Experimental Investigation of Silicon Carbide Power Device Reliability

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**Project Overview**

- **Wide-bandgap semiconductors have material properties that make them theoretically superior to Silicon for power device applications**
  - Lower power loss and reduced cooling requirements would increase the efficiency and reduce the size and complexity of power conversion systems linking energy storage to the grid, *thus reducing overall system cost*
  - However, wide-bandgap materials and devices are far less mature than their Si counterparts; many questions remain regarding their reliability, *limiting their implementation in systems*

- **Goal:** Develop a reliability model for a commercially available plastic- and metal-packaged 1200 V SiC power MOSFET under bias and temperature stress
Example of Motivation for WBG Power Electronics: Portable Energy Storage

**Benefits of portable storage**
- Low installation cost
- Short time from installation to operation
- System is optimized for use at multiple sites

**Typical portable power conversion system**
- PWM voltage sourced converter
- Silicon-based power electronics
- Water cooled (*complex, bulky, and expensive*)

**Typical Applications**
- Grid stabilization
- Frequency regulation
- Renewable integration
- Peak shaving
- Voltage support
SiC has Superior Material Properties for Power Devices

SiC

- Band Gap
- Breakdown Electric Field
- High Temperature
- High Voltage
- Low $n_i$
- SATuration Velocity
- Small Size
- Dielectric Constant
- Low Capacitance
- Thermal Conductivity
- High Temperature
- High Frequency
- High Temperature
- Low Capacitance

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>4H-SiC</th>
</tr>
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<tbody>
<tr>
<td>$E_G$ (eV)</td>
<td>1.1</td>
<td>3.2</td>
</tr>
<tr>
<td>$E_C$ (MV/cm)</td>
<td>0.3</td>
<td>3.0</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>11.8</td>
<td>10.0</td>
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<tr>
<td>$v_s$ ($10^7$ cm/s)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\kappa$ (W/cm$^\circ$K)</td>
<td>1.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>


Figure courtesy of Prof. D. K. Schroder, ASU (collaborator on this project).
Potentially Lower Power Loss for SiC compared to Si

Switch power loss mechanisms:
1. Leakage
2. Turn-on
3. Conduction ($R_{ON}$)
4. Turn-off

Figure courtesy of Prof. D. K. Schroder, ASU (collaborator on this project)

We have characterized the reliability of a commercially available 1200 V SiC power MOSFET
Leakage Loss Mechanism: Plastic vs. Metal Package

- Part is rated to 125°C
- Metal-packaged part shows negligible leakage for $T \leq 140°C$
- Plastic-packaged part shows significantly higher leakage at high $T$
Gate Voltage Dependence of OFF-State Leakage Current

- Metal package: Negative gate voltage may be used to turn device completely off.
- Plastic packaging appears to introduce an extrinsic drain-to-source leakage path.
Conduction Loss Mechanism: Threshold Voltage Instability

- Shift in threshold voltage $\Delta V_T$ (likely due to charge trapping in the gate oxide) will change $R_{ON}$ and thus the ON-state conduction power loss

- $\Delta V_T$ is a function of time $t$, gate voltage $V_G$, and temperature $T$

- Assume a power-law dependence on $t$ and $V_G$, and an Arrhenius dependence on $T$

- For positive $V_G$:
  $$\Delta V_T = 8.5 \times 10^{-3} t^{0.40} V_G^{3.8} \exp(-0.34/kT)$$

- For negative $V_G$:
  $$\Delta V_T = -1.4 \times 10^2 t^{0.42} |V_G|^{0.79} \exp(-0.33/kT)$$

Threshold voltage shift is independent of packaging type
Example of Statistical Prognostics: Integrated Free-Wheeling Diode

Free-wheeling diode ideality factor $\eta$ may be used as a statistical screening criterion to predict the $V_T$ shift for a particular device.
We have demonstrated that:

• Plastic packaging of a 1200 V SiC MOSFET increases OFF-state leakage current compared to metal packaging, especially at high temperature – *plastic package increases OFF-state power loss*

• Compared to zero gate voltage, negative gate voltage may be used to reduce leakage current (and hence OFF-state power loss) *in metal-packaged devices only*

• Gate electrical and thermal stress changes the MOSFET’s threshold voltage (and hence ON-state power loss), and we have developed models for $\Delta V_T(t, T, V_G)$ for positive and negative $V_G$ – *normal gate stress increases ON-state power loss*

• The reliability model contains a statistical element, and the free-wheeling diode ideality factor may be used to screen for the expected magnitude of $\Delta V_T$
Future Tasks

• Better understand the statistical nature of the MOSFET reliability model (test a larger number of parts)
• Examine switching loss mechanisms, especially in a realistic power circuit environment
• Investigate the physics of gate oxide degradation (collaboration with Auburn and Arizona State Universities)
• Characterize the reliability of competing WBG devices, and understand which device is best for the power electronics system in terms of performance, reliability, and cost
  • Examine the reliability of non-MOS SiC devices (e.g., BJT and JFET)
  • Compare SiC-based devices to GaN power HEMTs (we have recently initiated a collaboration with Hughes Research Labs for this purpose)
FY12 Publications


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