Effects of Thermal Cycling on Control & Irradiated EPC 2nd Generation GaN FETs

NASA Working Group on Wide Bandgap Semiconductor Power Devices

Richard L. Patterson, NASA GRC
Leif Scheick, JPL
Jean-Marie Lauenstein & Megan Casey, NASA GSFC
Ahmad Hammoud, VPL / NASA GRC

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Test Activity

- **Wide Bandgap Devices**
  - Second Generation GaN FETs (EPC)

- **Radiation Testing (JPL)**
  - TID (Total Ionization Dose)
  - SEE (Single Event Effect)
  - DDD (Displacement Damage Dose)

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

- 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

- Parametric measurements performed on devices before, during, and 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 room temperature

Equipment Used:
- SONY/Tektronix 370A Curve Tracer
- Keithley 238 Source-Measure-Units
- LN-cooled Sun Systems Chamber
2nd Generation GaN FET

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

Sample die mounted on test structure
**Test Parts:**
- Radiation testing was performed by JPL

<table>
<thead>
<tr>
<th>EPC2015 40V, 33A, 4mΩ</th>
<th>EPC2014 40V, 10A, 16mΩ</th>
<th>EPC2012 200V, 3A, 100mΩ</th>
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<tbody>
<tr>
<td><strong>Control Parts</strong></td>
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# EPC2015 Enhancement Mode Power FET

<table>
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<th>Control Parts</th>
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<td>K7311</td>
<td></td>
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<tr>
<td>K7312</td>
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</table>

**EPC2015**
40V, 33A, 4mΩ
I-V Curves for K7301 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7302 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7304 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7306 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7311 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7312 (control EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7303 (irradiated EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7305 (irradiated EPC2015)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
EPC2105
GATE THRESHOLD VOLTAGE, $V_{TH}$

Number of Thermal Cycles

$V_{TH}$ (V)

0 200 400 600 800 1000

K7301 Un-irradiated
K7302 Un-irradiated
K7304 Un-irradiated
K7306 Un-irradiated
K7311 Un-irradiated
K7312 Un-irradiated
K7303 Irradiated
K7305 Irradiated
EPC2015

Drain-Source On Resistance, $R_{DS(ON)}$
OBSERVATIONS

• All eight EPC2015 GaN transistors, control & irradiated, remained functional after exposure to radiation followed by 1000 thermal cycles between -55 & +125 °C

• Irradiated devices had a higher $R_{DS(ON)}$ and a higher $V_{TH}$

• Insignificant changes in the I-V characteristics of control samples due to cycling

• Thermal cycling seemed to cause a slight reduction in the $R_{DS(ON)}$ and the $V_{TH}$ of the irradiated parts

• No alteration in device packaging or terminations
# EPC2014 Enhancement Mode Power FET

<table>
<thead>
<tr>
<th>Control Parts</th>
<th>Irradiated Parts</th>
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<td>K7346</td>
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<td>K7072</td>
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</table>
I-V Curves for K6985 (control EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K6986 (control EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7333 (control EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7336 (control EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7346 (control EPC2104)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7072 (control EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7325 (irradiated EPC2014)
I-V Curves for K7328 (irradiated EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7347 (irradiated EPC2014)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
EPC2014
GATE THRESHOLD VOLTAGE, $V_{TH}$

Number of Thermal Cycles:
- 0
- 200
- 400
- 600
- 800
- 1000

$V_{TH}$ (V):
- 0.0
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5

Samples:
- k6985 Un-Irradiated
- k6986 Un-Irradiated
- k7333 Un-Irradiated
- k7336 Un-Irradiated
- k7346 Un-Irradiated
- k7072 Un-Irradiated
- k7325 Irradiated
- k7328 Irradiated
- k7347 Irradiated
EPC2014

**Drain-Source On Resistance, \( R_{DS(ON)} \)**

- k6985 Un-irradiated
- k6986 Un-irradiated
- k7333 Un-irradiated
- k7336 Un-irradiated
- k7346 Un-irradiated
- k7325 Irradiated
- k7328 Irradiated
- k7347 Irradiated
OBSERVATIONS

• All nine EPC2014 GaN transistors, control & irradiated, remained functional after exposure to radiation followed by 1000 thermal cycles between -55 & +125 °C

• Slight changes in I-V curves of irradiated parts

• Thermal cycling seemed to slightly improve the I-V characteristics of both control and irradiated samples

• Part-to-part variation in output characteristics

• No alteration in device packaging or terminations
## EPC2012 Enhancement Mode Power FET

<table>
<thead>
<tr>
<th>Control Parts</th>
<th>Irradiated Parts</th>
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<tbody>
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<td>A4754</td>
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</tbody>
</table>
I-V Curves for A4754 (control EPC2012)

Before Cycling

- $V_G = 2.0 \, V$
- $V_G = 1.9 \, V$
- $V_G = 1.8 \, V$
- $V_G = 1.7 \, V$
- $V_G = 1.6 \, V$
- $V_G = 1.5 \, V$
- $V_G = 1.4 \, V$
- $V_G = 1.3 \, V$

After 500 Cycles

- $V_G = 2.0 \, V$
- $V_G = 1.9 \, V$
- $V_G = 1.8 \, V$
- $V_G = 1.7 \, V$
- $V_G = 1.6 \, V$
- $V_G = 1.5 \, V$
- $V_G = 1.4 \, V$
- $V_G = 1.3 \, V$

After 1000 Cycles

- $V_G = 2.0 \, V$
- $V_G = 1.9 \, V$
- $V_G = 1.8 \, V$
- $V_G = 1.7 \, V$
- $V_G = 1.6 \, V$
- $V_G = 1.5 \, V$
- $V_G = 1.4 \, V$
- $V_G = 1.3 \, V$

$V_D (V)$

$0.0 \ 0.4 \ 0.8 \ 1.2 \ 1.6 \ 2.0$

$I_D (A)$

$0.0 \ 0.1 \ 0.2 \ 0.3 \ 0.4 \ 0.5 \ 0.6 \ 0.7 \ 0.8 \ 0.9 \ 1.0$
I-V Curves for A4755 (control EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for A4756 (control EPC2012)
I-V Curves for A4757 (control EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for A4758 (control EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for A4759 (control EPC2012)

Pre-Cycling

VDS (V) 0.0 0.4 0.8 1.2 1.6 2.0
ID (A) 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

VDS (V) 0.0 0.4 0.8 1.2 1.6 2.0
ID (A) 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

After 500 Cycles

After 1000 Cycles
I-V Curves for K7348 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7353 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7354 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7359 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7370 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7395 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7396 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7399 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for K7364 (irradiated EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
EPC2012
GATE THRESHOLD VOLTAGE, $V_{TH}$

![Graph showing Gate Threshold Voltage vs. Number of Thermal Cycles]

- **EPC2012**
- **GATE THRESHOLD VOLTAGE, $V_{TH}$**

<table>
<thead>
<tr>
<th>Un-irradiated</th>
<th>Irradiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4754</td>
<td>k7348</td>
</tr>
<tr>
<td>A4755</td>
<td>k7353</td>
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<tr>
<td>A4756</td>
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<td>A4757</td>
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<td>A4758</td>
<td>k7370</td>
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<tr>
<td>A4759</td>
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<td>A4758</td>
<td>k7396</td>
</tr>
<tr>
<td>A4759</td>
<td>k7399</td>
</tr>
<tr>
<td>k7364</td>
<td>k7364</td>
</tr>
</tbody>
</table>

- **$V_{TH}$ (V)**
- **Number of Thermal Cycles**
EPC2012

Drain-Source On Resistance, $R_{DS(ON)}$

Number of Thermal Cycles

R$_{DS}$ (Normalized)

Un-irradiated

Irradiated

A4754 Un-irradiated
A4755 Un-irradiated
A4756 Un-irradiated
A4757 Un-irradiated
A4758 Un-irradiated
A4759 Un-irradiated
k7348 Irradiated
k7353 Irradiated
k7354 Irradiated
k7359 Irradiated
k7370 Irradiated
k7395 Irradiated
k7396 Irradiated
k7399 Irradiated
k7364 Irradiated
OBSERVATIONS

- All fifteen EPC2012 GaN transistors, control & irradiated, remained functional after exposure to radiation followed by 1000 thermal cycles between -55 & +125 °C

- Radiation seemed to affect steepness of the I-V curves as reflected by the increase in $V_{TH}$ & $R_{DS(ON)}$

- Thermal cycling seemed to influence characteristics of control as well as irradiated samples:
  - While $V_{TH}$ of control parts increased slightly with cycling, those of the irradiated parts exhibited a decrease
  - No effect on $R_{DS(ON)}$ of majority of control parts but a decrease in this property was observed for the irradiated counterparts

- Part-to-part variability apparent in output characteristics

- No alteration in device packaging or terminations
Second Gen GaN FET

EPC2015 GaN FET (40V, 33A, 4mΩ), Precycling @ 20 ºC
Second Gen GaN FET

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

Control

I_{D} (A)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

V_{DS} (V)

0.0 0.4 0.8 1.2 1.6 2.0

K6985.pdw

I_{D} (A)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

V_{DS} (V)

0.0 0.4 0.8 1.2 1.6 2.0

K7325.pdw

Control

I_{D} (A)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

V_{DS} (V)

0.0 0.4 0.8 1.2 1.6 2.0

K6985.pdw

I_{D} (A)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

V_{DS} (V)

0.0 0.4 0.8 1.2 1.6 2.0

K7325.pdw

Irradiated
Second Gen GaN FET

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

Control

I₀ (A)

V_DS (V)

0.0 0.4 0.8 1.2 1.6 2.0

1.0

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0.0

V GS = 2.0 V

1.9 V

1.8 V

1.7 V

1.6 V

1.5 V

1.4 V

1.3 V

0.0

A4754.pdw

V GS = 2.0 V

1.9 V

1.8 V

1.7 V

1.6 V

1.5 V

1.4 V

1.3 V

0.0

K7353.pdw

I₀ (A)

V_DS (V)

0.0 0.4 0.8 1.2 1.6 2.0

1.0

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0.0

Irradiated
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

This collaborative work was performed in support of the NASA Electronic Parts and Packaging Program. Guidance and funding provided by the Program’s co-managers Michael Sampson and Kenneth LaBel are greatly appreciated. Part of this work was done at the NASA Glenn Research Center under GESS-3 Contract # NNC12BA01B.