The Effect of Dynamic On-State Resistance to System Losses in GaN-based Hard-Switching Applications

Presented by:

Introduction

What is dynamic $R_{DS(on)}$?

- Dynamic $R_{DS(on)}$ is due to charge trapping effect of electrons. It results in a decrease of the two-dimensional electron gas (2DEG) density, and therefore, cause the $R_{DS(on)}$ to increase. It will cause additional loss for the GaN-based power electronic applications.

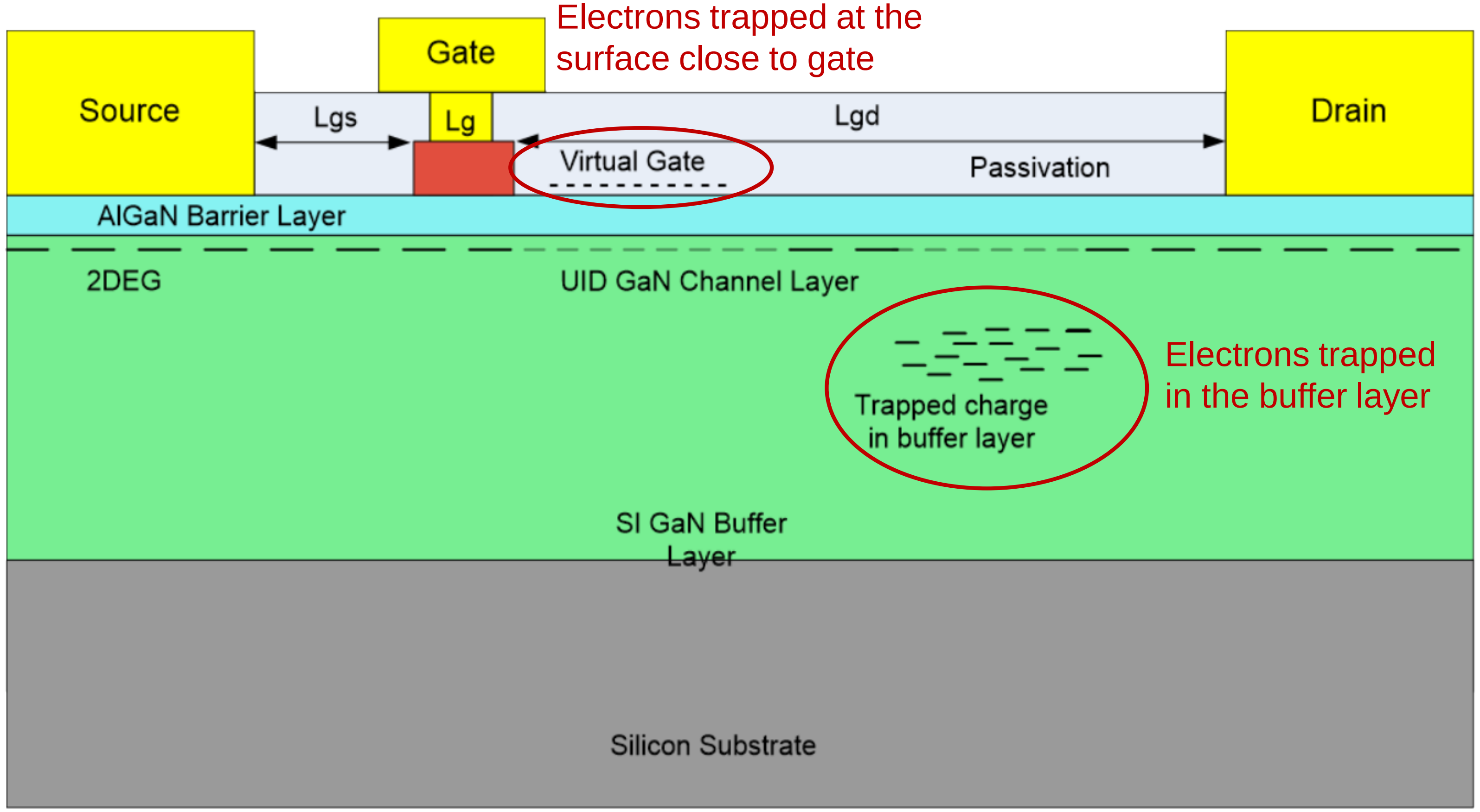
<u>**In this presentation, we will present:**</u>

1. What is the dynamic $R_{DS(on)}$ value?

2. How to measure it?

- Reasonable soak time for pulse test
- Separation of heating and trapping effects

3. What is the percentage of the dynamic $R_{DS(on)}$ loss from system-level in a real application?



Lateral GaN HEMT device structure

Agenda

- **Measuring dynamic $R_{DS(on)}$**
  - Test setups
  - Soak time variation and its importance
  - Junction temperature variation and conduction loss equation
- **Dynamic $R_{DS(on)}$ effect on system loss**
  - Energy loss distribution in GaN device
  - Comparison to Silicon and Silicon Carbide
- **Conclusions**

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Test setup I – pulse test

Test setup I:
Double pulse test (DPT) with soak time and T_j control

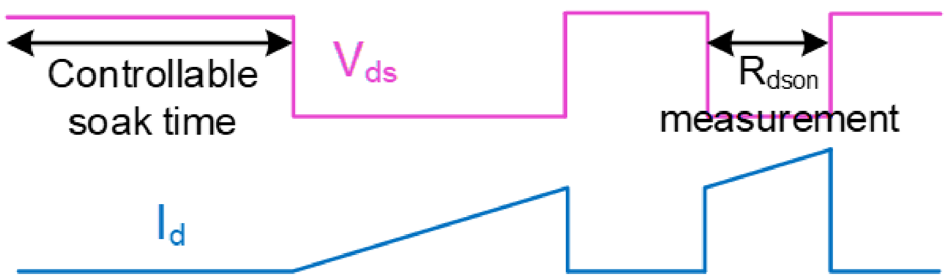
Device under test (DUT): GS66508T GaN HEMT

Measurement equipment:

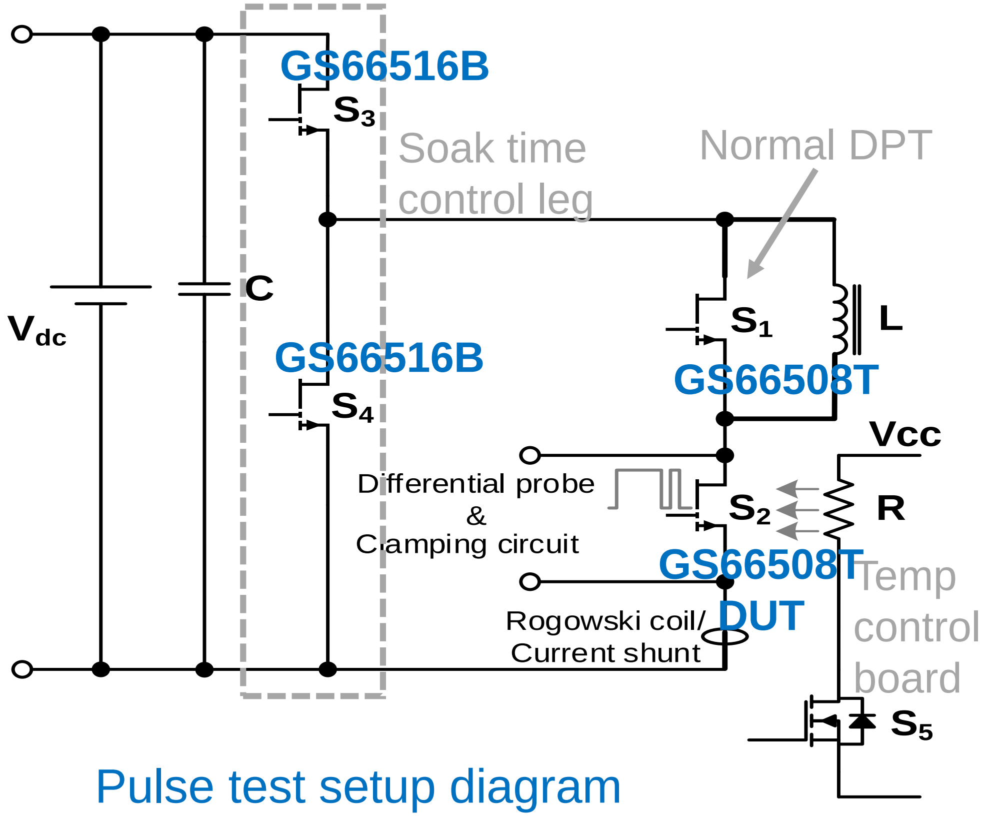
- Off-state V_{DS} measurement → Differential probe
- On-state $V_{DS(on)}$ measurement → Clamping circuit
- I_D measurement → Rogowski coil/Current shunt
- T_j measurement → Thermal camera

Control variables:

- Soak time Control → Extra half-bridge S_3/S_4
- T_j Control → Heating resistor/NTC thermistor
- V_{DS}, I_D, and on-time → DPT
- DSP controls all four gates (S_1-S_4)



Soak time control diagram

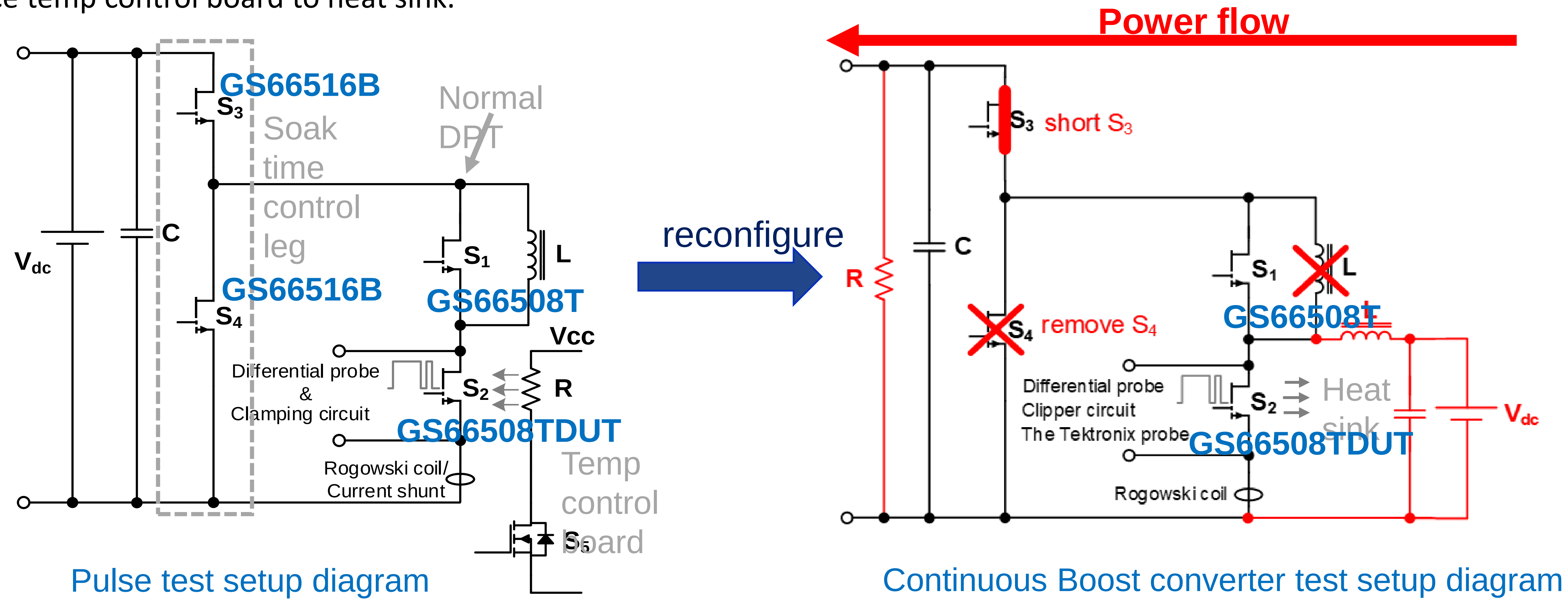


Pulse test setup diagram

Test setup II – continuous test

Test setup II: Continuous Boost converter setup

- **DPT test setup can be reconfigured to a Boost converter setup for continuous test with the following changes,**
    1. Remove/short soak time control leg;
    2. Change power source, load and inductor position;
    3. Replace temp control board to heat sink.

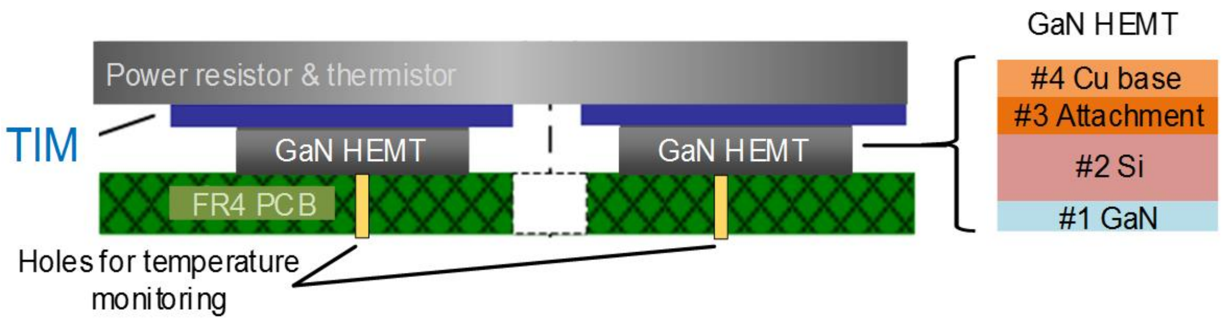


Pulse test setup diagram

Continuous Boost converter test setup diagram

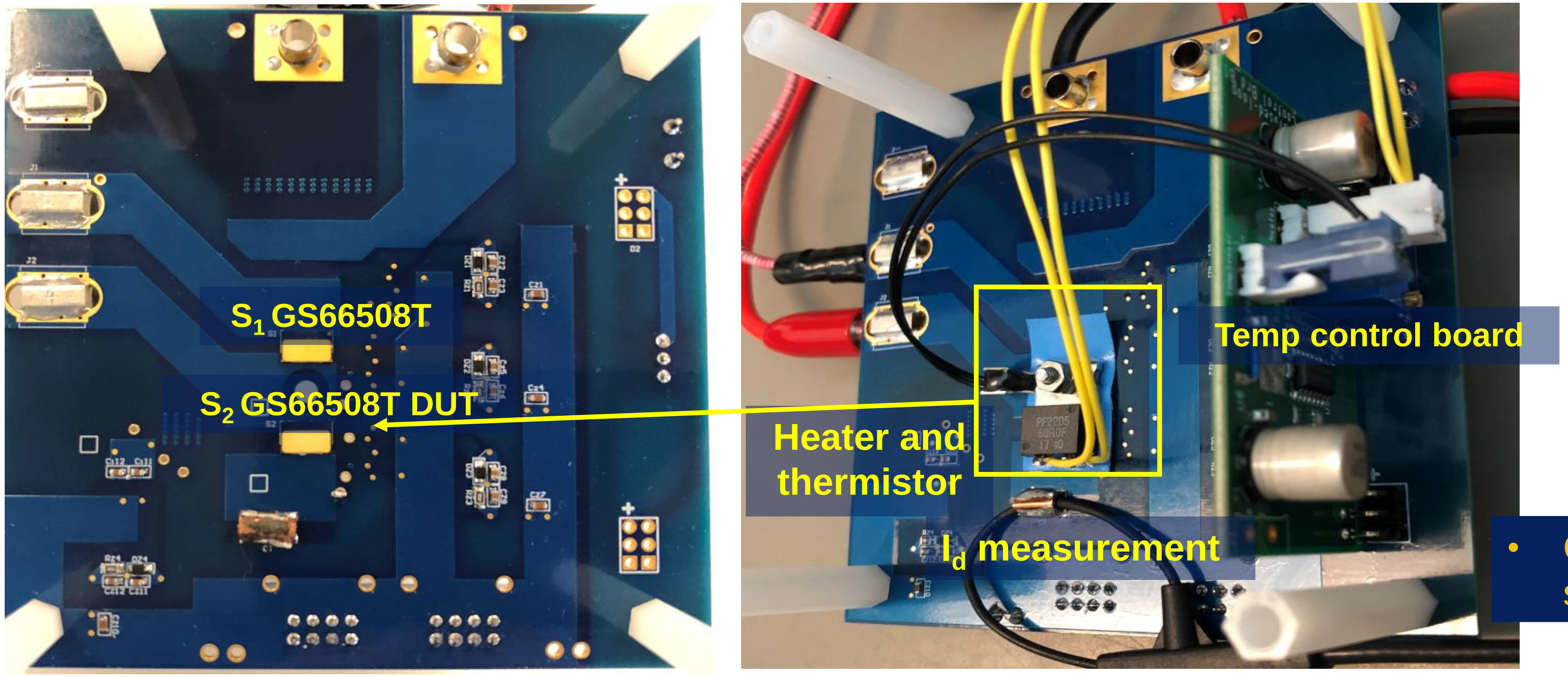
Pulse test setup – bottom view

- GS66508T-based half-bridge on the bottom side
- The heater and thermistor are installed upon DUT switch S_2
- Temperature is also monitored by thermal camera



Monitored temperature thru thermal holes on the back side

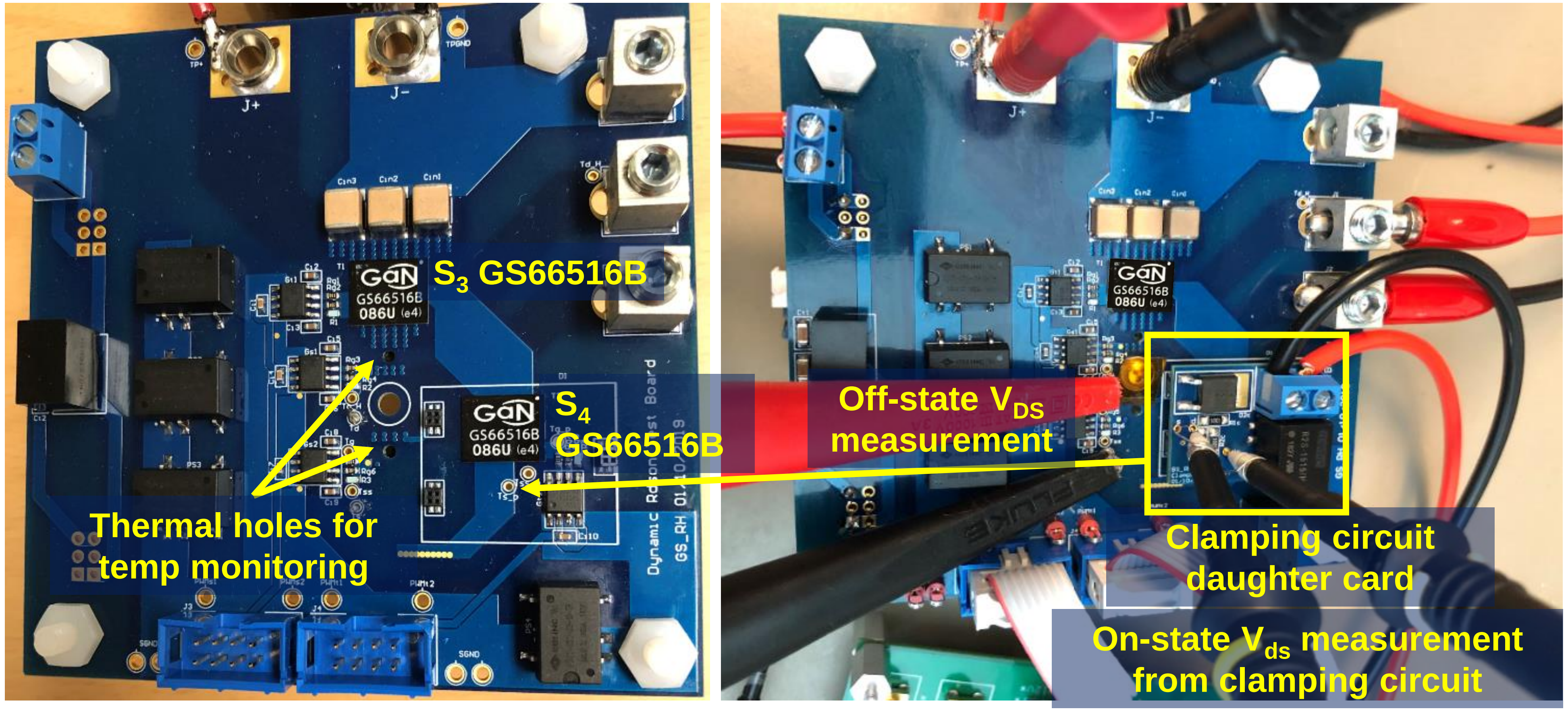
Bottom view with and without temperature control board



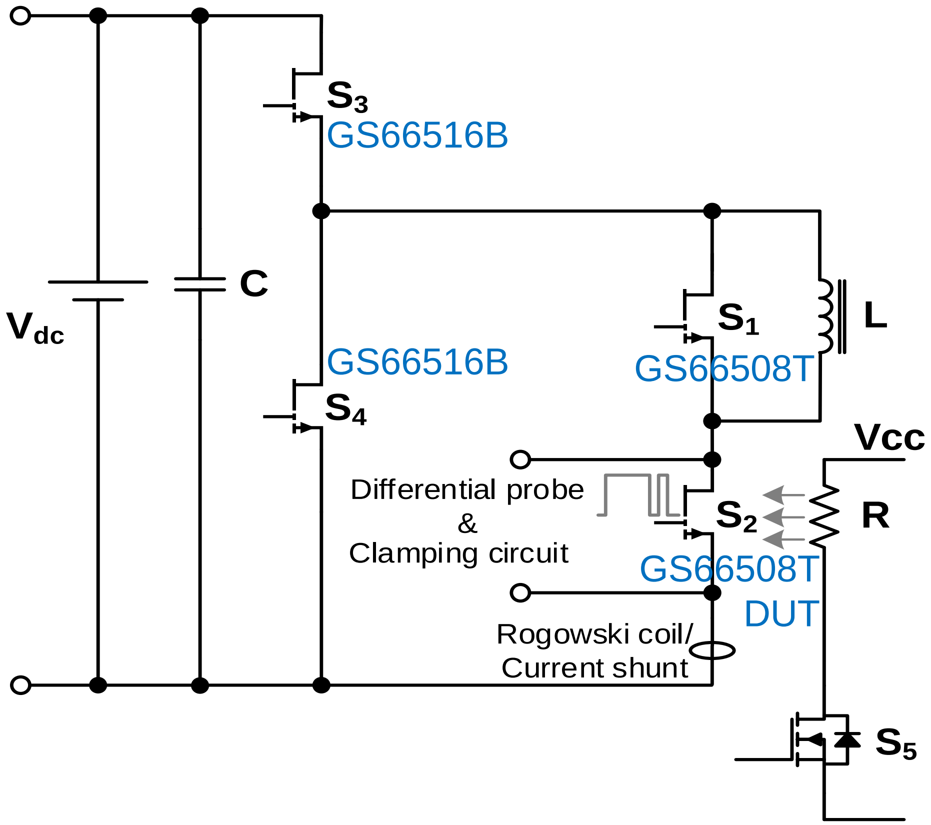
- Good T_j monitoring is important to separate heating and trapping effects

Pulse test setup – top view

- **GS66516B-based half-bridge on the top side**
- **The clamping circuit board is installed upon switch S_4 and close to DUT S_2**



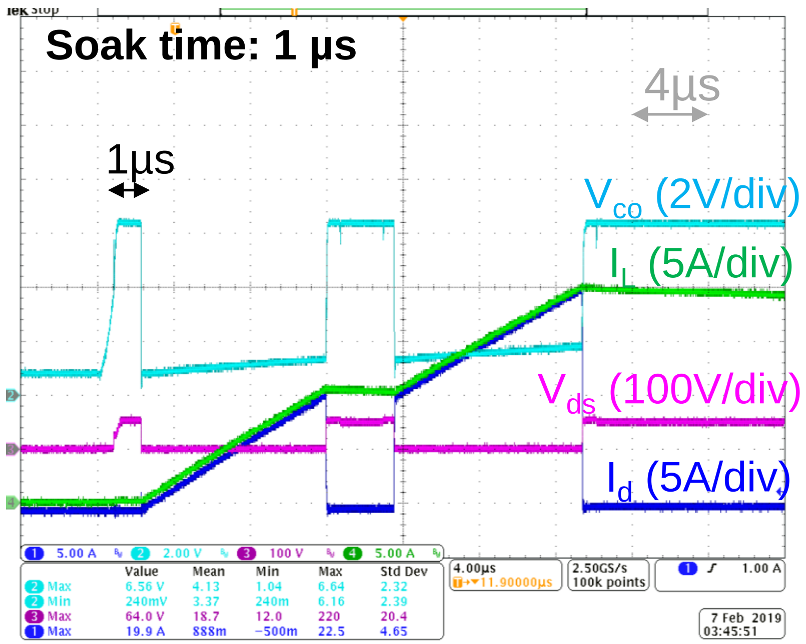
Top view with and without clamping circuit



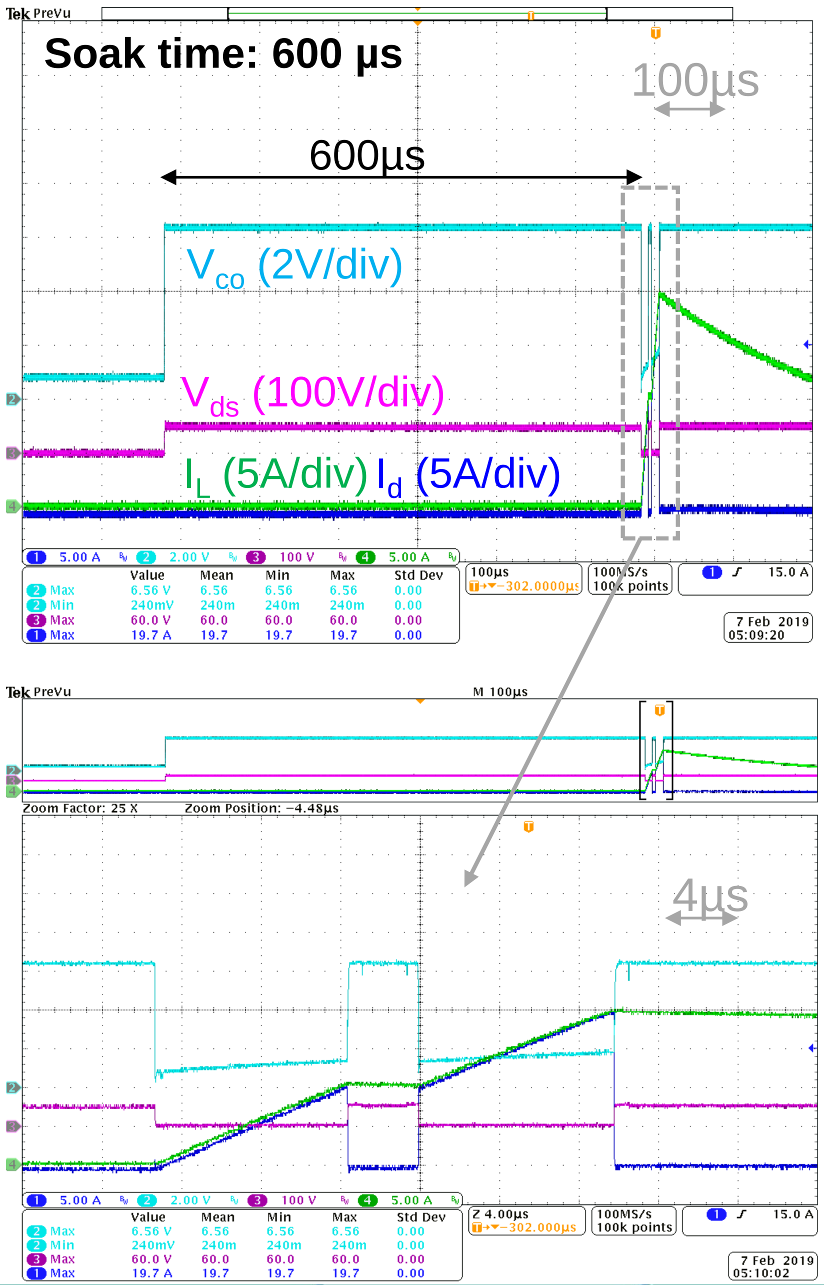
Pulse test setup diagram

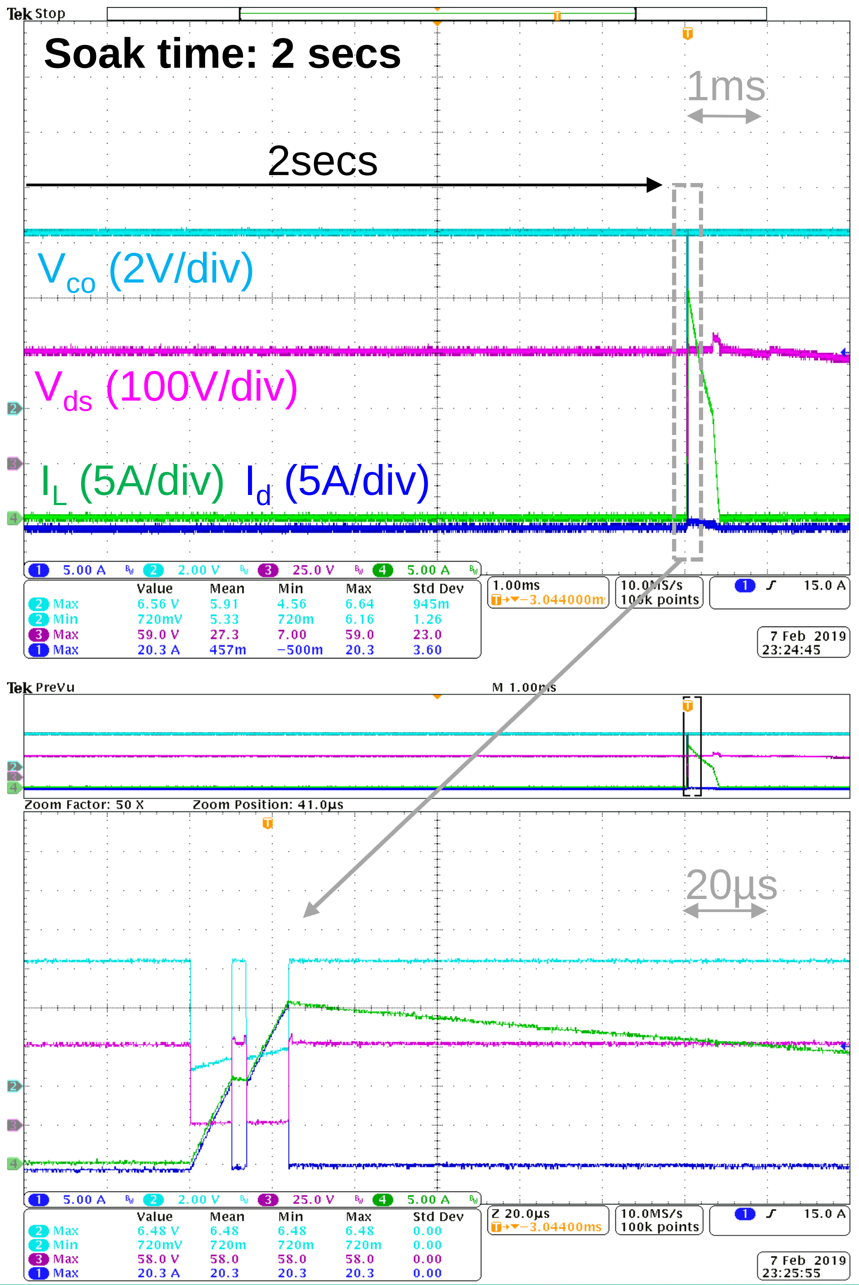
Soak time variation

DPT examples with different soak times



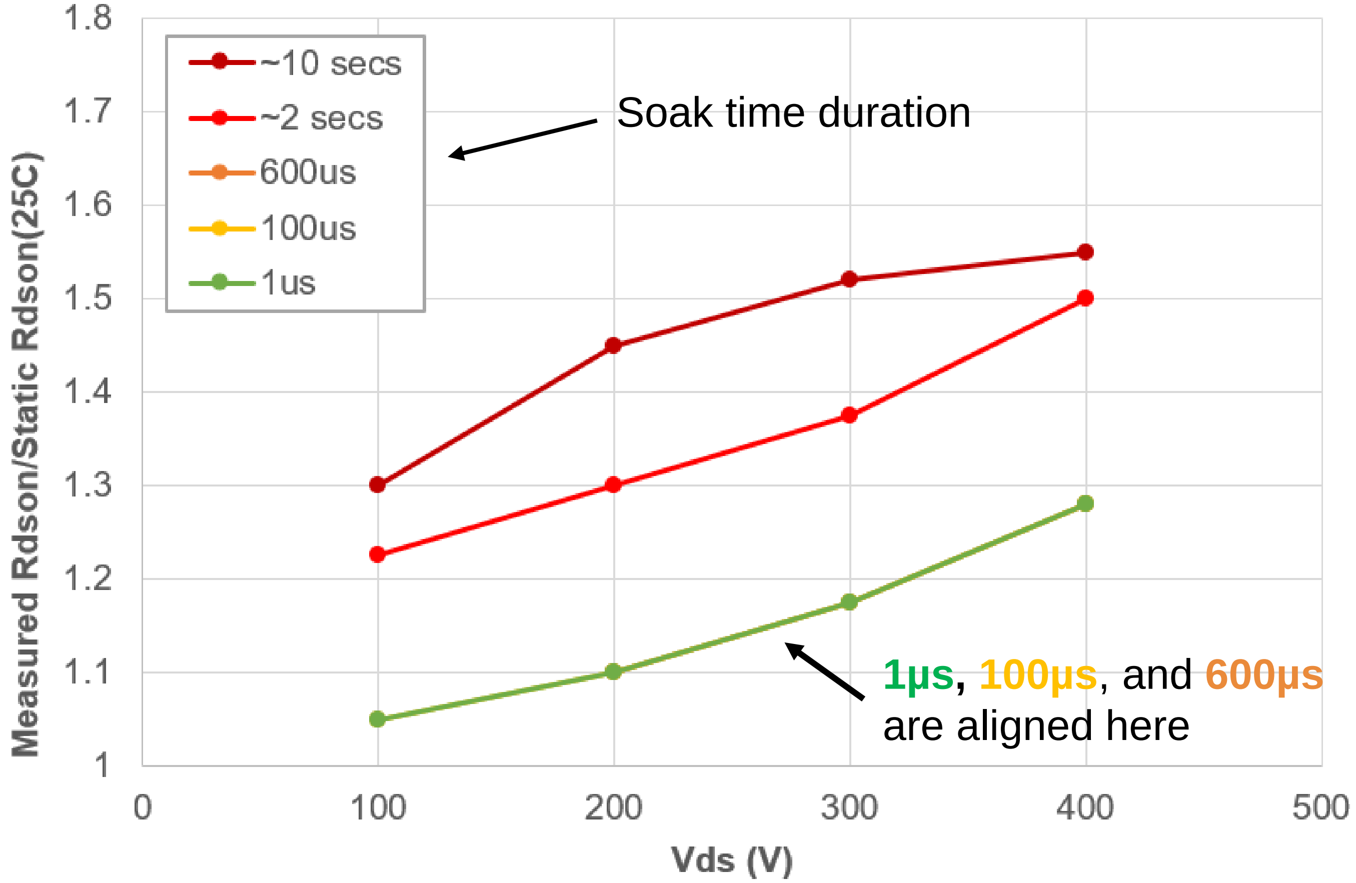
Controllable soak time is achieved by controlling the half-bridge S_3/S_4



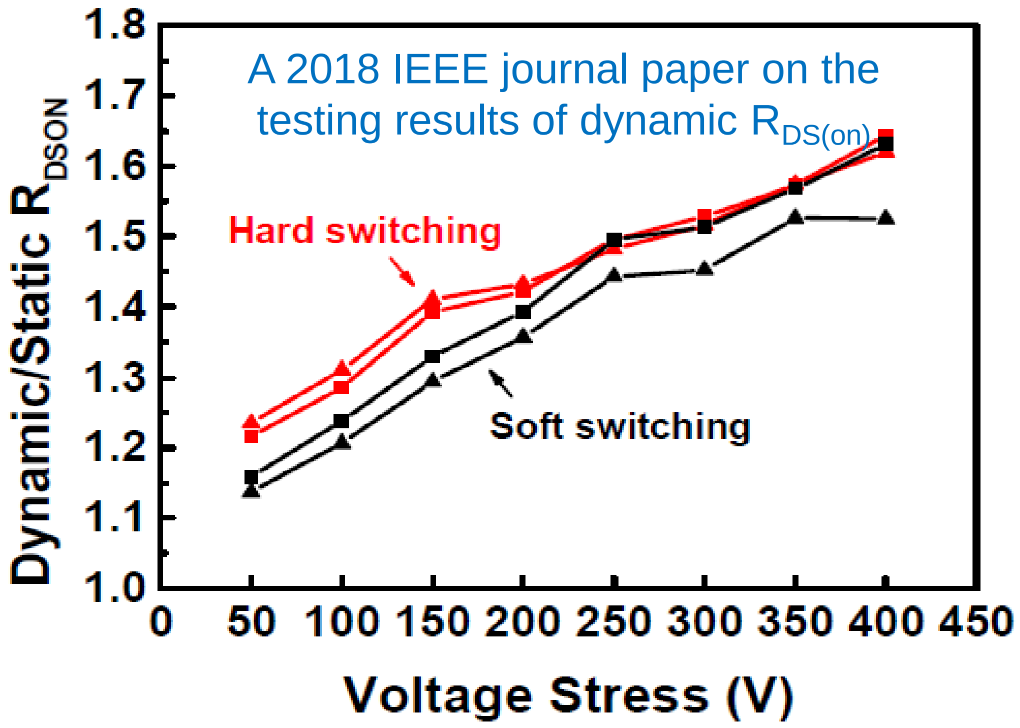


Dynamic $R_{DS(on)}$ results with soak time control

Summary on soak time vs. V_{ds}



A Typical example of academic technical papers (without soak time control):



- Soak time impacts dynamic $R_{DS(on)}$ results. Improper soak time give erroneous results
- For accurate power loss evaluation, evaluate dynamic $R_{DS(on)}$ at the soak time of your power system, 1 to 100 µs

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$R_{DS(on)}$ heating effect, k_{Tj} factor

Heating effect on the GS66508T DUT (device is characterized before all tests):

$R_{DS(on)}$@25°C = 43.28 mohm

$R_{DS(on)}$@75°C = 64.5 mohm

$R_{DS(on)}$**@75°C**/$R_{DS(on)}$@25°C=**1.49**

The normalized increased $R_{DS(on)}$ due to 75°C heating is 0.49

(k_{Tj}=0.49)

$R_{DS(on)}$@125°C = 91.7 mohm

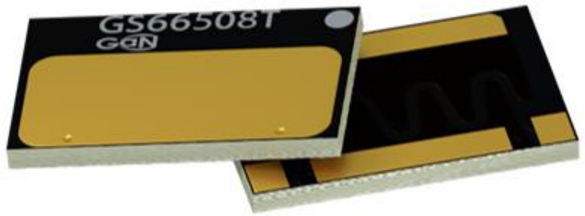
$R_{DS(on)}$@**125°C**/$R_{DS(on)}$@25°C=**2.12**

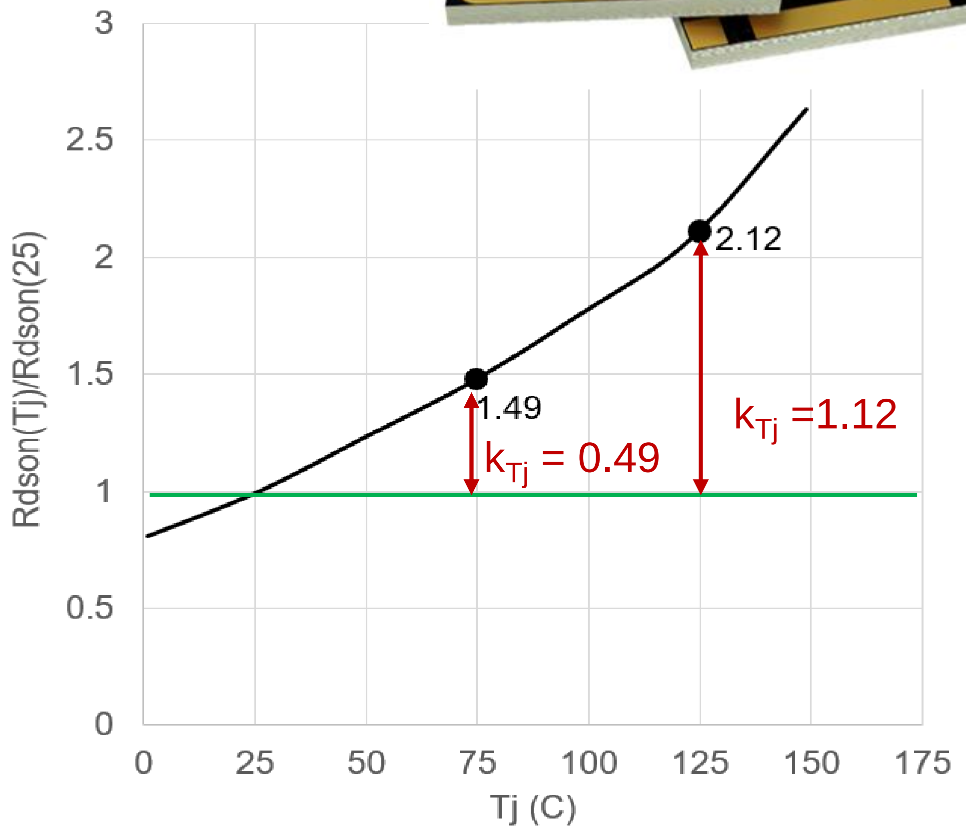
The normalized increased $R_{DS(on)}$ due to 125°C heating is 1.12

(k_{Tj}=1.12)

- **k_{Tj} is the normalized increased $R_{DS(on)}$ from heating effect**

GS66508T GaN HEMT





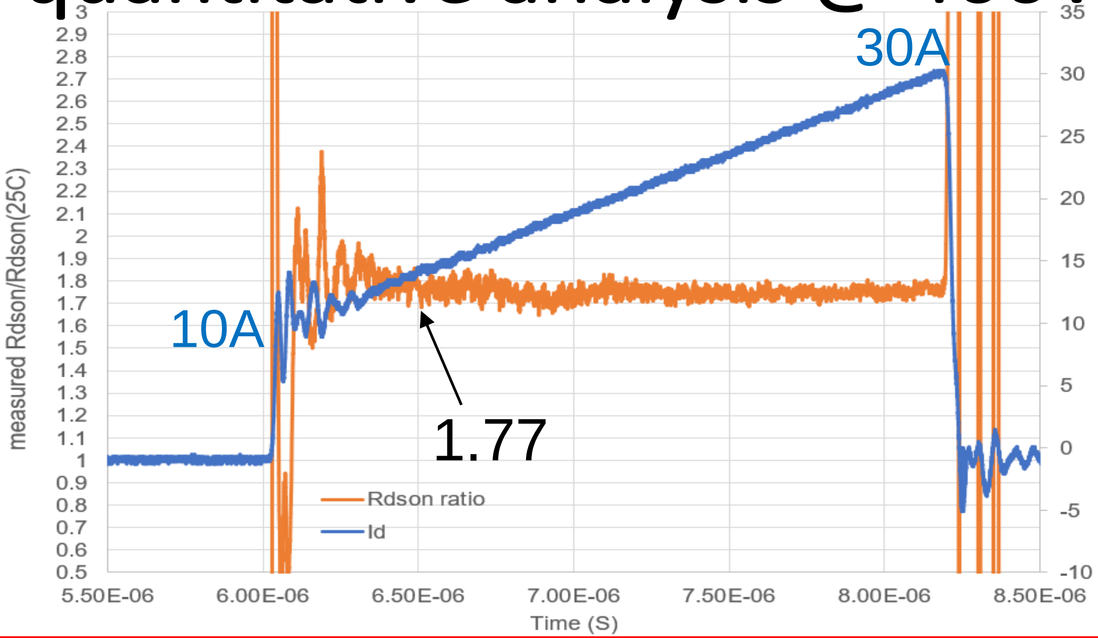
DUT $R_{DS(on)}$ vs. T_j characterization

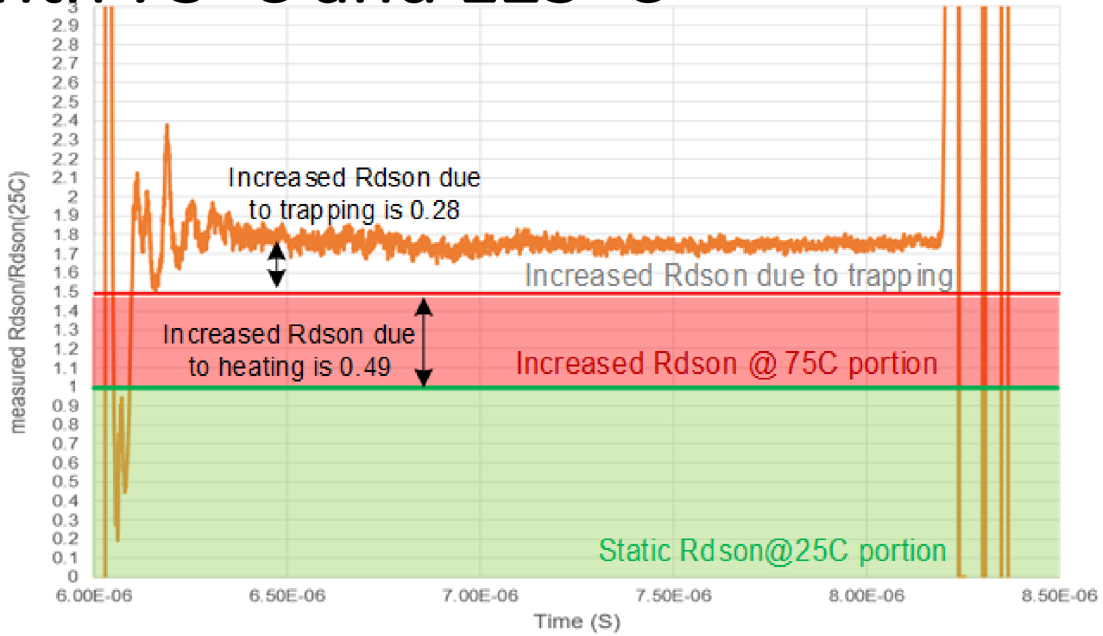
$R_{DS(on)}$ decoupling quantitative analysis @ 400V with 75°C and 125°C

Measured $R_{DS(on)}$ @ **75°C**, 400V, I_D ramp up from 10A to 30A, T_{soak}=1µs

k_{Tj}=0.49

k_{dr}=0.28



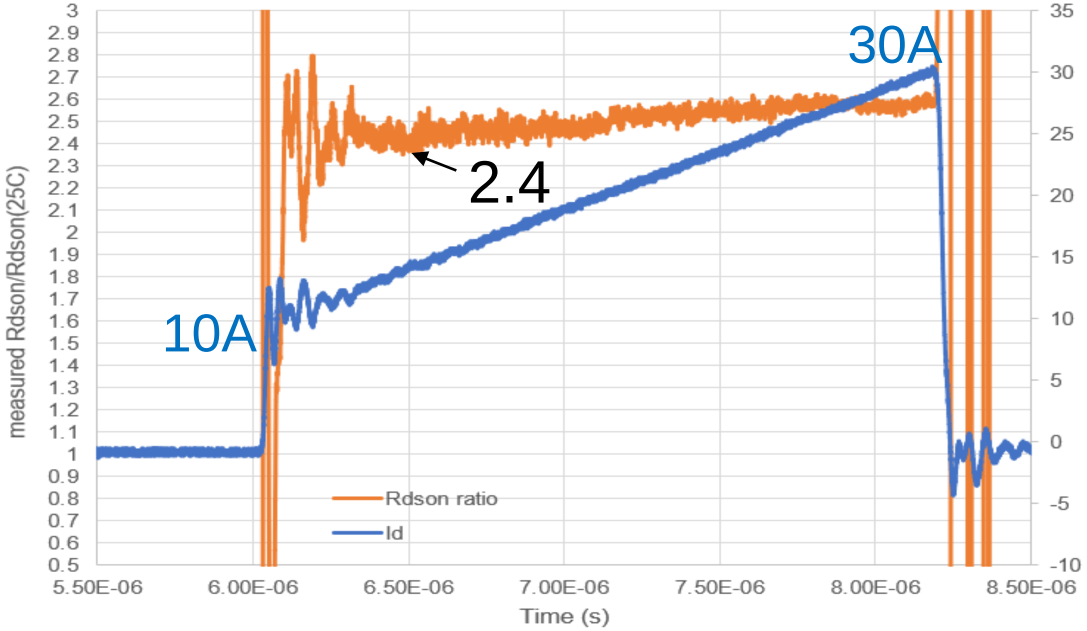


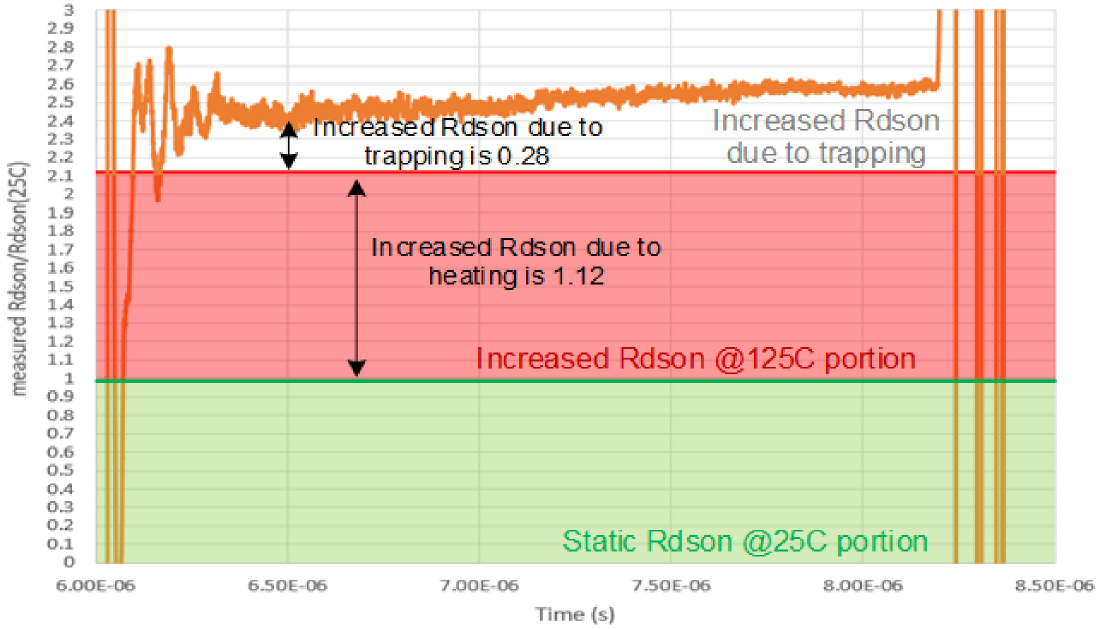
Measured $R_{DS(on)}$ @ **125°C**, 400V, I_D ramp up from 10A to 30A, T_{soak}=1µs

k_{Tj}=1.12

k_{dr}=0.28

- Good T_j monitoring is important to separate heating and trapping effects





Conduction loss calculation with *k* factors

Different types of conduction loss calculation considering dynamic $R_{DS(on)}$

	$I^2R_{DS(on)(25C)}*(1+k_{Tj})*(1+k_{dr})$	$I^2R_{DS(on)(25C)}*(1+k_{Tj}+k_{dr})$
	Previous misunderstanding on loss calculation	Proposed loss calculation
Accuracy?	✗	✓

Definition of *k* factors:

- k_{Tj} is the normalized increased $R_{DS(on)}$ portion from heating effect. Normalized to static $R_{DS(on)(25C)}$.
- k_{dr} is the normalized increased $R_{DS(on)}$ portion from trapping effect. Normalized to static $R_{DS(on)(25C)}$.

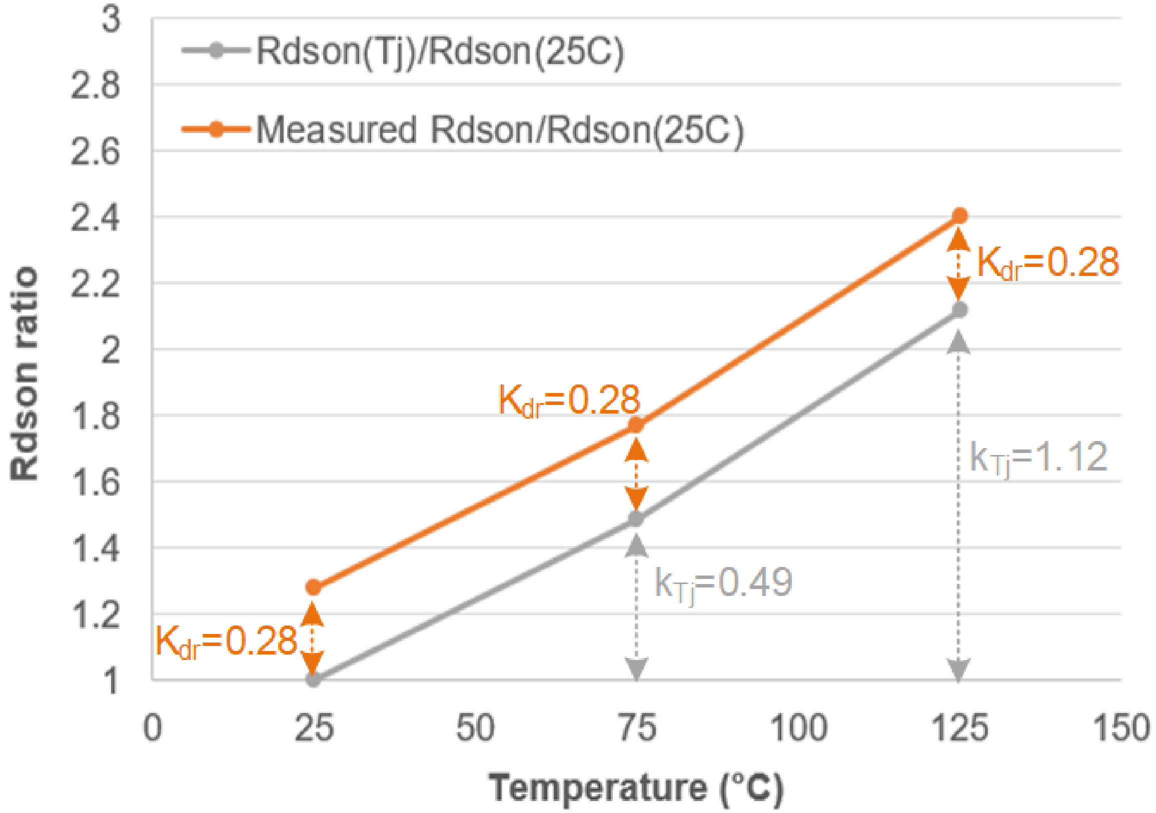
Loss iteration with *k* factors:

- Good thing about using the factor k_{dr} is it is temperature independent.

1. An simpler loss calculation (still only one curve fittings with T_j: k_{Tj}).
2. Easy for loss iteration calculation.

As T_j ↗ → $R_{DS(on)(Tj)}$ or k_{Tj} ↗

→ k_{dr} constant with T_j



Summary on $R_{DS(on)}$ ratios vs. junction temperature T_j

Conduction loss calculation made simple and accurate

Example: conduction loss calculation considering dynamic $R_{DS(on)}$

If $R_{DS(on)(25C)}$=43.27 mohm, I_{RMS}=10 A, and T_j=125 °C

Different types of conduction loss calculation considering dynamic $R_{DS(on)}$

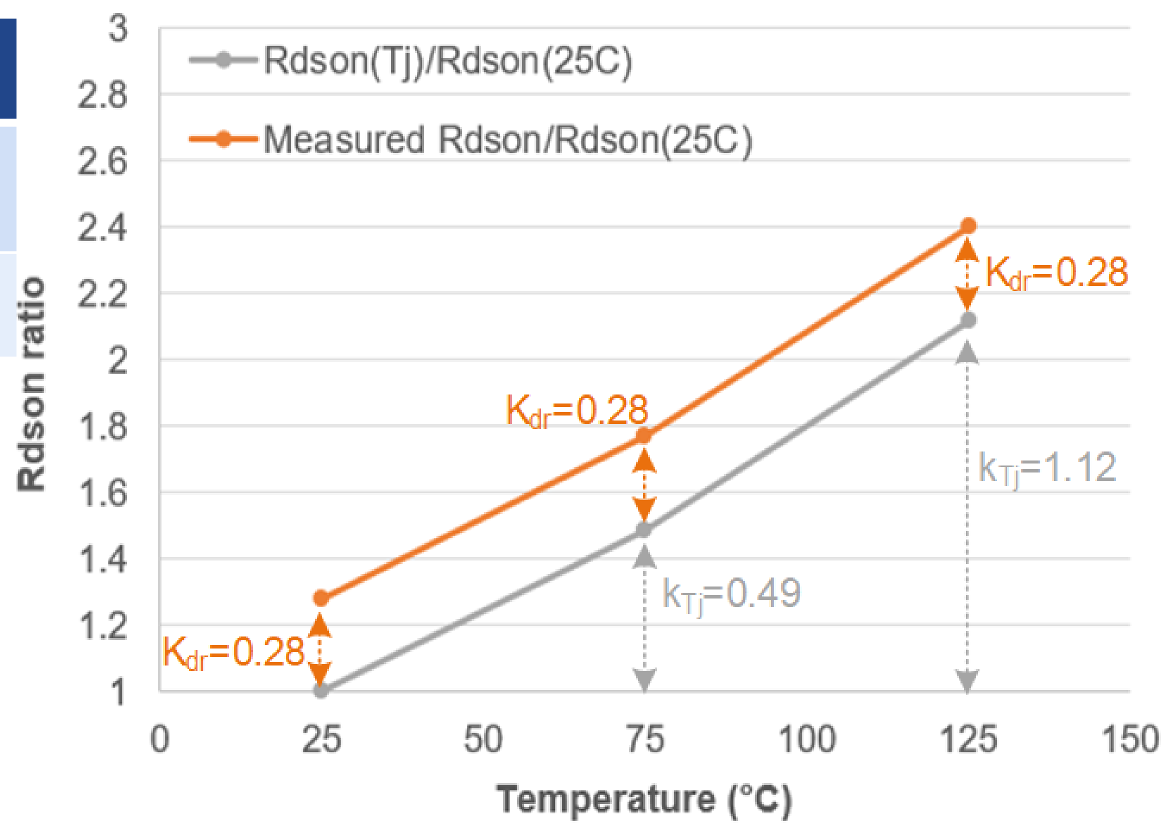
	$I^2R_{DS(on)(25C)}*(1+k_{Tj})*(1+k_{dr})$	$I^2R_{DS(on)(25C)}*(1+k_{Tj}+k_{dr})$
	4.327x(1+1.12)x(1+0.28)=11.74 W	4.327x(1+1.12+0.28)=10.38 W
Accuracy?	✗	✓

That's 11.74-10.38=1.36 W difference, even without considering self-heating;

For engineers who are more familiar with energy loss, this is like
13.6 μJ*100 kHz=1.36 W;

If the thermal resistance is about 8 °C/W, that's 10 °C difference.

- k_{dr} is the simple easy way to calculate dynamic $R_{DS(on)}$
- Use power loss = $I^2R_{DS(on)(25C)}*(1+k_{Tj}+k_{dr})$ for simple and accurate results



Summary on $R_{DS(on)}$ ratios vs. junction temperature T_j

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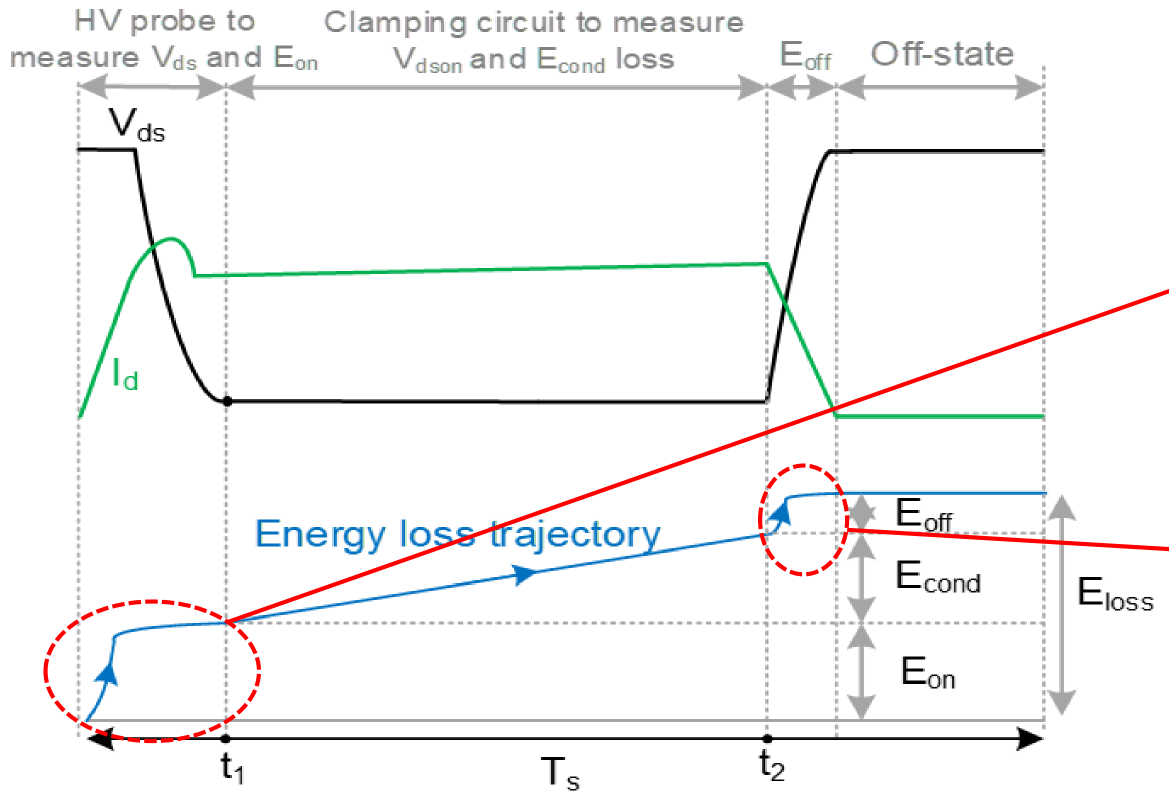
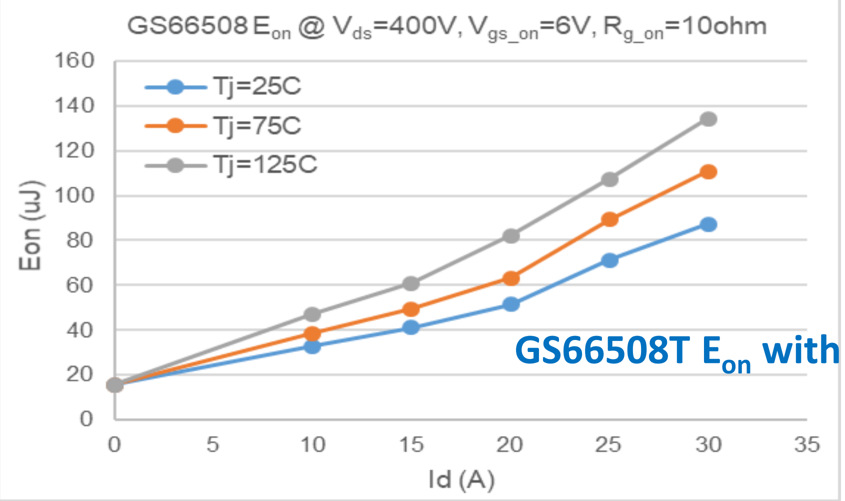
Energy loss distribution in GaN device

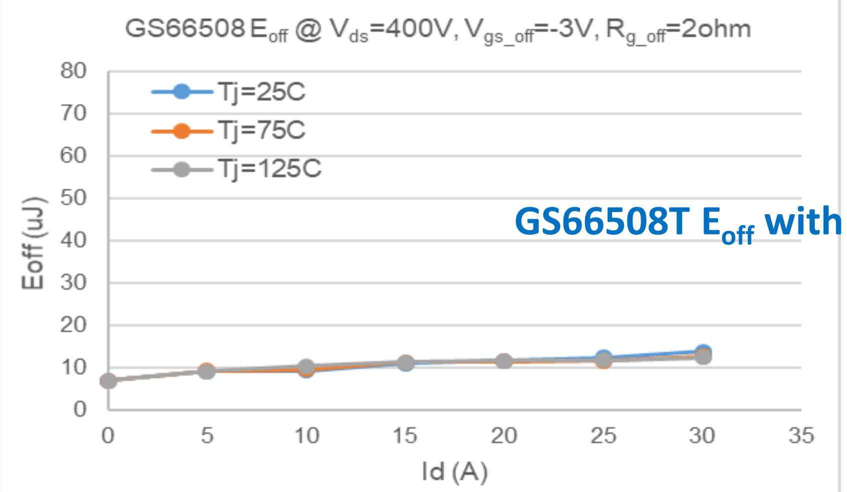
- By knowing V_{DS}, I_D, conduction time, and T_j, the energy loss is accumulated and the final overall loss can be obtained.
- The energy loss trajectory also presents the overall loss breakdown.



A hard-switching cycle of GaN HEMT and its energy loss trajectory



GS66508T E_{on} with T_j variation



GS66508T E_{off} with T_j variation

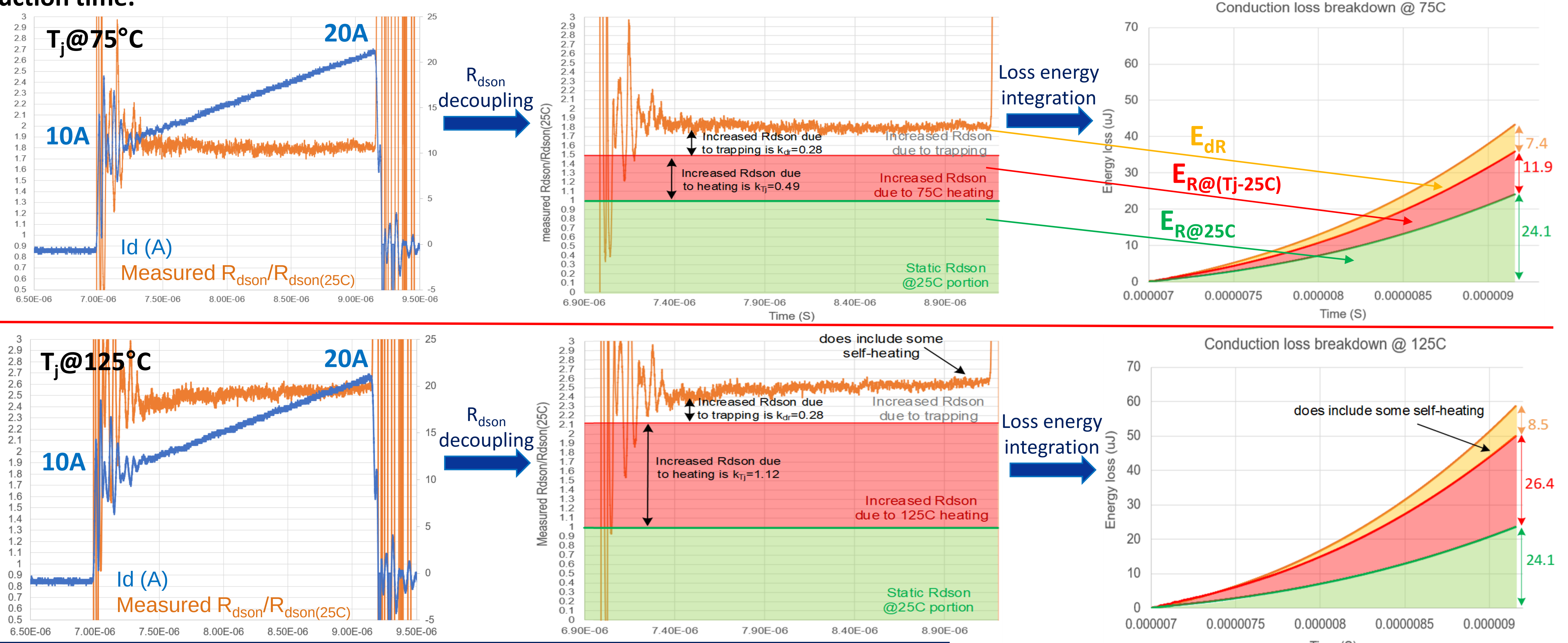
The impact of dynamic $R_{DS(on)}$ should be compared to the overall loss in a switching cycle

Please refer to GS technical papers below for more details on switching loss E_{on}/E_{off} :

1. R. Hou, J. Lu, and D. Chen, "Parasitic capacitance E_{qoss} loss mechanism, calculation, and measurement in hard-switching for GaN HEMTs," in *Proc. 2018 IEEE APEC*, San Antonio, TX, Mar. 2018.
2. R. Hou, J. Xu, and D. Chen, "Multivariable turn-on/turn-off switching loss scaling approach for high-voltage GaN HEMTs in a hard-switching half-bridge configuration," in *Proc. 2017 IEEE WiPDA*, Albuquerque, NM, Oct. 2017.

Examples - conduction loss distribution @ 75°C and 125°C

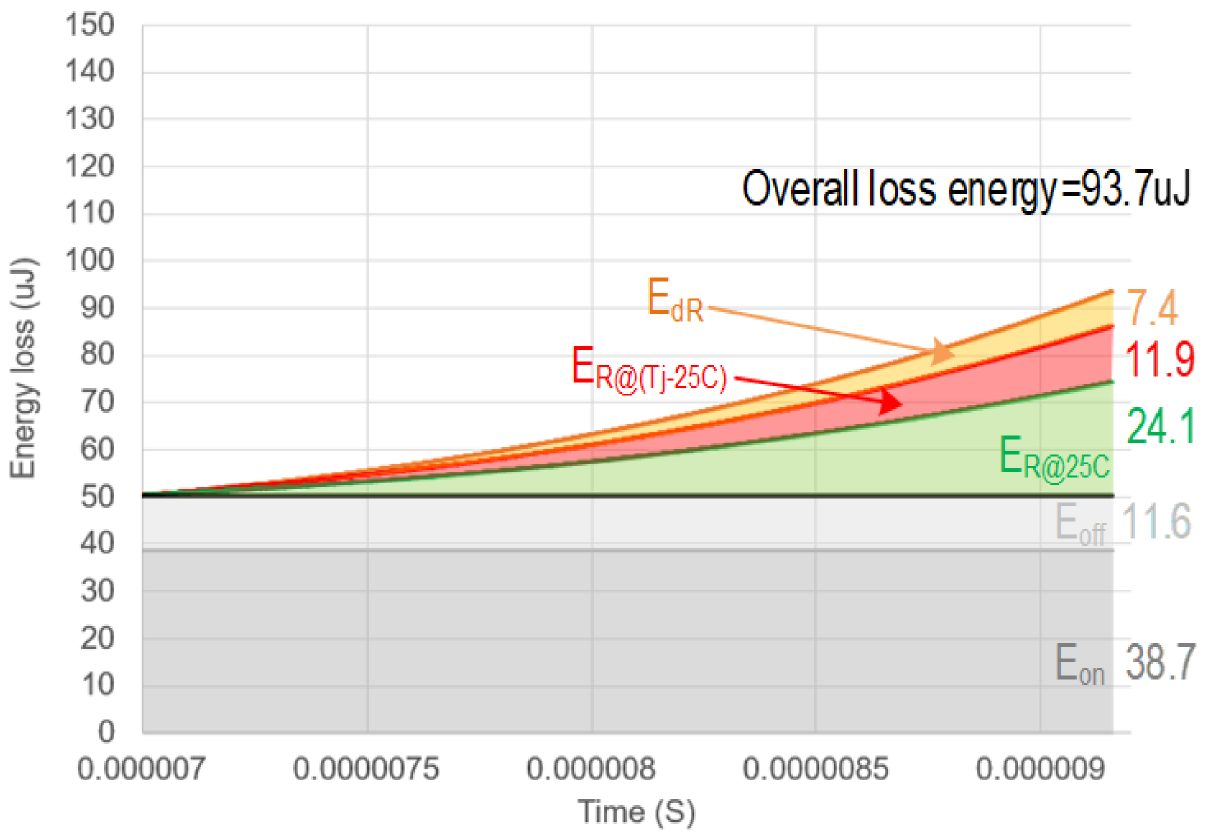
- **Two 400 V examples: T_j of 75 °C & 125 °C. For both, device V_{DS} voltage is 400 V, current starts at 10 A then ramps up to 20 A with a 2.2 µS conduction time.**



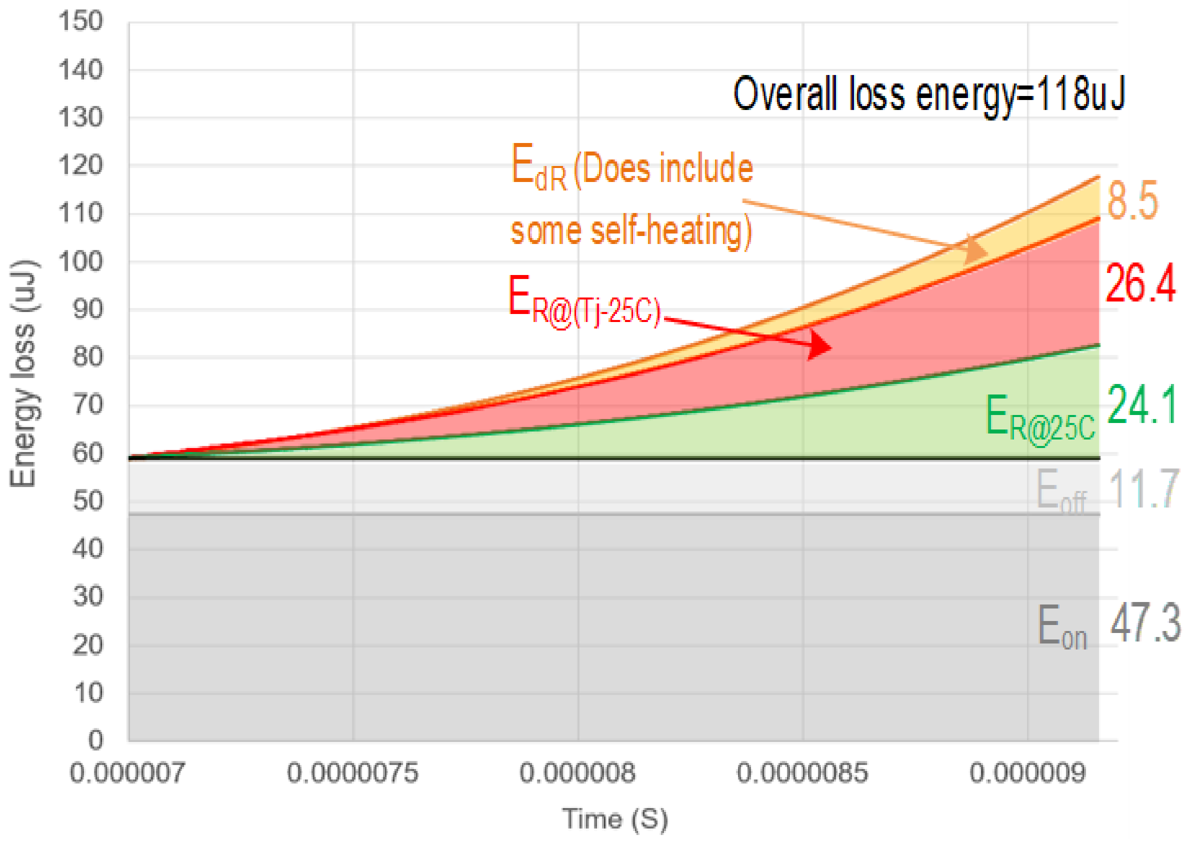
- **With increasing T_j, trapping effect loss becomes less significant compared to heating effect loss**

Examples – overall loss distribution based on pulse test

- In conduction loss, with T_j increasing, the $R_{DS(on)}$ loss from trapping effect becomes **less significant** than heating effect.
- By adding the switching loss E_{on}/E_{off}, the overall loss for one switching cycle can be obtained.



Overall loss breakdown @ 75 °C

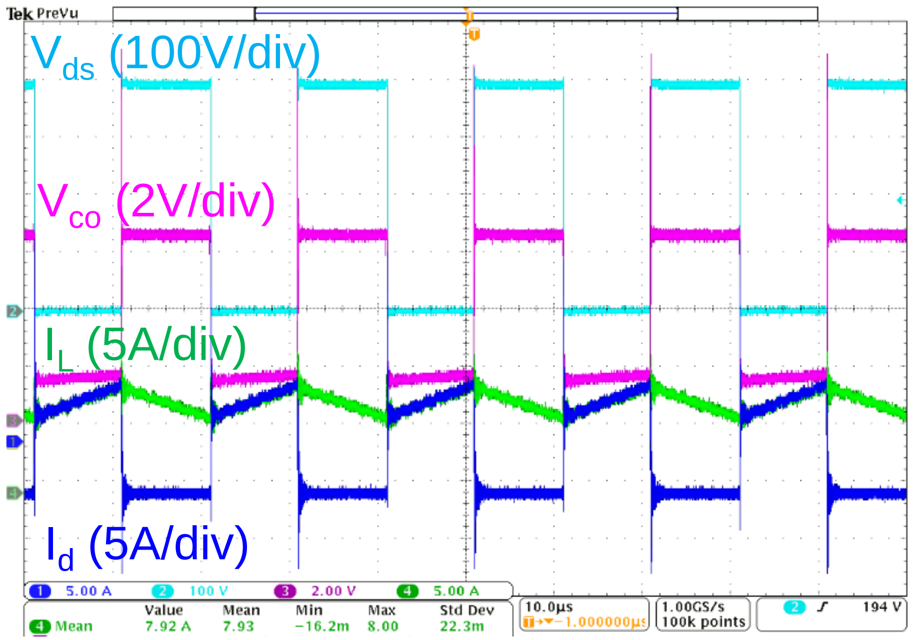


Overall loss breakdown @ 125 °C

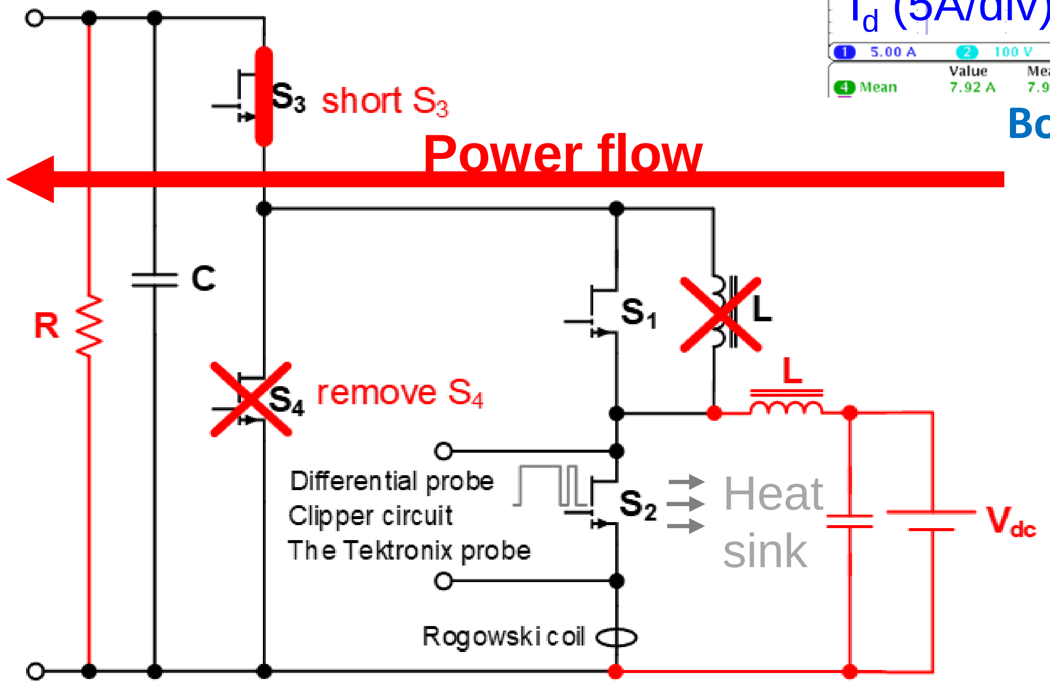
- **Compared to E_{on}, the dynamic $R_{DS(on)}$ loss has a very small effect on the system efficiency**

Loss distribution for GaN HEMT based on continuous Boost test

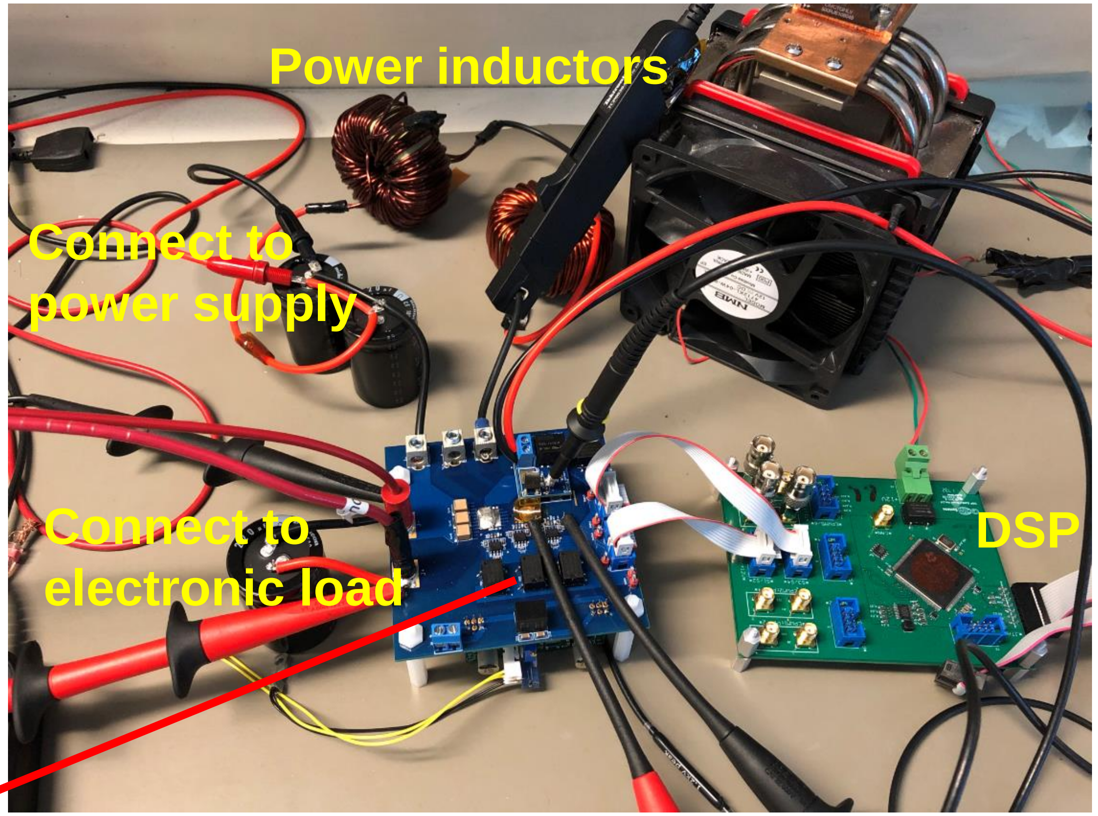
- **The test setup is reconfigured to a Boost converter for continuous running.**



Boost converter waveforms



Boost converter test setup diagram



Boost converter test setup

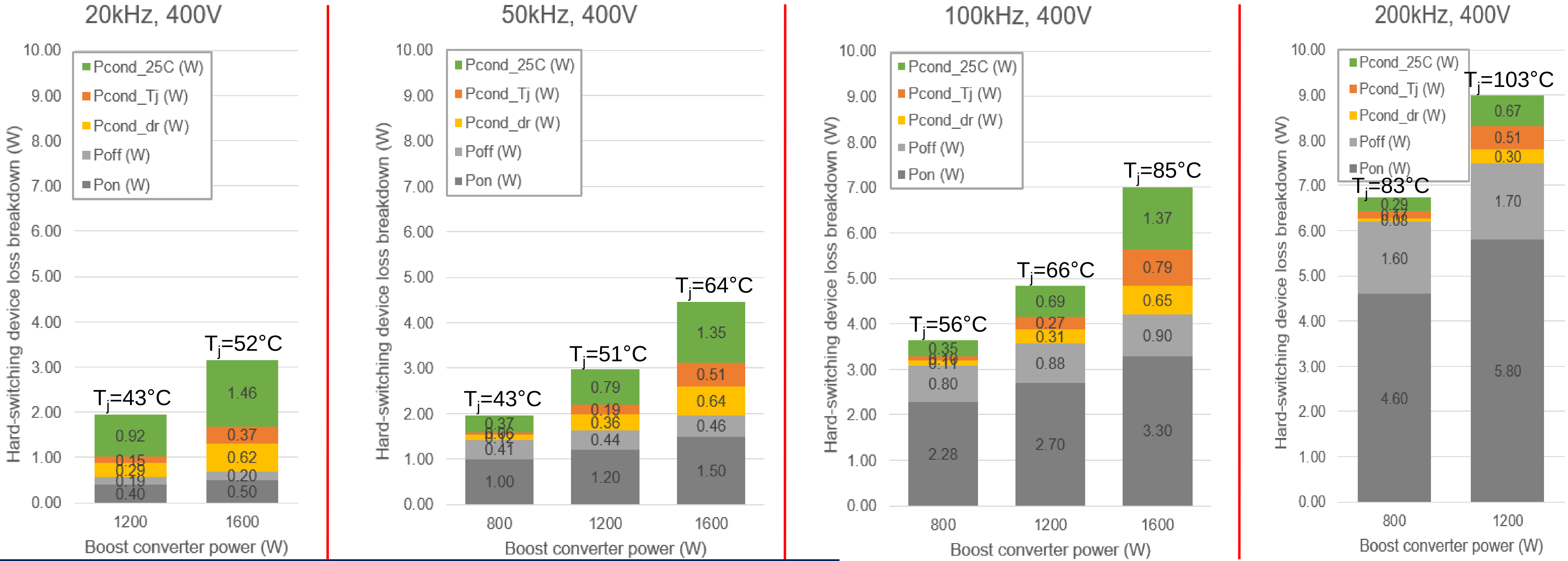

Heatsink installation

- **Temperature control board is removed and replaced by a heatsink attached on the GS66508T device on the PCB bottom side.**
- **T_j is still monitored through thermal hole.**

Loss distribution for GaN HEMT based on continuous Boost test

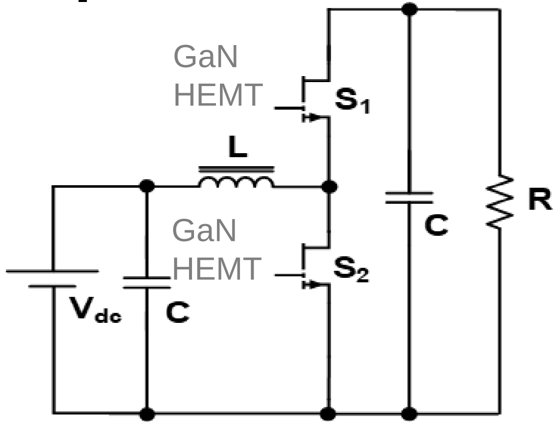
- **Converter continuous tests are performed with different load currents and switching frequencies**
- **V_{in}=200 V, V_{out}=400 V, R_{th_ja}=8.7 °C/W, T_{amb}=25 °C**

Hard-switching device loss breakdown in a GaN-based Boost converter under different loads and switching frequencies

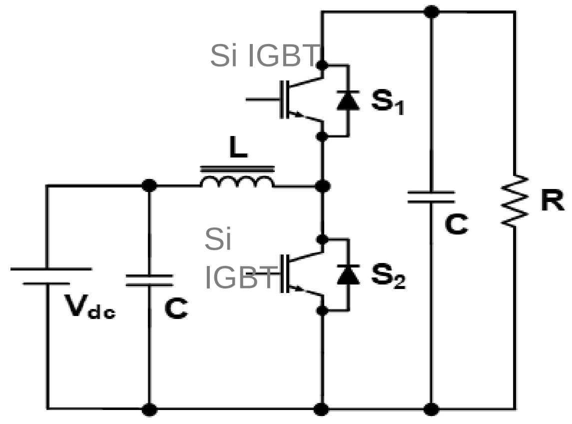


- **Power loss due to dynamic $R_{DS(on)}$ is a small portion of total system loss**

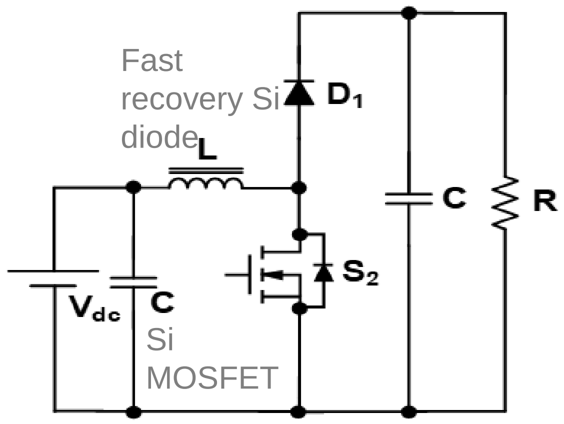
Comparison to Silicon and Silicon Carbide



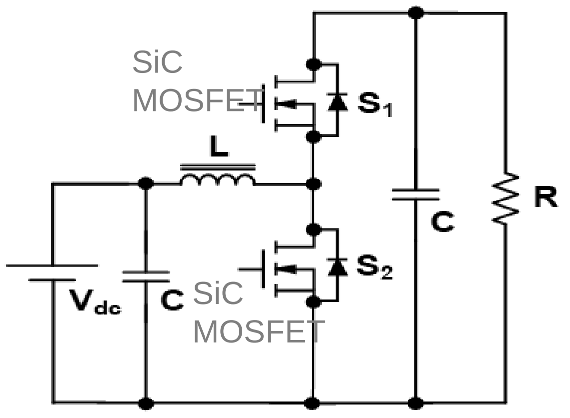
GaN HEMT-based Boost converter



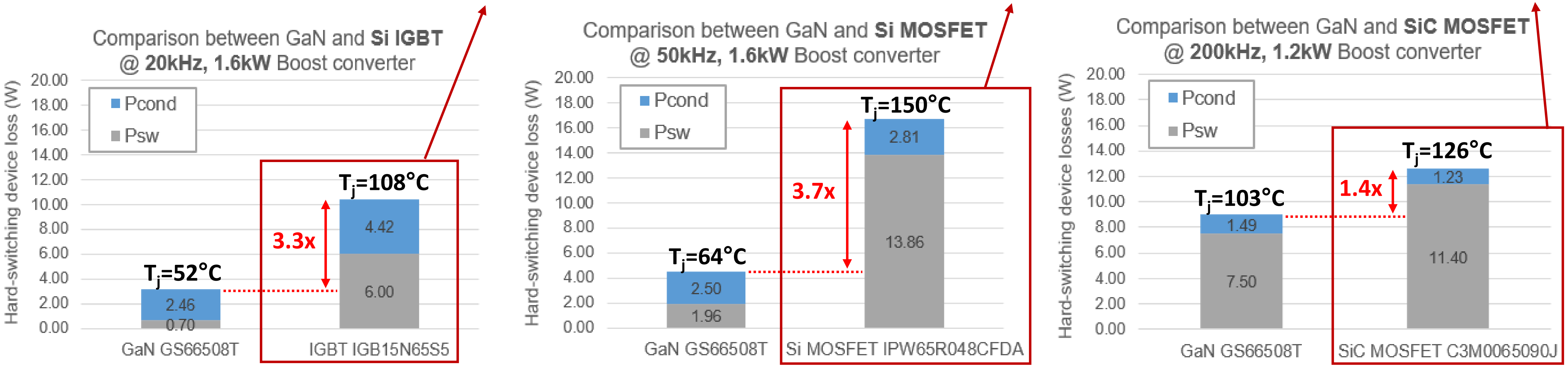
Si IGBT-based Boost converter



Si MOSFET-based Boost converter



SiC MOSFET-based Boost converter



- **Overall, GaN has much lower losses compared to Silicon and SiC, 1.4x to 3.7x lower**
- **GaN has significant advantages over other technologies on switching loss E_{on}/E_{off}**

Conclusions

- **Dynamic $R_{DS(on)}$**
  - **Measurement:**
    - Good T_j monitoring is important to separate heating and trapping effects;
    - Continuous mode test provides the most accurate results;
    - Soak time control (typically 1 to 100 µs) is needed.
  - **Loss calculation:** use $I^2R_{DS(on)(25C)}*(1+k_{Tj}+k_{dr})$ for simple and accurate results
  - The trapping effect (dynamic $R_{DS(on)}$) is **significantly less** than the heating (temperature) effect

- **System Power loss**
  - Power loss due to dynamic $R_{DS(on)}$ is **a small portion** of total system power loss
  - Total system power loss: GaN **outperforms** other technologies by **a wide margin**

Thank you for your attention !

Have a good day.

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