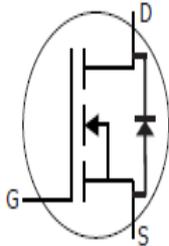


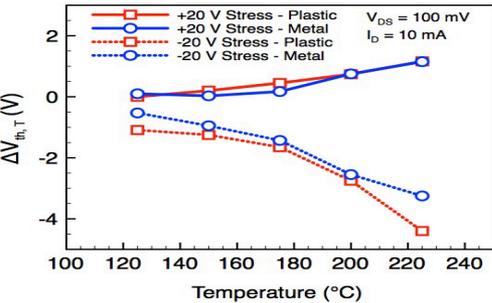
TO-247-3



# Experimental Investigation of Silicon Carbide Power Device Reliability

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*Exceptional  
service  
in the  
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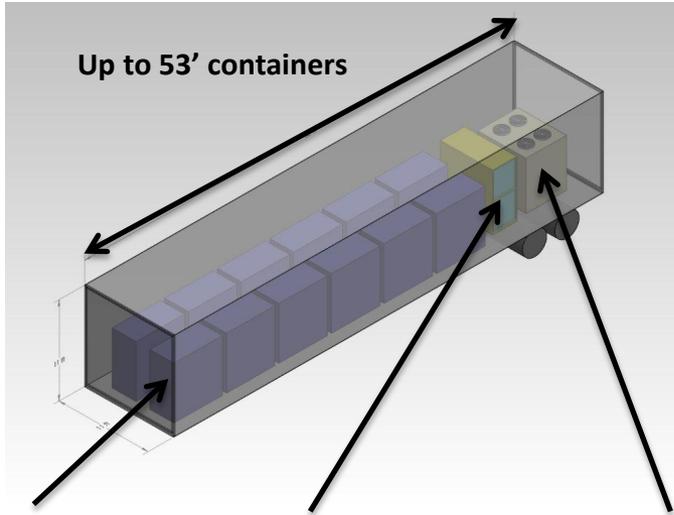
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# Project Overview

- ***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



Energy storage    Power conversion system    Thermal management

## Typical Applications

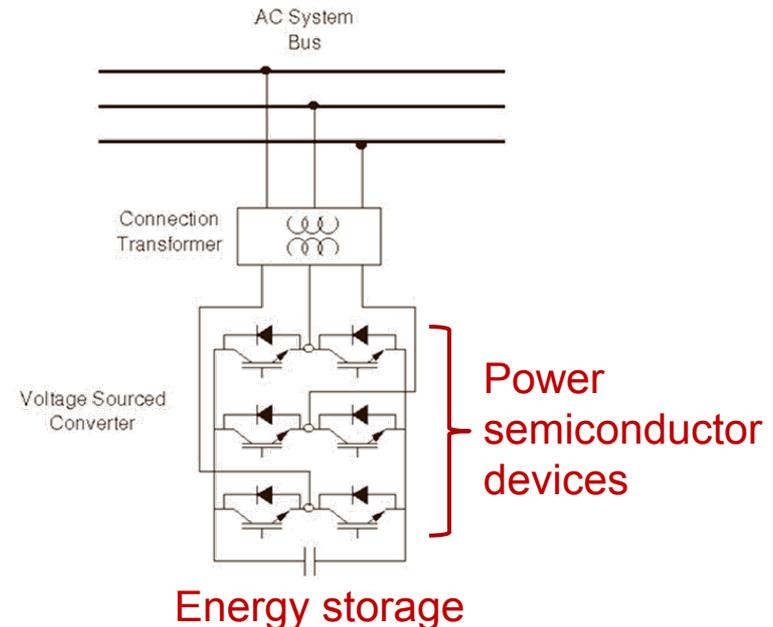
- Grid stabilization
- Frequency regulation
- Renewable integration
- Peak shaving
- Voltage support

## 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

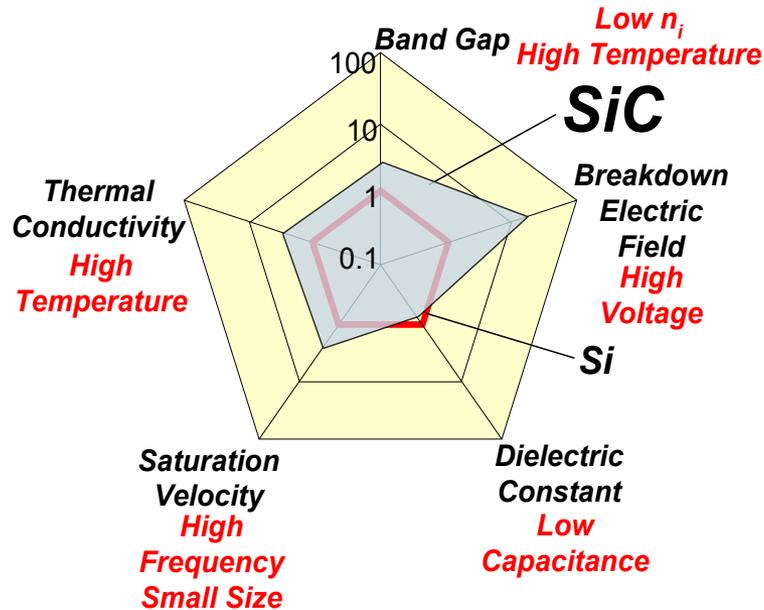
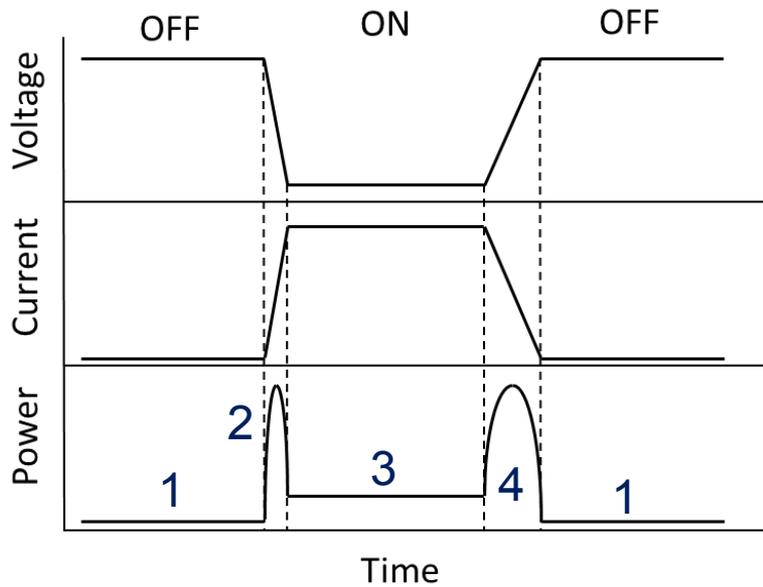


Figure courtesy of Prof. D. K. Schroder, ASU (collaborator on this project)

Property	Si	4H-SiC
$E_G$ (eV)	1.1	3.2
$E_C$ (MV/cm)	0.3	3.0
$\epsilon_r$	11.8	10.0
$v_s$ ( $10^7$ cm/s)	1.0	2.0
$\kappa$ (W/cm $^\circ$ 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

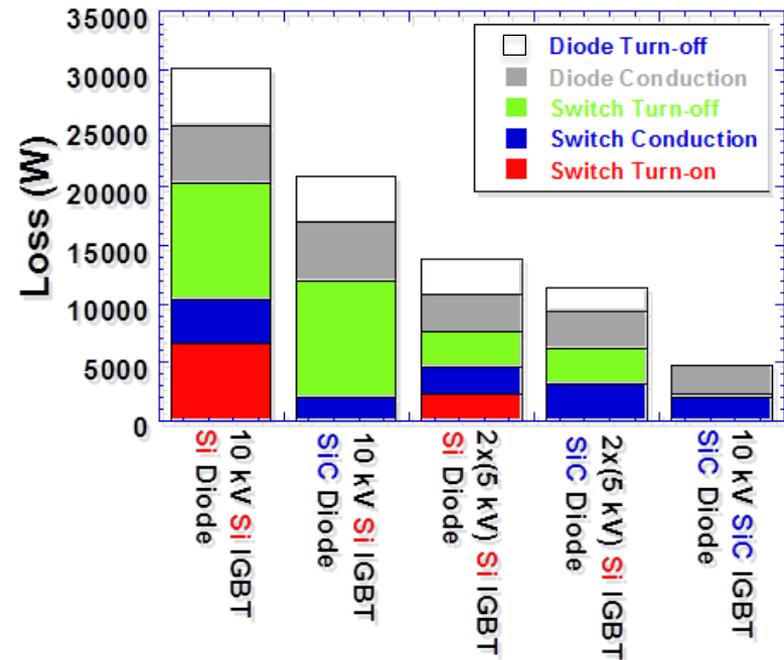
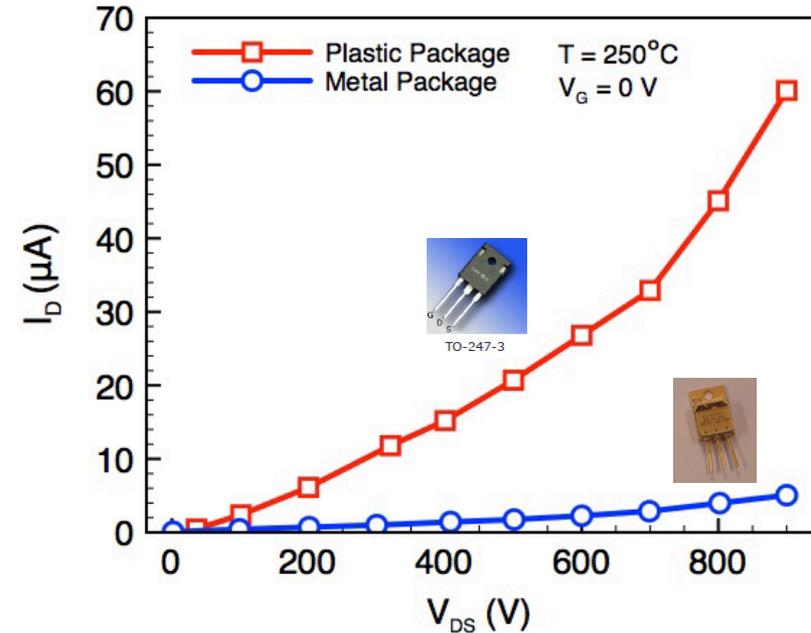
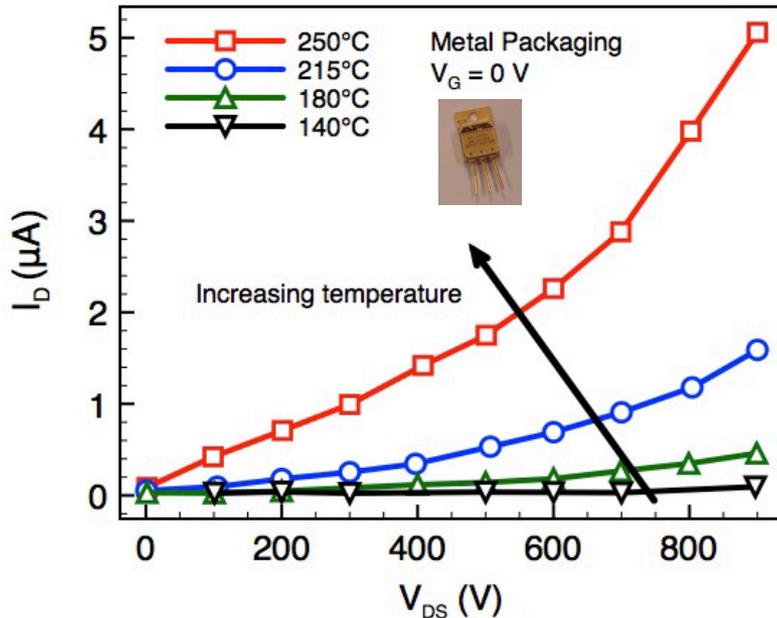


Figure courtesy of Prof. D. K. Schroder, ASU (collaborator on this project)

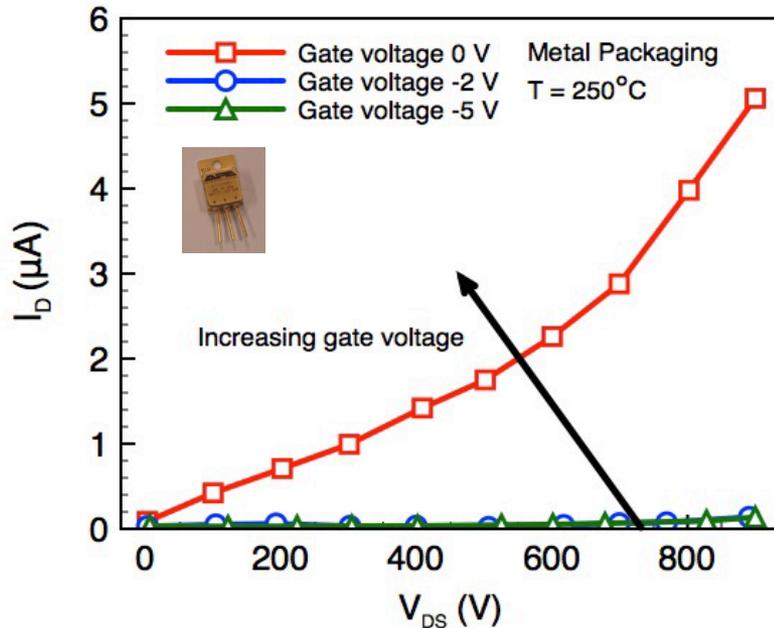
***We have characterized the reliability of a commercially available 1200 V SiC power MOSFET***

# Leakage Loss Mechanism: Plastic vs. Metal Package

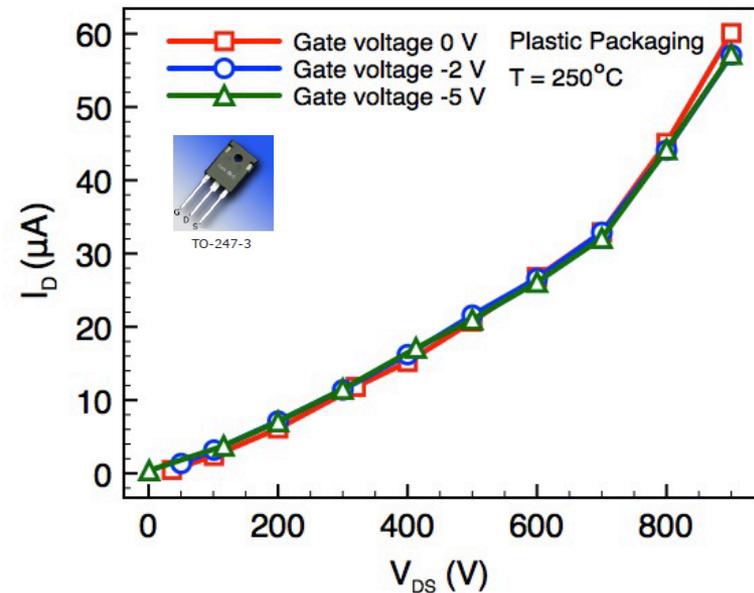


- Part is rated to  $125^\circ\text{C}$
- Metal-packaged part shows negligible leakage for  $T \leq 140^\circ\text{C}$
- *Plastic-packaged part shows significantly higher leakage at high  $T$*

# 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*

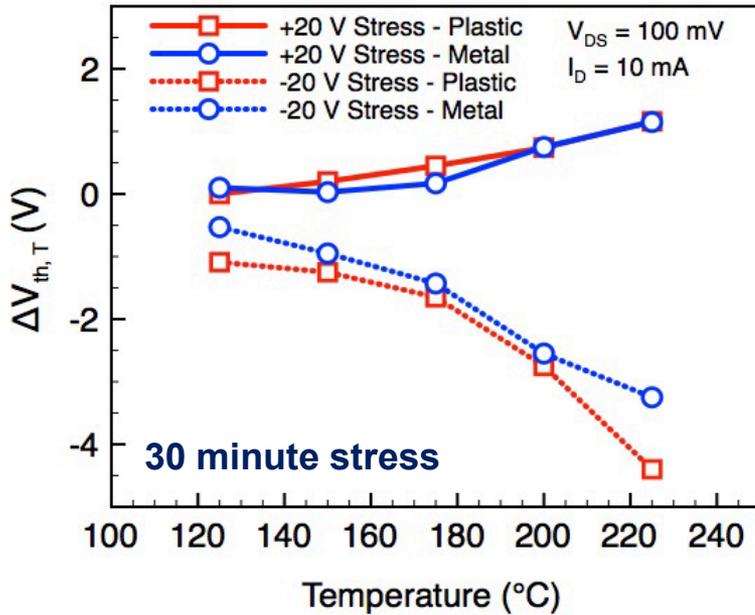
# Conduction Loss Mechanism: Threshold Voltage Instability



Plastic



Metal



**Threshold voltage shift is independent of packaging type**

- Shift in threshold voltage  $\Delta V_T$  (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  $T$

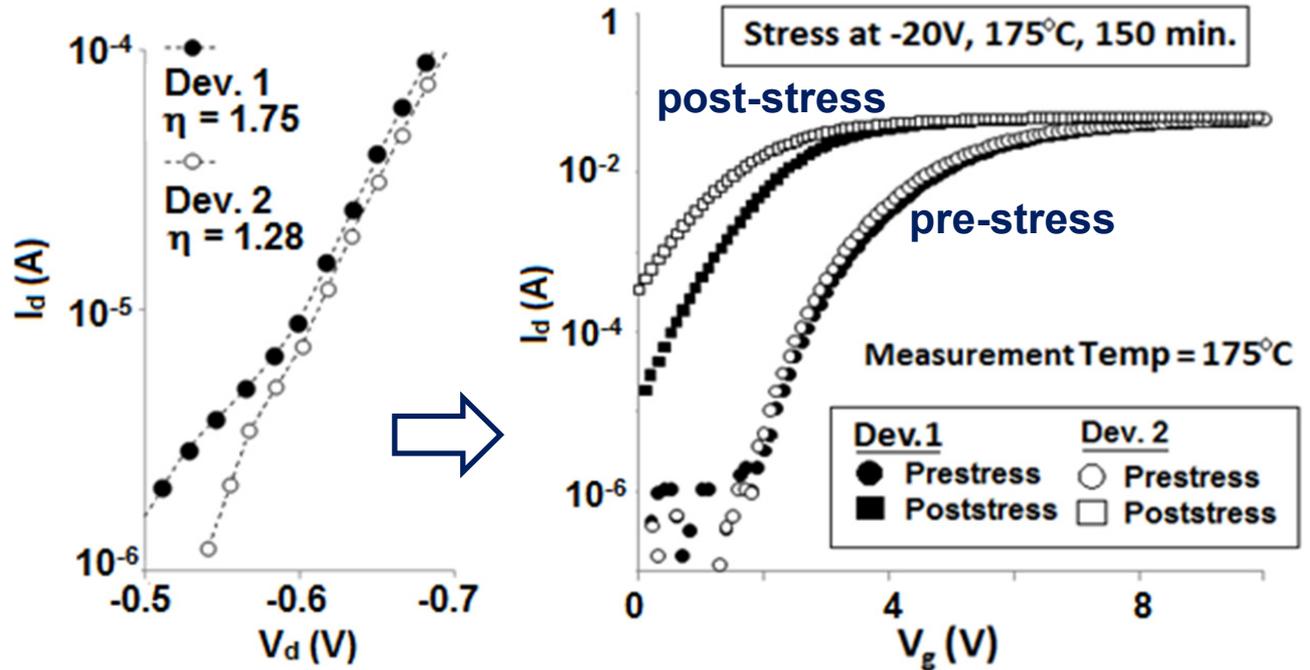
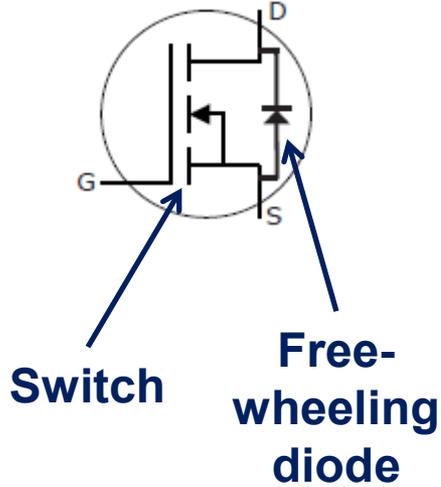
- For *positive*  $V_G$ :

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

- For *negative*  $V_G$ :

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

# 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**



# 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  $\Delta V_T$



# 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

- [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 *50<sup>th</sup> 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<sub>2</sub>/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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