)</td>
<td>Simple Heat Sink</td>
</tr>
<tr>
<td>Bandgap (3X) (10(^{16})X smaller (n_i))</td>
<td>High Intrinsic Adiabatic Pulsed Current Level (3-10X?)</td>
<td>Higher Current Capability</td>
</tr>
</tbody>
</table>
- Maximum Voltage and Current Ratings of SiC Devices significantly higher than theoretical capability of Si
- Further SiC offers larger margins from failures
Immediate Application Areas (1)

- **Solar Inverter power Modules**
  - Driver: High Efficiency
  - 600-1200V: 20A

- **Hybrid Electric Vehicle power Modules**
  - Driver: Compact, High Temp
  - 600-1200V: 20-50A

- **Oil Drilling, Aerospace, power components**
  - Driver: High Temperature
  - 600-1200 V
Immediate Application Areas (2)

- **Wind Inverter power Modules**
  - Driver: High Voltage, Efficiency
  - 1200-3300V: 20A
  - Rectifiers, Transistors, Thyristors

- **Electric Trains**
  - Driver: High Voltage, Efficiency
  - 3300-6500V: >100A
  - Rectifiers, Transistors, Thyristors

- **Power Grid, HVDC Power T&D**
  - Driver: High Voltage, Efficiency
  - 6500-12000V: >100A
  - Rectifiers, Transistors, Thyristors
# All-SiC (SJT+Rectifier) Co-packaged Parts

<table>
<thead>
<tr>
<th>Rated Blocking Voltage (V)</th>
<th>Current Rating / $R_{\text{DS(ON)}}$</th>
<th>TO-247</th>
<th>TO-263 / D2PAK</th>
<th>SOT-227</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GA10SICP12-247</td>
<td>GA10SICP12-263</td>
<td>GA50SICP12-227</td>
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<td>GA20SICP12-263</td>
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<tr>
<td></td>
<td></td>
<td>GA50SICP12-227</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>10A / 100mΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>20A/ 50mΩ</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>50A/ 20mΩ</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>100A/ 10mΩ</td>
<td></td>
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</tr>
</tbody>
</table>

- **SiC Module - Co-Pack**
- **Digi-Key**
- **Mouser Electronics**
- **Newark**
- **Premier Farnell**
- **Element14**
- **onlinecomponents.com**
# Commercial SiC Schottky Rectifiers

<table>
<thead>
<tr>
<th>Rated Blocking Voltage (V)</th>
<th>Current Rating (A)</th>
<th>TO247-3L</th>
<th>TO247-2L</th>
<th>TO220 / TO220FP</th>
<th>TO-252</th>
<th>SMB / DO-214AA</th>
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</thead>
<tbody>
<tr>
<td>650</td>
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<td>GB01SLT06-214</td>
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<tr>
<td>1200</td>
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<td>GB01SLT12-252</td>
<td>GB01SLT12-214</td>
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<tr>
<td></td>
<td>2</td>
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<td></td>
<td>GB02SLT12-220</td>
<td>GB02SLT12-252</td>
<td>GB02SLT12-214</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td>GB05SLT12-220</td>
<td>GB05SLT12-252</td>
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<tr>
<td></td>
<td>10</td>
<td>GB10SLT12-247D</td>
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<td>GB10SLT12-220</td>
<td>GB10SLT12-252</td>
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<tr>
<td>3300</td>
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<td></td>
<td>GAP3SLT33-220FP</td>
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<td>GAP3SLT33-214</td>
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<tr>
<td>8000</td>
<td>0.05</td>
<td></td>
<td></td>
<td>GAP05SLT80-220</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SJT Structure and Advantages

- Lowest $V_{DS(ON)}$ as compared to any other commercial SiC switch
- Best in class temperature independent switching
- Positive temperature coefficient of VF for easy paralleling
- Gate oxide free SiC switch - High Operating Temperature
- Avalanche Capable, Short Circuit rated
- Easy to drive using commercial drivers
- Suitable for connecting an anti-parallel diode
- Low gate charge, Low intrinsic capacitance,
- High Yielding, Smaller size, Lower cost
1700 V SJT-Si IGBT Output Characteristics

- Benchmarked with best-in-class 40-75 A 1700 V Si IGBTs
- The SJT’s $V_F$ is 50% lower than either IGBT at high operating temperatures
• The SJT’s leakage current increases marginally from 200 nA at 25°C to 1.5 µA at 175°C.

• On the other hand, the IGBT leakage currents are in the mA range at 150°C
  – Excessive off-state power loss > 5 W estimated
Turn-off Comparison 1700 V SJT with Si IGBTs

- SJT shows MOSFET-like fast turn-off waveforms, due to unipolar operation
- The bipolar IGBTs feature a long tail current, which increases the switching losses
• The conduction power loss of the SiC SJT is 2.2x smaller than the best Si IGBT during 150°C operation.
• 10.5 kV $BV_{CEO}$ measured on 3.65 mm x 3.65 mm discrete BJTs.
• 125 V/µm and 91% of the avalanche breakdown limit achieved.
Output characteristics at high temperatures

- Positive temperature co-efficient of on-resistance observed.
- Current Gain shows a negative temperature co-efficient due to increased ionization in the p-type base layer.
10 kV/8 A SiC BJT switching

- Commercial IGBT gate driver used for inductive load switching of 10 kV SiC BJTs
  - Standard double-pulse scheme used for acquiring turn-on and turn-off switching waveforms.
- Switching measurements performed up to 5 kV and 8 A.
- Capacitor $C_G$ in parallel with $R_G$ introduces high base current peaks during switching transitions
  - Recommended for fast charging and discharging of BJT capacitances.
5 kV/8 A BJT inductive load switching at 150° C

- Turn-on transition: $I_C$ rise time < 30 ns; $V_C$ fall time < 200 ns
- Turn-off transition: $I_C$ fall time < 150 ns; $V_C$ recovery time < 100 ns
- Switching Speed limited by package and circuit parasitics
• No difference in switching performance at 25°C and 150°C
  – Confirms lack of conductivity modulation in the n-collector layer.
**10 kV SiC BJT versus 6.5 kV/25 A Si IGBT**

<table>
<thead>
<tr>
<th>Device</th>
<th>BV</th>
<th>I&lt;sub&gt;c&lt;/sub&gt;</th>
<th>Temp. (°C)</th>
<th>V&lt;sub&gt;CE,sat&lt;/sub&gt; (V)</th>
<th>E&lt;sub&gt;on&lt;/sub&gt; (mJ)</th>
<th>E&lt;sub&gt;off&lt;/sub&gt; (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC BJT</td>
<td>10 kV</td>
<td>8 A</td>
<td>150°C</td>
<td>6.4</td>
<td>4.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Si IGBT</td>
<td>6.5 kV</td>
<td>10 A</td>
<td>125°C</td>
<td>4</td>
<td>80</td>
<td>40</td>
</tr>
</tbody>
</table>

- SiC BJT achieves 19 x lower turn-on energy loss and 25 x lower turn-off energy loss, as compared to a commercially available 6.5 kV/25 A Si IGBT

* Si IGBT switching data sourced from device datasheet
• 3.65 mm x 3.65 mm SiC BJT turned on to a short-circuited load at a DC link voltage of 4.5 kV.

• A short-circuit withstand time of ≥20 µs observed at $V_{CE} = 4.5$ kV and $T_C = 125^\circ$ C
  – Near-infinity output resistance (and Early voltage) results in $V_{CE}$ invariance of $I_{SC}$
High-temperature blocking performance of 6.5 kV SiC Thyristors
AST Switching in an Inductively Loaded Circuit

- 10 µF capacitor charged to desired switching voltage.
- Appropriately chosen load inductor sets a load current ramp rate.
- 10 kV SiC JBS Rectifier fabricated at GeneSiC used as free-wheeling diode.
AST Switching Up To 3600 V/14.5 A

- 2000 V/7 A AST Switching
- 3000 V/11.5 A AST Switching
- 3600 V/14.5 A AST Switching
On-state characteristics

- Ultra-low diff. $r_{on,sp}$ of **3 mΩ-cm$^2$** measured on packaged 2.4 mm x 2.4 mm diodes.
- Higher Emitter Injection Efficiency due to:
  - Lower base doping ($3 \times 10^{14}$ cm$^{-3}$)
  - Thicker p+ Emitter (2.5 µm)
- Higher Diff. $r_{on,sp}$ of **5.25 mΩ-cm$^2$** measured on packaged 6.4 mm x 6.4 mm diodes.
- Lower Emitter Injection Efficiency due to:
  - Higher base doping ($8 \times 10^{14}$ cm$^{-3}$)
  - Thinner p+ Emitter (2 µm)
High-Voltage Switching Measurements with a 6.5 kV/25 A Si IGBT

- 6.4 mm x 6.4 mm PiN Rectifier connected as FWD with a 6.5 kV/25 A Si IGBT.
- Switching characteristics evaluated by Inductively loaded chopper circuit and double-pulse technique.
- $Q_{rr} = 1.67 \, \mu\text{C}$ and $t_{rr} = 250 \, \text{ns}$ obtained for turning-off 24 A through the PiN Rectifier at a reverse bias of 2400 V.
High-CURRENT PiN Rectifier Module

- High-CURRENT PiN Rectifier Module fabricated by paralleling five 6.4 mm x 6.4 mm PiN Rectifiers
- On-State Measurements performed up to 225 A
- Switching measurements performed at 1100 V and 100 A by connecting as FWD with a 1200 V/100 A Si IGBT
8 kV JBS diodes – Blocking performance

- Measured BVs are close to the theoretical limit of 10 kV for the 4H-SiC epilayer used for device fabrication
High-Voltage Switching Measurements with a 6.5 kV/25 A Si IGBT

- SiC JBS or PiN Rectifier connected as FWD with a 6.5 kV/25 A Si IGBT.
- Switching characteristics evaluated by Inductively loaded chopper circuit and double-pulse technique.
A 10 kV/6.4 mm x 6.4 mm PiN rectifier and a parallel combination of five, 10 kV/4.25 mm x 4.25 mm SiC JBS rectifiers are compared.

- The PiN Rectifier displays significantly higher (15 A) reverse recovery current as compared to 2 A for the JBS rectifier module.
- Slow voltage rise time is due to large IGBT output capacitance.
Conclusions

• GeneSiC has developed commercially successful SiC-based discrete Rectifiers and Transistors for high temperature use in the 600-1200 V range

• Commercial discrete SiC devices offered with
  – Extensive voltage/current/packages
  – Industry leading performance/high power densities

• Pioneering commercialization of UHV SiC Devices
  – 6.5kV Thyristors commercially available since 2011
  – 8-15 kV Diodes commercially available