Radiation & Thermal Cycling Effects on Gallium Nitride and Silicon Carbide Power Transistors

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SCOPE OF WORK

• A NEPP (NASA Electronic Parts and Packaging) collaborative effort among NASA Centers to address performance and reliability of new COTS (Commercial-Off-The-Shelf) power devices based on wide bandgap semiconductor for use in space harsh environment

• Test and evaluate performance of emerging GaN (Gallium Nitride) & SiC (Silicon Carbide) power devices under the exposure to radiation and thermal cycling

• Document results and disseminate findings
**TECHNICAL APPROACH:**

- Identify and acquire candidate power devices
- Perform parametric evaluation
- Subject devices to radiation exposure representative of mission environment
- Perform long-term thermal cycling on survived parts
- Determine effects of radiation and temperature cycling on performance of devices
- Address reliability, determine risk factors, and identify mitigation techniques for device use in space missions
Accomplished/Ongoing Work

- **Radiation Testing (GSFC/JPL)**
  - TID (Total Ionization Dose)
  - SEE (Single Event Effect)

- **Thermal Cycling (GRC)**
  - Control (Un-irradiated) Samples
  - Irradiated Parts
  - Long-Term

- **Wide Bandgap Devices**
  - First Generation GaN FETs (EPC) from JPL
  - SiC MOSFETs (Cree) from GSFC
  - Second Generation GaN FETs (EPC) from JPL
Thermal Cycling
At NASA Glenn Research Center (GRC)

- Cycling Profile:
  - Total # of Cycles 1000
  - Temperature rate of change: 10 °C/min
  - Temperature range: -55 °C to +125 °C
  - Soak time at extreme temperatures: 10 min

- Repeat measurements on devices during cycling
- Perform measurements after conclusion of cycling activity
Parameters Investigated:
- I-V Output Characteristics
- Gate Threshold Voltage, $V_{TH}$
- Drain-Source On-Resistance, $R_{DS(on)}$
- Pre, during, & post-cycling, measurements at selected temperatures

Equipment Used:
- SONY/Tektronix 370A Curve Tracer
- Keithley 238 Source-Measure-Units
- LN-cooled Sun Systems Chamber
First Generation GaN FETs
Irradiated by JPL at TAMU

- Efficient Power Conversion, EPC1001, GaN transistors grown on Si wafer; [http://www.epc-co.com](http://www.epc-co.com)
- Passivated-die form with solder bumps

Sample die mounted on test structure

<table>
<thead>
<tr>
<th># of Parts</th>
<th>Device Label</th>
<th>Condition</th>
<th>Ion</th>
<th>Energy (MeV)</th>
<th>LET (MeV cm² /gm)</th>
<th>Range (μm)</th>
<th>Dose (rad (Si))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K7063</td>
<td>Irradiated</td>
<td>Au</td>
<td>2342</td>
<td>84.7</td>
<td>122.9</td>
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<tr>
<td>1</td>
<td>K7064</td>
<td>Irradiated</td>
<td>Xe</td>
<td>1569</td>
<td>98.8</td>
<td>124.5</td>
<td>8301</td>
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<tr>
<td>1</td>
<td>K7044</td>
<td>Irradiated</td>
<td>Xe</td>
<td>1569</td>
<td>50.9</td>
<td>124.5</td>
<td>7886</td>
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<tr>
<td>1</td>
<td>K7065</td>
<td>Irradiated</td>
<td>Xe</td>
<td>1569</td>
<td>98.8</td>
<td>124.5</td>
<td>15838</td>
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<tr>
<td>4</td>
<td>K7068-K7071</td>
<td>Control (un-irradiated)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
## EPC1001 Enhancement-Mode GaN Power FETs

### Manufacturer’s Specifications

<table>
<thead>
<tr>
<th>Part #</th>
<th>EPC1001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain-Source Voltage, $V_{DS}$ (V)</td>
<td>100</td>
</tr>
<tr>
<td>Gate Threshold Voltage, $V_{TH}$ (V)</td>
<td>$1.4 @ V_{DS} = V_{GS}, I_D = 5$ mA</td>
</tr>
<tr>
<td>Drain Current, $I_D$ (A)</td>
<td>25</td>
</tr>
<tr>
<td>Drain-Source On Resistance, $R_{DS(ON)}$ (mΩ)</td>
<td>$5.6 @ V_{GS} = 5V, I_D = 25$ A</td>
</tr>
<tr>
<td>Operating Temperature, $T_J$ (°C)</td>
<td>-40 to +125</td>
</tr>
<tr>
<td>Package Type</td>
<td>Passivated-Die with Solder Bumps</td>
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</tbody>
</table>
Focused Ion Beam and SEM Cross-Section of EPC GaN FETs

SEM Micrograph, 65X, 52 deg. Tilt

SEM Micrograph after FIB Cut, 2500X, 52 deg. Tilt

Sn/Pb
Devices were irradiated under bias at increasing drain biases
Transfer curves were measured between irradiations
Devices still functioned but were well out of spec after irradiation

**Device K7044** (EPC1001 First Gen GaN FET irradiated with Xe to 7.9 krad (Si))
RADIATION DATA
from JPL

Device K7063 (EPC1001 First Gen GaN FET
irradiated with Au to 27.7 krad (Si))

Graphs showing the changes in Drain Voltage, Drain Current, and Gate Current over elapsed time and gate-to-source voltage.
I-V Curves for K7068 control (un-irradiated)

- **Pre-Cycling**
  - After 824 Cycles: Transconductance Increase
  - After 1000 Cycles: Similar to 824 Cycles
I-V Curves for K7069 control (un-irradiated)

After 1000 Cycles  Drop in Transconductance

After 500 Cycles  Transconductance Increase

After 824 Cycles  More Transconductance Increase

Pre-Cycling

VGS = 2.0 V
VGS = 1.950 V
VGS = 1.95 V
I-V Curves for K7070 control (un-irradiated)

Pre-Cycling

After 824 Cycles

After 1000 Cycles

Transconductance Increase
I-V Curves for K7071 control (un-irradiated)

Pre-Cycling

After 824 Cycles  More Transconductance Increase

After 500 Cycles  Transconductance Increase

After 1000 Cycles  Drop in Transconductance
IV Curves for K7063 (irradiated, Au ions, 22.7 krad (Si))

**Pre-Cycling**

- $V_{GS} = 2.0 \text{ V}$
- $1.6 \text{ V}$
- $1.5 \text{ V}$
- $1.4 \text{ V}$
- $1.3 \text{ V}$
- $1.2 \text{ V}$

**After 500 Cycles**

- $V_{GS} = 1.98 \text{ V}$
- $1.48 \text{ V}$
- $1.38 \text{ V}$
- $1.28 \text{ V}$
- $1.18 \text{ V}$
- $1.08 \text{ V}$

**After 824 Cycles**

- $V_{GS} = 1.98 \text{ V}$
- $1.48 \text{ V}$
- $1.38 \text{ V}$
- $1.28 \text{ V}$
- $1.18 \text{ V}$
- $1.08 \text{ V}$

**After 1000 Cycles**

- $V_{GS} = 1.92 \text{ V}$
- $1.42 \text{ V}$
- $1.32 \text{ V}$
- $1.22 \text{ V}$
- $1.12 \text{ V}$
- $1.02 \text{ V}$
I-V Curves for K7064 (irradiated, Xe ions, 8.3 krad (Si))

Pre-Cycling

After 824 Cycles

After 1000 Cycles
I-V Curves for K7044 (irradiated, Xe ions, 7.9 krad (Si))

Pre-Cycling

After 500 Cycles  Transconductance Increase

After 824 Cycles

After 1000 Cycles
I-V Curves for K7065 (irradiated, Xe ions, 15.8 krad)

Pre-Cycling

After 824 Cycles

After 500 Cycles  Transconductance Increase

After 1000 Cycles
Drain Current of EPC1001 GaN FETs to 1000 Thermal Cycles

- K7063 Au 22.7 krad
- K7044 Xe  7.9 krad
- K7064 Xe  8.3 krad
- K7065 Xe 15.8 krad
- K7068 not-irradiated
- K7069  
- K7071  
- K7070  

$V_g = 1.3 \text{ V}$
$V_d = 0.2 \text{ V}$
GATE THRESHOLD VOLTAGE, $V_{TH}$

EPC1001 GaN FETs

Number of Thermal Cycles

$V_{TH}$ (V)

0.0 0.5 1.0 1.5 2.0 2.5

K7068
K7069
K7070
K7071
K7044 (irrad.)
K7063 (irrad.)
K7064 (irrad.)
K7065 (irrad.)

Number of Thermal Cycles
Drain-Source On Resistance, $R_{DS(ON)}$

EPC1001 GaN FETs

Number of Thermal Cycles

$R_{DS}$ (mΩ)

K7068
K7069
K7070
K7071
K7064 (irrad.)
K7063 (irrad.)
K7044 (irrad.)
K7065 (irrad.)

0 200 400 600 800 1000

0 50 100 150 200 250 300 350 400 450 500

0 200 400 600 800 1000

National Aeronautics and Space Administration
OBSERVATIONS

• All eight GaN FETs remained functional after exposure to radiation followed by 1000 thermal cycles between -55 & +125 °C

• Main impact of radiation was increase in leakage current of devices

• Thermal cycling seemed to introduce inconsistent variation in I-V characteristic curves of the GaN FETs; notably in their transconductance

• $V_{TH}$ of tested devices experienced an initial decrease with cycling but seemed to level off after exposure to about 130 cycles; possibly due to thermal conditioning

• For the $R_{DS(ON)}$ data, at 1000 thermal cycles the values of $R_{DS(ON)}$ occurred in two distinct clusters. A two-sample t-test ($p<0.005$) showed that the means of the clusters were different. The cause of the two distinct clusters is not known, but further investigation should probably wait until the second generation of the devices is tested.
SiC Power MOSFETs
Irradiated by GSFC at GSFC REF

- **Cree Z-FET transistor, part # CMF20120D**
- [http://www.cree.com](http://www.cree.com)

<table>
<thead>
<tr>
<th>Part #</th>
<th>CMF20120D</th>
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<tbody>
<tr>
<td>Drain-Source Breakdown Voltage, $V_{(VBR)DSS}$, (V)</td>
<td>1200</td>
</tr>
<tr>
<td>Gate Threshold Voltage, $V_{TH}$ (V)</td>
<td>2.5</td>
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<tr>
<td>Drain Current, $I_D$ (A)</td>
<td>33</td>
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<tr>
<td>Drain-Source On Resistance, $R_{DS(ON)}$ (mΩ)</td>
<td>80</td>
</tr>
<tr>
<td>Operating Temperature, $T_C$ (°C)</td>
<td>-55 to +125</td>
</tr>
<tr>
<td>Package</td>
<td>Plastic TO-247-3</td>
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</tbody>
</table>
Radiation Testing
CMF20120D SiC MOSFETs

- Radiation done using Cobalt-60 source for a total dose of 600 krad (Si)
- Damage Criteria: gate threshold voltage shifted below 1V, or turn-on delay time increased by more than 200%
- Thermal annealing after 400 krad (one week at RT) and after 600 krad (one week @ 100 °C) per MIL-STD-883

<table>
<thead>
<tr>
<th>Device Label</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Control</td>
</tr>
<tr>
<td>5</td>
<td>Control</td>
</tr>
<tr>
<td>4</td>
<td>Irradiated, Biased ON: Vgs = 20V, Vds = 0V</td>
</tr>
<tr>
<td>7</td>
<td>Irradiated, Biased OFF: Vgs = 0V, Vds = 900V</td>
</tr>
<tr>
<td>9</td>
<td>Irradiated, GRND: Vgs = 0V, Vds = 0V</td>
</tr>
</tbody>
</table>
Threshold Voltage

CMF20120D SiC MOSFETs

Threshold Voltage [V] vs. Dose [krad(Si)]

- Control
- Biased ON
- Biased OFF
- Pins GND

Legend:
- Control, 24 hr Anneal
- Biased ON, 24 hr Anneal
- Biased OFF, 24 hr Anneal
- Pins GND, 24 hr Anneal
- Control, 1 week Anneal
- Biased ON, 1 week Anneal
- Biased OFF, 1 week Anneal
- Pins GND, 1 week Anneal
- Control, High Temp Anneal
- Biased ON, High Temp Anneal
- Biased OFF, High Temp Anneal
- Pins GND, High Temp Anneal
Breakdown Voltage

CMF20120D SiC MOSFETs

Breakdown Voltage [V] vs. Dose [krad(Si)]

- Control
- Biased ON
- Biased OFF
- Pins GND

Legend:
- Control, 24 hr Anneal
- Biased ON, 24 hr Anneal
- Biased OFF, 24 hr Anneal
- Pins GND, 24 hr Anneal
- Control, 1 week Anneal
- Biased ON, 1 week Anneal
- Biased OFF, 1 week Anneal
- Pins GND, 1 week Anneal
- Control, High Temp Anneal
- Biased ON, High Temp Anneal
- Biased OFF, High Temp Anneal
- Pins GND, High Temp Anneal
Threshold Voltage
CMF20120D SiC MOSFETs

Temperature (°C)

Gate Threshold Voltage, $V_{th}$ (V)

Pre-cycling

Dev 2
Dev 4
Dev 5
Dev 7
Dev 9

Temperature (°C)
On-State Resistance
CMF20120D SiC MOSFETs

Temperature (°C)

Normalized $R_{DS}$ (ON)

Pre-cycling

Dev 2
Dev 4
Dev 5
Dev 7
Dev 9
I/V Curves (SiC Dev 2, un-irradiated)

Pre-cycling

Dev 2 Precycling at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

After 500 cycles

Dev 2 after 500 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

Dev 2 after 500 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

Dev 2 after 1000 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

Dev 2 after 1000 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V
I/V Curves (SiC Dev 4 Biased ON, irradiated)

Pre-cycling

Dev 4 Pre-cycling at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V
VGS = 4 V

Dev 4 after 750 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

Dev 4 after 500 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V

Dev 4 after 1000 cycles at 20 °C

VGS = 14 V
VGS = 12 V
VGS = 10 V
VGS = 8 V
VGS = 6 V
I/V Curves (SiC Dev 7  Biased OFF, irradiated)
I/V Curves

**Pre-cycling**
- Dev 9 Precycling at 20 °C
- VGS = 14 V
- VGS = 12 V
- VGS = 10 V
- VGS = 8 V
- VGS = 6 V

**Dev 9 after 750 cycles at 20 °C**
- VGS = 14 V
- VGS = 12 V
- VGS = 10 V
- VGS = 8 V
- VGS = 6 V

**Dev 9 after 500 cycles at 20 °C**
- VGS = 14 V
- VGS = 12 V
- VGS = 10 V
- VGS = 8 V
- VGS = 6 V

**Dev 9 after 1000 cycles at 20 °C**
- VGS = 14 V
- VGS = 12 V
- VGS = 10 V
- VGS = 8 V
- VGS = 6 V

(SiC Dev 9 GRND, irradiated)
Threshold Voltage
CMF20120D SiC MOSFETs

Pre-cycling
Gate Threshold Voltage, $V_{th}$ (V)

Temperature (°C)

After 500 cycles

After 750 cycles

After 1000 cycles

Gate Threshold Voltage, $V_{th}$ (V)

Temperature (°C)
On-State Resistance
CMF20120D SiC MOSFETs

Pre-cycling

After 500 cycles
Increase at -50 °C

After 750 cycles
Continued Increase at -50 °C

After 1000 cycles
Continued Increase at -50 °C
OBSERVATIONS
CMF20120D SiC MOSFETs

**Radiation**
- All parameters, except breakdown voltage, stayed within “specifications” to 600 krad
- There is a time-dependent dose effect (evident between 250 and 300 krad steps)
- Small sample size and large part-to-part variability

**Thermal Cycling**
- All devices maintained functionality after 1000 cycles
- No effect on gate threshold voltage
- On-state resistance increased with cycling, notably at low temperatures. Trend was same for control and irradiated parts
- No alteration in device packaging or terminations
Second Generation GaN FETs
Irradiated by JPL at TAMU

EPC 2012 GaN FET (Rated 200V, 3A, 100mΩ), Precycling @ 20 ºC

Control (un-irradiated)  Irradiated
Decrease in Transconductance
Second Generation GaN FETs

Irradiated by JPL at JPL

EPC 2014 GaN FET (Rated 40V, 10A, 16mΩ), Precycling @ 20 ºC

Control (un-irradiated)  Irradiated

Slight Increase in Transconductance
Second Generation GaN FETs

Irradiated by JPL at TAMU

EPC 2015 GaN FET (Rated 40V, 33A, 4mΩ), Precycling @ 20 °C

Control (un-irradiated)

Irradiated
Decrease in Transconductance
Planned Work

- Conduct multi-stress tests (electrical/thermal) on these control and irradiated GaN & SiC power devices
- Perform overstress tests to determine failure mechanisms
- Repeat work on newly-developed GaN and SiC COTS power devices in support of NEPP Program
ACKNOWLEDGMENT

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