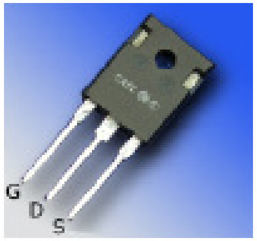

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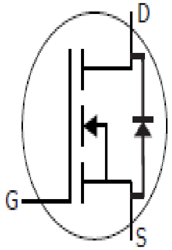

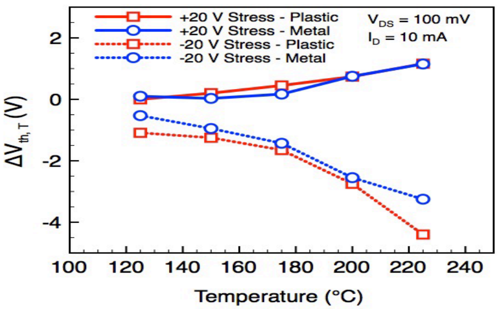

Experimental Investigation of Silicon Carbide Power Device Reliability

September 27, 2012

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Sandia National Laboratories

Exceptional service in the national interest

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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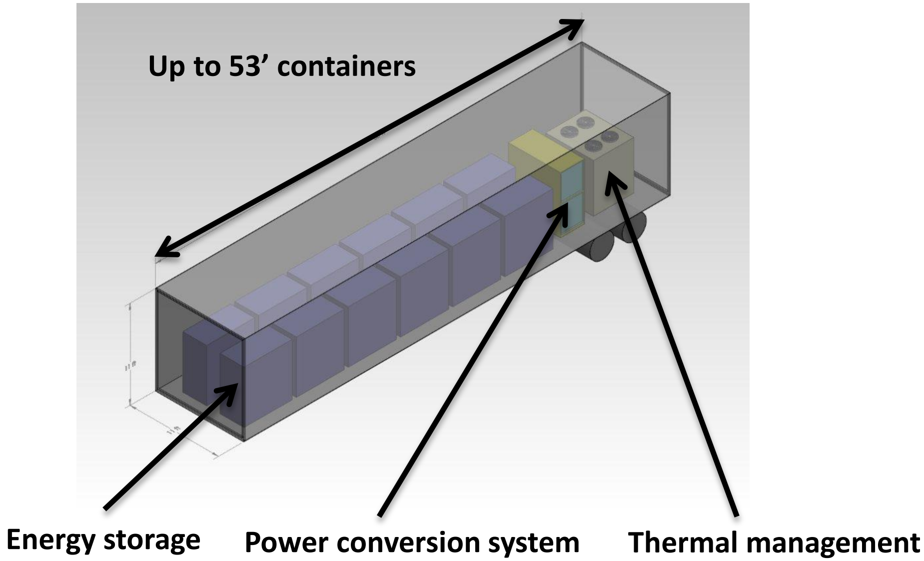
Project Overview

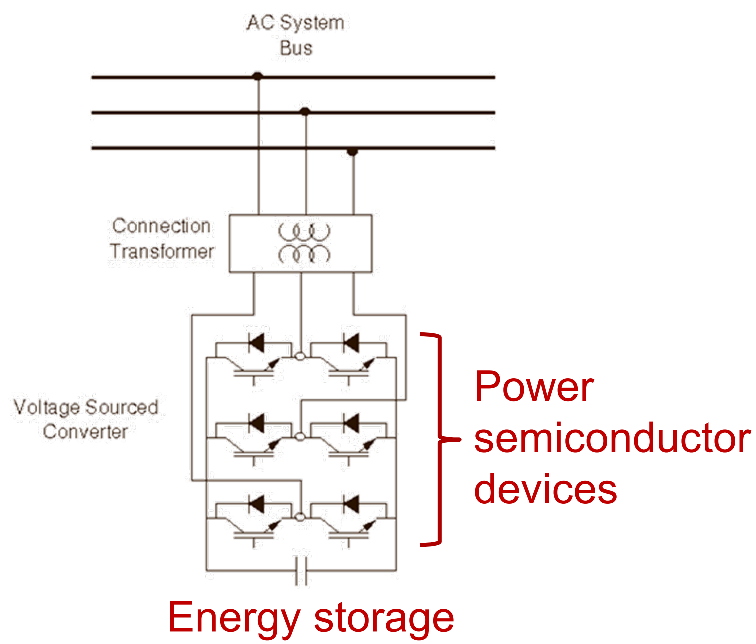
- ***Wide-bandgap semiconductors have material properties that make them theoretically superior to Silicon for power device applications***
  - Lower power loss and reduced cooling requirements would increase the efficiency and reduce the size and complexity of power conversion systems linking energy 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



Typical Applications

- Grid stabilization
- Frequency regulation
- Renewable integration
- Peak shaving
- Voltage support



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*)

SiC has Superior Material Properties for Power Devices

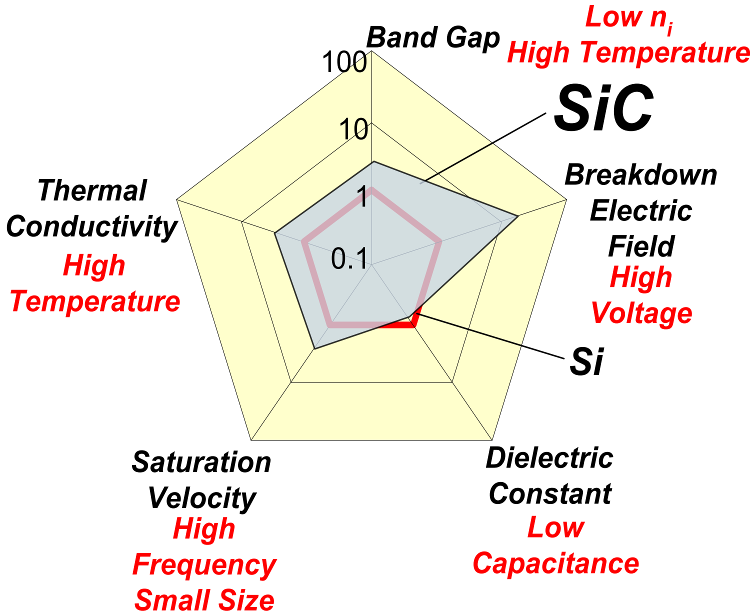
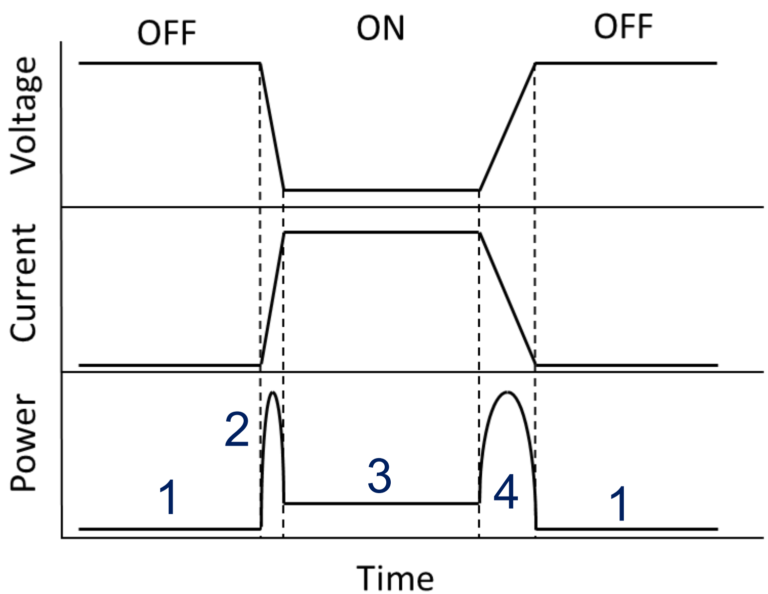


Figure courtesy of Prof. D. K. Schroder, ASU (collaborator on this project)

Property	Si	4H-SiC
E_G (eV)	1.1	3.2
E_C (MV/cm)	0.3	3.0
ε_r	11.8	10.0
v_s (10^7 cm/s)	1.0	2.0
κ (W/cm˚K)	1.5	4.5

Source: T. P. Chow, “High-Voltage SiC Power Rectifiers,” in *Wide Energy Bandgap Electronic Devices*, edited by F. Ren and J. C. Zolper (World Scientific, 2003).

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

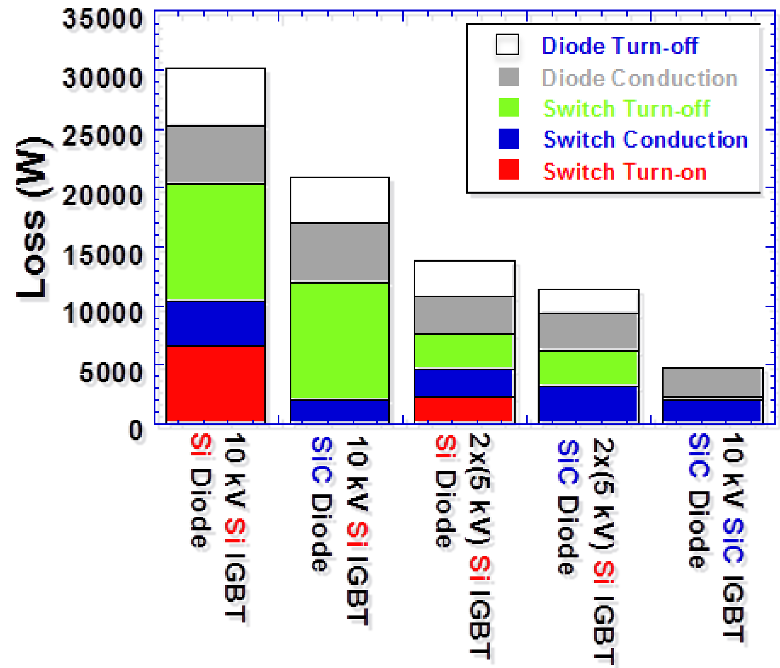
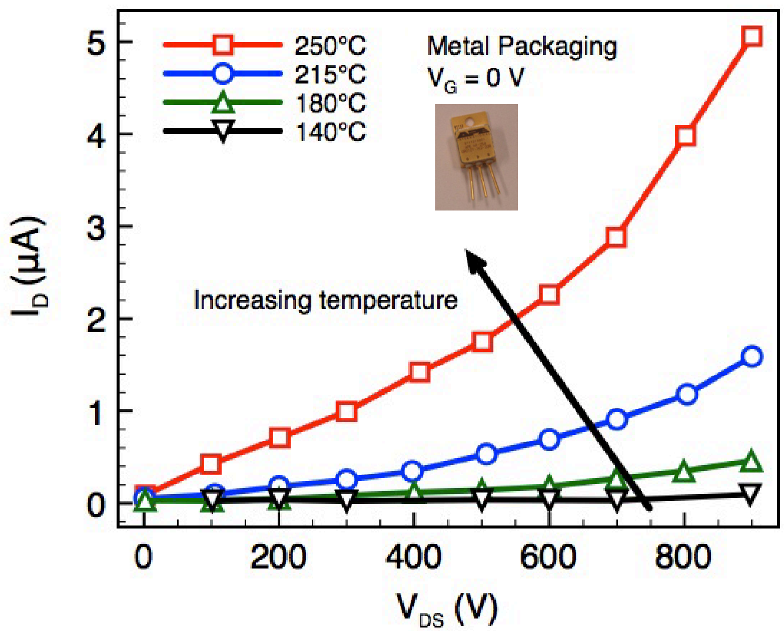
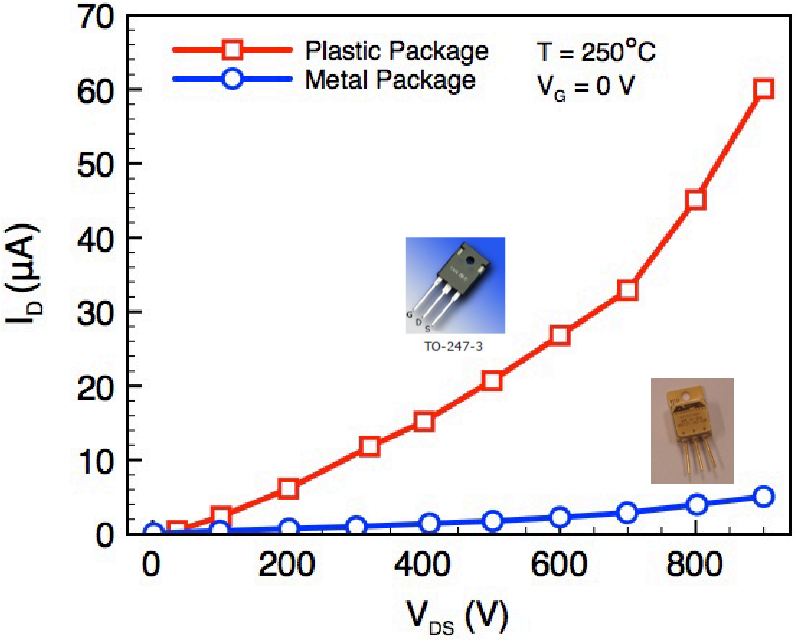


Figure courtesy of Prof. D. K. Schroder, ASU
(collaborator on this project)

We have characterized the reliability of a commercially available 1200 V SiC power MOSFET

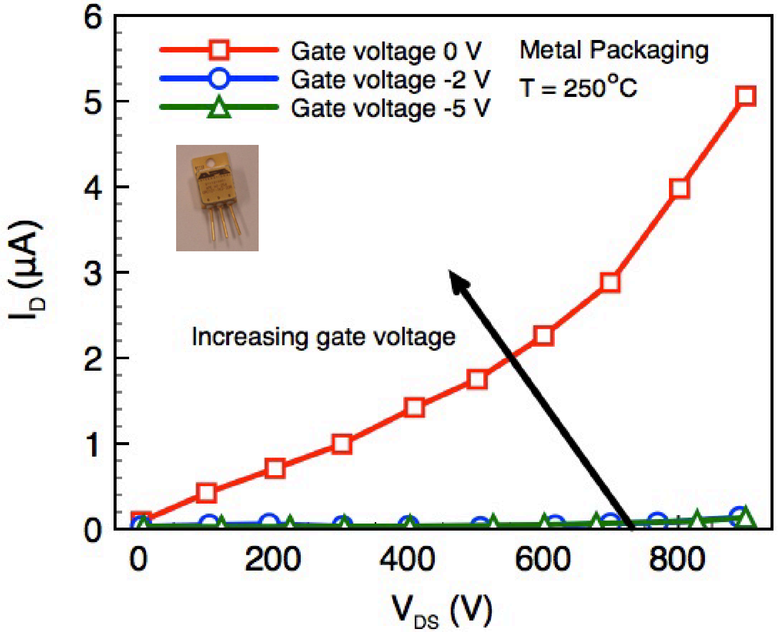
Leakage Loss Mechanism: Plastic vs. Metal Package



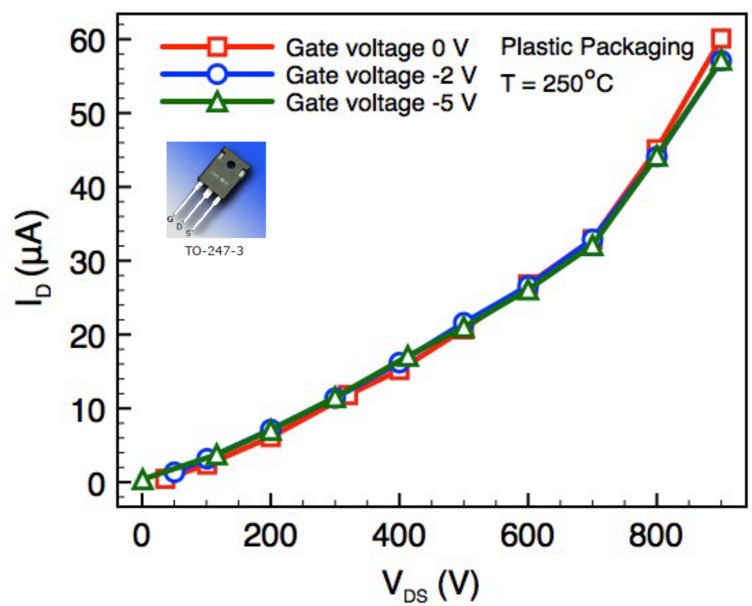


- Part is rated to 125˚C
- Metal-packaged part shows negligible leakage for T ≤ 140˚C
- *Plastic-packaged part shows significantly higher leakage at high T*

Gate Voltage Dependence of OFF-State Leakage Current



Metal package:
Strong V_G dependence



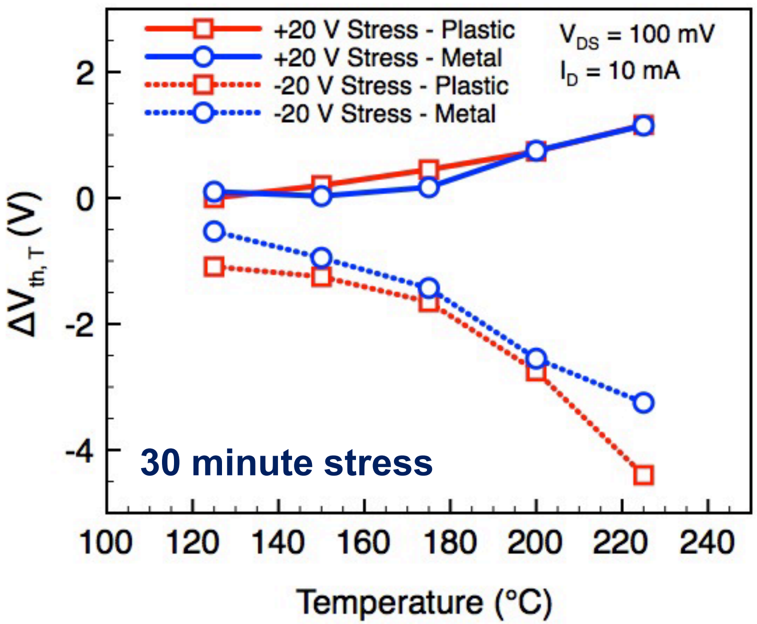
Plastic package:
No V_G dependence

- 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

Plastic

Metal



Threshold voltage shift is independent of packaging type

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

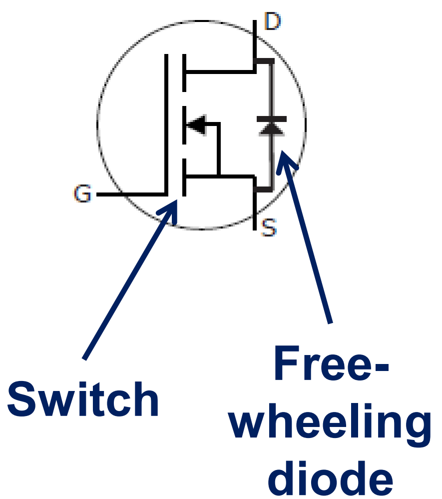
- ΔV_T is a function of time t, gate voltage V_G, and temperature T

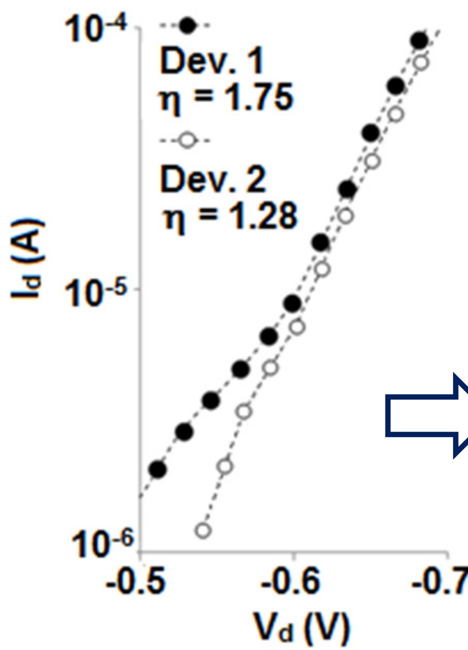
- Assume a power-law dependence on t and V_G, and an Arrhenius dependence on T

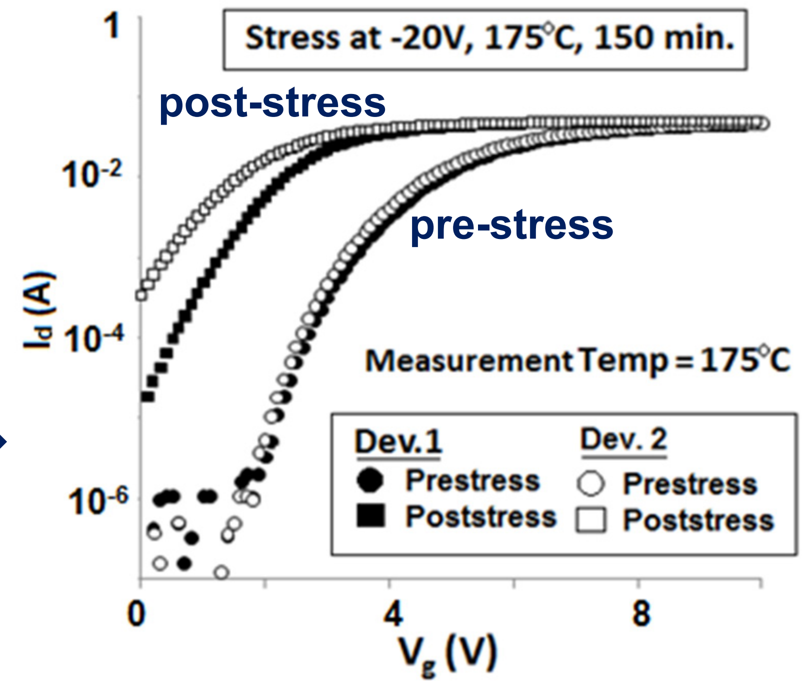
- **For *positive* V_G:**
$\Delta V_T = 8.5\times10^{-3} t^{0.40} V_G^{3.8} \exp(-0.34/kT)$

- **For *negative* V_G:**
$\Delta V_T = -1.4\times10^{2} t^{0.42} |V_G|^{0.79} \exp(-0.33/kT)$

Example of Statistical Prognostics: Integrated Free-Wheeling Diode







Free-wheeling diode ideality factor η may be used as a statistical screening criterion to predict the V_T shift for a particular device

Summary / Conclusions

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 ΔV_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

[1] S. DasGupta, A. Armstrong, R. Kaplar, M. Marinella, R. Brock, M. Smith, and S. Atcitty, "Sub-Bandgap Light-Induced Carrier Generation at Room Temperature in Silicon Carbide MOS Capacitors," *Applied Physics Letters*, vol. 99, no. 17, p. 173502 (October 2011).

[2] S. DasGupta, R. J. Kaplar, M. J. Marinella, M. A. Smith, and S. Atcitty, "Reliability Analysis and Prediction of Commercial 1200 V, 33A, 4H-SiC MOSFETs under DC and Pulsed Stress," presented at the *50th IEEE International Reliability Physics Symposium*, Anaheim, CA (April 2012).

[3] R. Kaplar, M. Marinella, S. DasGupta, M. Smith, S. Atcitty, M. Sun, and T. Palacios, "Characterization and Reliability of SiC- and GaN-Based Power Transistors for Renewable Energy Applications," presented at *IEEE Energy Tech*, Cleveland, OH (May 2012).

[4] S. Atcitty, R. Kaplar, S. DasGupta, M. Marinella, M. Smith, M. Sun, and T. Palacios, "Wide-Bandgap Power Switch Reliability for Energy Storage and Grid Applications," presented at the *Army Research Lab Advanced Microgrid Concepts and Technologies Workshop*, Beltsville, MD (June 2012).

[5] W.-C. Kao, S. DasGupta, M. J. Marinella, R. J. Kaplar, S. Atcitty, and D. K. Schroder, "SiO_2/SiC Interface Trap extraction with MOS Capacitors," presented at the *Army Research Lab SiC MOS Workshop*, College Park, MD (August 2012).

[6] D. R. Hughart, S. DasGupta, R. J. Kaplar, M. J. Marinella, and S. Atcitty, "High Temperature Reliability of 1200 V, 33 A SiC DMOSFETs," presented at the *Army Research Lab SiC MOS Workshop*, College Park, MD (August 2012).

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