Switching Reliability Characterization of Vertical GaN PiN Diodes

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Project Goal

- **Power semiconductor devices are a necessary interface between energy storage systems and the electric grid**

- **Wide-bandgap semiconductors have material properties that make them theoretically superior to silicon for power applications**
  - Higher switching frequency and lower conduction and switching losses reduce the size and complexity of power conversion systems, **thus reducing overall system cost**
  - However, questions remain regarding the reliability of wide-bandgap materials and devices, **limiting their implementation in systems**

- **Program goal: Understand the performance and reliability of SiC and GaN wide-bandgap power switches, and how this impacts circuit- and system-level performance and cost**
Superior Properties of WBG Materials and their Impact on Power Conversion Systems

- WBG semiconductors can have a strong impact on system size and weight due to reduced size of passive components and reduced thermal management requirements.
- But their reliability is far less mature than traditional Si devices.

Huang Material FOM = $E_c^3\mu_n^{1/2}$

Baliga FOM = $V_B^2/R_{on,sp} = \varepsilon\mu_nE_C^{3/4}$

- Conduction losses only
- Switching and conduction losses

Suggested reliability improvements for components, software, and operation of Silicon Power Corporation’s Solid-State Current Limiter

Characterized and evaluated commercial SiC MOSFETs, including the impacts of bias, temperature, packaging, and AC gate stress on reliability

Developed and documented a general process for analyzing the reliability of any power electronics system

Created a physics-based model for GaN HEMTs linking defect properties to device design

Developed models for SiC threshold voltage instability, and identified the free-wheeling diode ideality factor as a potential screening metric for threshold voltage shifts

Developed an easy to use method that can be used by circuit designers to evaluate the reliability of commercial SiC MOSFETs

Characterized switching of vertical GaN PiN devices using double-pulse test circuit

Participating in JEDEC WBG reliability working group

30 papers and presentations over the course of the project

Three this year including EESAT
For Si technology, most power device reliability studies focus on the packaging and thermal management
- Devices are mature and well-understood, and manufacturing is well-controlled

For WBG materials, devices are new and (relatively) unproven
- Materials are much newer, and manufacturing is not as well-controlled (but this is advancing quickly)
- SiC is most mature, followed by GaN power HEMTs (cousins of RF HEMTs)
- Newest type of device is GaN vertical device, which combines the material advantages of GaN with the high-voltage capability of a vertical architecture (>1200 V)

Little information on reliability characterization of vertical GaN devices in the literature
- Especially true under realistic switching conditions

Thus, this year’s work focuses on newly developed vertical GaN devices and continuous switching reliability testing
Why Vertical GaN Devices?

- Historically, GaN power devices have lateral architecture
  - Limits voltage hold-off to ≈<600 V due to electric field management
  - High frequency, but no avalanche

- Vertical GaN (v-GaN) devices are now becoming available
  - Better potential for high-voltage operation (≈>1200 V)
  - Avalanche capability
  - Reliability and switching performance are largely uncharacterized in literature
Area Advantage of Vertical GaN

For a given on-resistance ($R_{on}$) of 10mΩ:

- Tested Avogy vertical GaN PiN diodes
  - 0.72 mm² area
  - 1200 V, 15 A peak forward current

GaN-on-GaN lowers die cost while improving $R_{on} \times C_{off}$ switching characteristic

500mΩ, 50 chips
Si-MOSFET

40mΩ, 4 chips
GaN-on-Si
SiC

10mΩ, 1 chip
GaN-on-GaN

The devices tested were fabricated at Avogy under the ARPA-E SWITCHES program managed by Dr. Tim Heidel

Current-Voltage Characteristics of v-GaN PiN Diodes

- I-V characteristics taken in 25 °C steps
  - Reverse to 125 °C
  - Forward to 150 °C
- Confirmed datasheets

- Positive temperature coefficient of breakdown
  - Suggests avalanche process
- Some hysteresis observed for 25°C breakdown
  - Burn-in effect?
Double-Pulse Test Circuit

- Usually used to characterize switching of inductively-loaded power transistors
  - But for this work, we use a known good switch and characterize the diode

- Two modes of operation
  - Transient (double-pulse): Traditional use, characterizes switching behavior
  - Steady-state (continuous): New use for reliability testing
Switching Characterization with DPTC

Double-pulse

1st pulse off 2nd pulse

- 1st gate pulse: Increase stored energy in inductor – “charge up” to quasi-steady-state
- Gate off: Current circulates through diode/inductor loop
- 2nd gate pulse: Characterize switching transients

Reported last year

Diode voltage
Diode current
Reverse recovery

C. Matthews et al., WiPDA 2016
Continuous Waveforms in Ideal DPTC

- Idealized analysis of the double-pulse circuit
  - All elements are lossless
  - Inductor causes current to increase indefinitely
  - Not realistic!
Realistic circuit has some lossy elements

- Represented by lumped resistance in free-wheeling loop
- Causes switch (and diode) current to saturate
- Realistic DPTC is useful for continuous reliability testing!
Parameters for Steady-State Operation of DPTC

Switching duty cycle:
- \( t_{on} = \frac{\Delta I_L \cdot L}{V_{in}} \)

Current in loop:
- \( I_L(t) = I_{max} \cdot e^{-\frac{L}{R}t} \)

Decay time:
- \( t_{off} = -\frac{L}{R} \ln \left(1 - \frac{t_{on} \cdot V_{in}}{L \cdot I_{max}}\right) \)

Frequency and duty cycle must be adjusted based on supply voltage and device ratings to achieve desired steady-state operation.
Operation of circuit was limited by thermal dissipation of package
  - Not adequately heat-sinked
  - Limited voltage to 500 V, current to 2.2 A

Switching times adjusted to achieve steady-state under these conditions
  - Switching frequency = 1 kHz
  - $t_{on} = 3.5 \, \mu s$
  - Duty = 0.35%
  - $L = 3 \, mH$ implies $R \approx 1 \, \Omega$
I-V Measured Periodically During Switching Stress

- Vertical GaN diode subjected to 800 minutes of switching stress
  - Stress interrupted approximately every 10 minutes
  - Forward and reverse IV curves taken
  - Both curves show minimal change under these stress conditions
v-GaN Diode Parameters During Switching Stress

- Reverse voltage at 1 nA
- Reverse current at -1 kV
- Forward voltage at 1 mA
- Forward current at 2.16 V

- Electrical parameters extracted from curves on previous slide
- Negligible parameter degradation observed
- Drift observed in reverse current at -1 kV is at very low level
Double-Pulse Waveforms Before and After Switching Stress

Conclusion: Vertical GaN diodes are robust under the switching conditions and total stress time utilized.
Summary and Continuing Work

➢ Summary of this year’s work:
  • Vertical GaN power devices are at the forefront of WBG power semiconductor device technology – great potential to further improve system performance and reduce system cost
  • Modified DPTC to perform continuous switching stress of vertical GaN PiN diodes
  • Diodes look robust under the stress conditions examined

➢ Work for the coming year:
  • Install proper heat-sinking in the DPTC to allow for a wider range of stress conditions (higher current and voltage)
  • Install additional voltage and current monitors to record electrical data at more points in the circuit
  • Further automate testing to stress more devices, to understand the statistics of vertical GaN device reliability
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