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

NASA Working Group on Wide Bandgap Semiconductor Power Devices

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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](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>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Parts</strong></td>
<td><strong>Irradiated Parts</strong></td>
<td><strong>Control Parts</strong></td>
</tr>
<tr>
<td>K7301</td>
<td>K7303</td>
<td>A4754</td>
</tr>
<tr>
<td>K7302</td>
<td>K7305</td>
<td>A4755</td>
</tr>
<tr>
<td>K7304</td>
<td></td>
<td>A4756</td>
</tr>
<tr>
<td>K7306</td>
<td></td>
<td>A4757</td>
</tr>
<tr>
<td>K7311</td>
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<td>A4758</td>
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<tr>
<td>K7312</td>
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<td>K7396</td>
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<td>K7399</td>
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<td>K7364</td>
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**EPC2015 Enhancement Mode Power FET**

<table>
<thead>
<tr>
<th>Control Parts</th>
<th>Irradiated Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>K7301</td>
<td>K7303</td>
</tr>
<tr>
<td>K7302</td>
<td>K7305</td>
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<td>K7306</td>
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</tr>
<tr>
<td>K7311</td>
<td></td>
</tr>
<tr>
<td>K7312</td>
<td></td>
</tr>
</tbody>
</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

VGS = 2.0 V
VGS = 1.9 V
VGS = 1.8 V
VGS = 1.7 V
VGS = 1.6 V
VGS = 1.5 V
VGS = 1.4 V
VGS = 1.3 V
VGS = 1.2 V
VGS = 1.1 V
VGS = 1.0 V
VGS = 0.9 V
VGS = 0.8 V
VGS = 0.7 V
VGS = 0.6 V
VGS = 0.5 V
VGS = 0.4 V
VGS = 0.3 V
VGS = 0.2 V
VGS = 0.1 V
VGS = 0.0 V

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)
EPC2105
GATE THRESHOLD VOLTAGE, $V_{TH}$

Number of Thermal Cycles

$V_{TH}$ (V)

0.0 0.5 1.0 1.5 2.0 2.5

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

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

Number of Thermal Cycles

$R_{DS}$ (Normalized)

- K7301 Un-irradiated
- K7302 Un-irradiated
- K7304 Un-irradiated
- K7306 Un-irradiated
- K7311 Un-irradiated
- K7303 Irradiated
- K7312 Un-irradiated
- K7305 Irradiated
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>
</tr>
</thead>
<tbody>
<tr>
<td>K6985</td>
<td>K7325</td>
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<tr>
<td>K6986</td>
<td>K7328</td>
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<td>K7333</td>
<td>K7347</td>
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<tr>
<td>K7336</td>
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<td>K7346</td>
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<tr>
<td>K7072</td>
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</tbody>
</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

<table>
<thead>
<tr>
<th>VGS (V)</th>
<th>I-V Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 V</td>
<td><img src="K7333.pdw" alt="I-V Curves Pre-Cycling" /></td>
</tr>
<tr>
<td>1.9 V</td>
<td></td>
</tr>
<tr>
<td>1.8 V</td>
<td></td>
</tr>
<tr>
<td>1.7 V</td>
<td></td>
</tr>
<tr>
<td>1.6 V</td>
<td></td>
</tr>
<tr>
<td>1.5 V</td>
<td></td>
</tr>
<tr>
<td>1.4 V</td>
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</table>

After 500 Cycles

<table>
<thead>
<tr>
<th>VDS (V)</th>
<th>ID (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.4</td>
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</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>1.2</td>
<td>0.3</td>
</tr>
<tr>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>2.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

After 1000 Cycles

<table>
<thead>
<tr>
<th>VDS (V)</th>
<th>ID (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>1.2</td>
<td>0.3</td>
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<tr>
<td>1.6</td>
<td>0.4</td>
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<tr>
<td>2.0</td>
<td>0.5</td>
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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

$V_{TH}$ (V)

EPC2014
GATE THRESHOLD VOLTAGE, $V_{TH}$

Number of Thermal Cycles

$V_{TH}$ (V)
EPC2014
Drain-Source On Resistance, $R_{DS(ON)}$

$R_{DS}$ (Normalized)

Number of Thermal Cycles

- k6985 Un-irradiated
- k6986 Un-irradiated
- k7333 Un-irradiated
- k7336 Un-irradiated
- k7346 Un-irradiated
- k7072 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>
</tr>
</thead>
<tbody>
<tr>
<td>A4754</td>
<td>K7348</td>
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<td>A4755</td>
<td>K7353</td>
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<td>A4756</td>
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<td>A4757</td>
<td>K7359</td>
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<td>A4758</td>
<td>K7370</td>
</tr>
<tr>
<td>A4759</td>
<td>K7395</td>
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<td></td>
<td>K7396</td>
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<tr>
<td></td>
<td>K7399</td>
</tr>
<tr>
<td></td>
<td>K7364</td>
</tr>
</tbody>
</table>

**EPC2012**

200V, 3A, 100mΩ
I-V Curves for A4754 (control EPC2012)

Pre-Cycling

After 500 Cycles

After 1000 Cycles
I-V Curves for A4755 (control EPC2012)

Pre-Cycling

After 500 Cycles

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

Pre-Cycling

After 500 Cycles

After 1000 Cycles
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

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, $V_{TH}$

Number of Thermal Cycles

$V_{TH}$ (V)

0 400 800 1200 1600

0.0 0.5 1.0 1.5 2.0

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
EPC2012

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

Number of Thermal Cycles

$R_{DS}$ (Normalized)

- 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

Un-irradiated

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

Control

I\(_D\) (A)

V\(_DS\) (V)

I\(_D\) (A)

V\(_DS\) (V)

Irradiated
Second Gen GaN FET

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

Control

I₀ (A) vs. V_DS (V)

I₀ (A) vs. V_DS (V)

Irradiated
Second Gen GaN FET

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

Control

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0

I(_D)(A)

V(_D)(V)

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0.0 0.4 0.8 1.2 1.6 2.0
**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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