Outline

Overview
• The Importance of Measurement Technique

GaN E-HEMTs Switching Test Measurement Techniques
• Short loops matter
• Low-side voltage probing
• High-side floating voltage probing
• Current sensing for high-speed GaN E-HEMTs

Double Pulse Switching Test
• Double Pulse Switch Test Set up
• 400V/30A hard switching turn-on and turn-off test results

Switching Energy Eon/Eoff Measurement
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• Switching loss distribution of GaN E-HEMTs
• Eqoss measurement example
• 400V/30A Eon/Eoff Test results

Summary and Conclusions

Appendix: Bandwidth Requirements
Outline

Overview

- The Importance of Measurement Technique

GaN E-HEMTs Switching Test Measurement Techniques

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- 400V/30A hard switching turn-on and turn-off test results

Switching Energy Eon/Eoff Measurement

- $V_{GS}$, $V_{DS}$, $I_{DS}$ probing techniques to increase measurement accuracy
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- $\Delta q_{oss}$ measurement example
- 400V/30A Eon/Eoff Test results

Summary and Conclusions

Appendix: Bandwidth Requirements
GaN E-HEMTs have a significantly faster switching speed than Si and SiC MOSFETs. This application note provides details on how to accurately characterize the performance of high speed GaN E-HEMTs so that designers can release optimized designs.

An overview of proper current and voltage measurement techniques is presented for obtaining test results that accurately reflect the performance of GaN devices.

The Double Pulse Switching Test is presented, along with an example of test results. This test is used to characterize hard switching turn-on and turn-off.

An overview of Eon/Eoff measurement is presented along with test results. This test is used to characterize the switching loss distribution.
GaN Systems’ E-HEMTs have very low parasitic components. GaN switches with very short delay, very fast, at very high frequencies, and operates at higher efficiencies than equivalent Si and SiC transistors.

Without proper care, the parasitic elements introduced by test equipment and measurement techniques can overshadow the GaN device parameters and lead to erroneous measurement results.

### Key device parameters that affect switching performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Impact</th>
<th>650V/30A/50mΩ GS66508B</th>
<th>650V/33A/65mΩ IPB65R065C7</th>
<th>900V/35A/65mΩ C3M0065090J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qg (nC)</td>
<td>Switching speed</td>
<td>5.8</td>
<td>64</td>
<td>30</td>
</tr>
<tr>
<td>Coss (pF)</td>
<td>Switching frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>t_delay(on) / t_delay(off) (ns)</td>
<td></td>
<td>4.1 / 8.0</td>
<td>7 / 72</td>
<td>9 / 16</td>
</tr>
<tr>
<td>t_rise / t_fall (ns)</td>
<td></td>
<td>3.7 / 5.2</td>
<td>14 / 7</td>
<td>10 / 6</td>
</tr>
<tr>
<td>Eon / Eoff (µJ)</td>
<td>Efficiency</td>
<td>47.5 / 8 (Vds 400V/Ids 15A)</td>
<td>Not listed</td>
<td>39 / 17 (Vds 400V/Ids 20A)</td>
</tr>
<tr>
<td>Eoss (µJ)</td>
<td></td>
<td>8</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Qrr (µC)</td>
<td></td>
<td>0</td>
<td>10</td>
<td>131</td>
</tr>
<tr>
<td>τrr (ns)</td>
<td></td>
<td>0</td>
<td>800</td>
<td>16</td>
</tr>
</tbody>
</table>
GaN Systems

Short Loops Matter – Proper Probing Technique

GaN® Systems

GaNPX®, DESIGNED WITH SHORT LOOPS \rightarrow AVOID INTRODUCING LONG LOOPS AT TEST

GaNPX® packaging is carefully designed with ultra-low source inductance to fully exploit the high switching speed capability of GaN E-HEMTs. GaNPX® packaging enables fast, clean, high frequency switching with minimal ringing and EMI.

A long ground wire introduces unwanted inductance into the probe measurement path. This results in overshoot and ringing associated with the rising and falling edges of the signals. Minimizing the length of the ground loop is especially important for GaN E-HEMTs which have very fast rise/fall times that are affected by the probe's ground inductance.

For accurate measurement results, use a scope probe with a short ground clip.

GaNPX® Package

\( L_s = 0.10 \text{nH} \)

\( L_s = <0.2 \text{nH} \)

LONG LOOP

SHORT LOOP
Low side voltages

- Use a passive high bandwidth probe (recommended 300 MHz B/W or better)
- The ground lead must be short
- PCB test points: Use 2 Plated Through Hole (PTH) points for probe insertion or solder two wires and make a short loop.
High Side Voltage Measurement Technique

High side floating signals

HV differential probes

- Important specifications: Bandwidth, CMRR, input impedance.
  Example: PMK bumblebee HV probe:
  400 MHz, 875 ps rise/fall, 4 pF input

- Using an isolated transformer to float the oscilloscope ground is **NOT RECOMMENDED** for GaN E-HEMT voltage measurements with a high dV/dt.
  - Line frequency isolated transformer is not completely isolated for high dV/dt signal due to capacitive coupling.
  - Potential ground loop and common mode noise.

Considerations when using the oscilloscope’s MATH function to calculate Eon and Eoff. (E = I_d * V_DS)

- Standard high Bandwidth passive probes can be used
- The accuracy is usually poor.
### Types of Current Sense Devices for High Speed GaN

<table>
<thead>
<tr>
<th></th>
<th><strong>Current shunt resistor</strong></th>
<th><strong>Current transformer</strong></th>
<th><strong>Rogoski coil current probe</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>• Best accuracy</td>
<td>• Isolated output</td>
<td>• Minimum insertion inductance</td>
</tr>
<tr>
<td></td>
<td>• High bandwidth</td>
<td></td>
<td>• Isolated output</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>• Large size</td>
<td>• Large size</td>
<td>• Smallest size</td>
</tr>
<tr>
<td></td>
<td>• Added loop inductance</td>
<td>• Added loop inductance</td>
<td>• Low bandwidth</td>
</tr>
<tr>
<td></td>
<td>• Not suitable for switching energy measurement</td>
<td></td>
<td>• Not suitable for switching energy measurement</td>
</tr>
<tr>
<td><strong>Best Use</strong></td>
<td>• Eon/Eoff measurement</td>
<td>• Application where high bandwidth is not required</td>
<td>• High current measurement. e.g. Double pulse test</td>
</tr>
<tr>
<td><strong>Equipment</strong></td>
<td><strong>T&amp;M research co-axial current shunt</strong></td>
<td><strong>Pearson 2877 current monitor</strong></td>
<td><strong>PEM CWT Ultra Mini</strong></td>
</tr>
<tr>
<td></td>
<td>• SDN-414-10 (0.1Ω, 2GHz bandwidth)</td>
<td>• 1V/A output</td>
<td>• 9.2Hz-30MHz, 300A</td>
</tr>
<tr>
<td></td>
<td>• SSDN series for low insertion inductance</td>
<td>• 200MHz/100A</td>
<td></td>
</tr>
</tbody>
</table>

#### SDN series

- **T&M research co-axial current shunt**
  - SDN-414-10 (0.1Ω, 2GHz bandwidth)
  - SSDN series for low insertion inductance

- **Pearson 2877 current monitor**
  - 1V/A output
  - 200MHz/100A

- **PEM CWT Ultra Mini**
  - 9.2Hz-30MHz, 300A
Outline

Overview
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Summary and Conclusions

Appendix: Bandwidth Requirements
Double Pulse Switching Test Waveform Example

\[ t_1: \text{Device Under Test (DUT) turned on. Inductor charged to desired current (30A in this example)} \]

\[ t_2: \text{DUT turned off. Inductor current freewheels in Q1.} \]

\[ t_3: \text{DUT turn-on \to Measure, } dV/dt, t_{\text{rise}} \]

\[ t_4: \text{DUT turned off} \]
**GS66508**– Double Pulse Switching Test

**V_{DS}=400V, I_D=30A** Hard Switching Turn-on

- $I_L = 30A$
- $V_{DS} = 400V$
- Peak turn-on $dV/dt = 80 \text{ V/ns}$
- VDS dip due to loop inductance: $\Delta V = Lp \times di/dt$

Estimated Loop inductance = 3nH

**V_{DS}=400V, I_D=30A** Hard Switching Turn-off

- $I_L = 30A$
- $V_{DS}$ peak = 450V
- Peak Turn-off $dV/dt > 100 \text{ V/ns}$

Clean rising edge w/ low Vds overshoot (low loop inductance)

---

* GS66508 – 650V / 30A / 50mΩ
Hard Switching Performance Comparison: GaN vs SiC

Using the measurement techniques described in this document, the clean switching edges and fast switching speeds of GaN Systems’ E-HEMT were accurately captured. This results in a true comparison of GaN to SiC.

Test: 400V/15A Half Bridge hard switching double pulse test
- Gate Drive: Silab Si8271. $R_{G(on)} = 10\Omega$, $R_{G(off)} = 1\Omega$
- GaN device: 650V / 30A / 50mΩ
- SiC device: 900V / 35A / 65mΩ
Outline

Overview
  • The Importance of Measurement Technique

GaN E-HEMTs Switching Test Measurement Techniques
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  • Low-side voltage probing
  • High-side floating voltage probing
  • Current sensing for high-speed GaN E-HEMTs

Double Pulse Switching Test
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  • 400V/30A hard switching turn-on and turn-off test results

Switching Energy Eon/Eoff Measurement
  • $V_{GS}$, $V_{DS}$, $I_{DS}$ probing techniques to increase measurement accuracy
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Summary and Conclusions

Appendix: Bandwidth Requirements
Eon/Eoff Measurement Techniques

- GaN Systems’ daughterboard EVBs are commonly used to characterize the GaN E-HEMT switching losses.
- A current shunt is the best choice for conducting the Eon/Eoff measurements.
- The EVBs’ test points are designed for use with the T&M Research SDN-414 high B/W coaxial current shunt.

VGS probe: TP4-TP6
TP3 (VSW): solder a wire and make a short loop
Switching node VSW: solder a short ground lead to Source of Q2 (before current shunt)
Source of bottom GaN HEMT is Common node for oscilloscope ground. All probe grounds are referenced to this node
During the voltage commutation period, the $E_{on}/E_{off}$ that occurs intrinsically within the device differs slightly from what is captured through measurement.

<table>
<thead>
<tr>
<th>Loss distribution</th>
<th>External measurement</th>
<th>Intrinsic to device</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{on}$ - Turn on loss</td>
<td>$E_{V_{on}} + E_{qoss}$</td>
<td>$E_{V_{on}} + E_{qoss} + E_{oss}$</td>
</tr>
<tr>
<td>$E_{off}$ - Turn off loss</td>
<td>$E_{V_{off}} + E_{oss}$</td>
<td>$E_{V_{off}}$</td>
</tr>
</tbody>
</table>

- $E_{qoss}$ and $E_{oss}$ loss affect the overall $E_{on}$ loss, especially under light load operating condition.
- Accurate $E_{qoss}$ and $E_{oss}$ loss calculations are necessary and are fully explained in [Parasitic Capacitance Eqoss Loss Mechanism, Calculation, and Measurement in Hard-Switching for GaN HEMTs](#).
**Eon Switching Loss**

**E\textsubscript{V\text{ill}} loss:** The overlapping loss of voltage and current during the switching period.

**E\textsubscript{oss} loss:** The internal discharge of S2 C\textsubscript{oss} through S2. This occurs within the GaN device and is not captured by an oscilloscope measurement*.

**E\textsubscript{qoss} loss:** The charging of C\textsubscript{oss} of S1, the high side device. Because S1 isn’t conducting, C\textsubscript{oss} is charged through S2.

<table>
<thead>
<tr>
<th>External loss measurements</th>
<th>Intrinsic device losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{V\text{ill}} + E_{qoss}$</td>
<td>$E_{V\text{ill}} + E_{qoss} + E_{oss}$</td>
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</table>

* There is an extra $I_{DS}$ current spike caused by displacement current of high side C\textsubscript{oss}.
## Eoff Switching Loss

**E\text{Vloff loss}:** The overlapping loss of voltage and current during the switching period

**E\text{oss loss}:** $E_{\text{oss}}$ appears as a measured loss, however, it is not part of the turn-off loss. It is dissipated into S2 at the next switch turn-on

### During the turn-off period:

- When $V_{\text{GS}} < V_{\text{GS(th)}}$
  - The E-HEMT is not conducting.
  - $I_{\text{load}}$ charges $C_{\text{oss}} \rightarrow$ reactive power = $E_{\text{oss}} @ V_{\text{DS}}$. There is no real loss during this period.
  - The measured $E_{\text{off}}$ include $C_{\text{oss}}$ energy. This is not part of the turn-off loss. Instead, it will be dissipated at the next switch turn-on.
  - The load current defines the turn-off $dV/dt$ and rise time, not $V_{\text{GS}}$

### Tables and Diagrams

<table>
<thead>
<tr>
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<th>Intrinsic device losses</th>
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</thead>
<tbody>
<tr>
<td>$E_{\text{Vloff}} + E_{\text{oss}}$</td>
<td>$E_{\text{Vloff}}$</td>
</tr>
</tbody>
</table>

![Diagram 1](image1)

![Diagram 2](image2)
GS66508 Eon/Eoff test results

Eon = 15uJ @ V_{DS}=400V, I_D=0A (Eqoss Loss* only)

\[ V_{DS} = 400V \]

Math: \( V_{ds} \times I_d \)

Channel de-skewing is critical for accurate Eon/Eoff test results. De-skewing insures that all current and voltage probe delays are the same. Manually calibrate the current shunt channel timing against Vds. The rising edge of Id should match the falling edge of Vds.

GS66508 Eon/Eoff test results: Eon

Eon = 87μJ @ V_{DS}=400V, I_D=30A

The dip in V_{ds} is due to loop inductance inserted by the current shunt.

V_{DS} = 400V

Math: V_{ds} \times I_d

I_L = 30A

Current shunt I_d
GS66508 Eon/Eoff test results: Eoff

Eoff = 15μJ @ \( V_{DS} = 400\text{V} \), \( I_D = 30\text{A} \)

This is an example of a well conducted Eoff test. The scope shot accurately captures the ultra-fast slew rate of a GaN E-HEMT at a dV/dt > 100V/ns.

Fast switching results in very low switching losses, and ultimately enable high efficiency operating even at high switching frequencies.
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Overview
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Double Pulse Switching Test
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  • 400V/30A hard switching turn-on and turn-off test results

Switching Energy Eon/Eoff Measurement
  • $V_{GS}$, $V_{DS}$, $I_{DS}$ probing techniques to increase measurement accuracy
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  • Eqoss measurement example
  • 400V/30A Eon/Eoff Test results

Summary and Conclusions

Appendix: Bandwidth Requirements
Accurately characterizing the ultra-fast switching speeds of GaN Systems’ GaN E-HEMTs requires attention to test methodologies.

This application note provided an overview of appropriate measurement equipment and measurement techniques. In addition, two common transistor characterization tests and results were presented: The Double Pulse Switching Test and Eon/Eoff Test.

With the information provided in this document, power electronic designers can accurately characterize GaN Systems’ E-HEMTs and design power systems that are optimized and differentiated in performance.
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Overview
  • The Importance of Measurement Technique

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  • Low-side voltage probing
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  • Current sensing for high-speed GaN E-HEMTs

Double Pulse Switching Test
  • Double Pulse Switch Test Set up
  • 400V/30A hard switching turn-on and turn-off test results

Switching Energy Eon/Eoff Measurement
  • Vgs, Vds, Ids probing techniques to increase measurement accuracy
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Summary and Conclusions

Appendix: Bandwidth Requirements
Appendix: The Impact of Bandwidth on Measurement

The measurement bandwidth is determined by the capability of oscilloscope and probes

\[ Bandwidth_{measurement} = \sqrt{\frac{1}{Bandwidth^2_{Scope}} + \frac{1}{Bandwidth^2_{Probe}}} \]

The delay caused by limited bandwidth is

\[ t_{rise} \approx \frac{0.35}{Bandwidth_{measurement}} \]

Circuit resonant frequency is

\[ f_r = \frac{1}{2\pi \sqrt{L_{loop} \cdot C}} \]

\( L_{loop} \): loop parasitic inductance
\( C \): parasitic capacitance

Due to the ultra-fast switching transition and low parasitic capacitance of GaN E-HEMTs, high-bandwidth equipment is required for measurement. Refer to pages 7-9 for detailed recommendations.

*Source of equations: Tektronix: Understanding Oscilloscope Bandwidth, Rise Time and Signal Fidelity*
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