Parasitic Capacitance E_{qoss} Loss Mechanism, Calculation, and Measurement in Hard-Switching for GaN HEMTs

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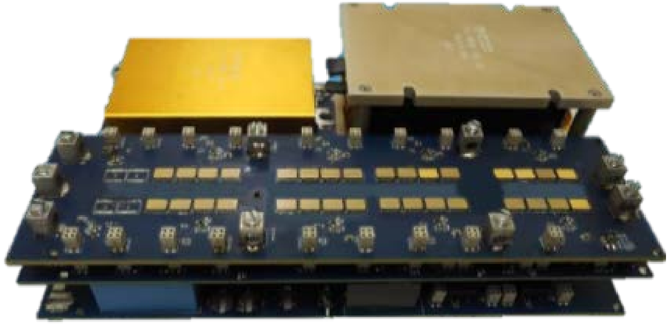
Agenda

1. Introduction
2. E_{qoss} loss mechanism
3. E_{qoss} loss calculation
4. E_{qoss} loss measurement method and experimental verification
5. Conclusions

1. Introduction

- GaN HEMTs can be applied to both soft-switching and hard-switching applications.
- For soft-switching ZVS technique, the turn-on switching loss is zero.
- This application note is about the parasitic capacitance loss during the turn-on of the hard-switching application.

10 kW Three-phase traction inverter from OSU (hard-switching)

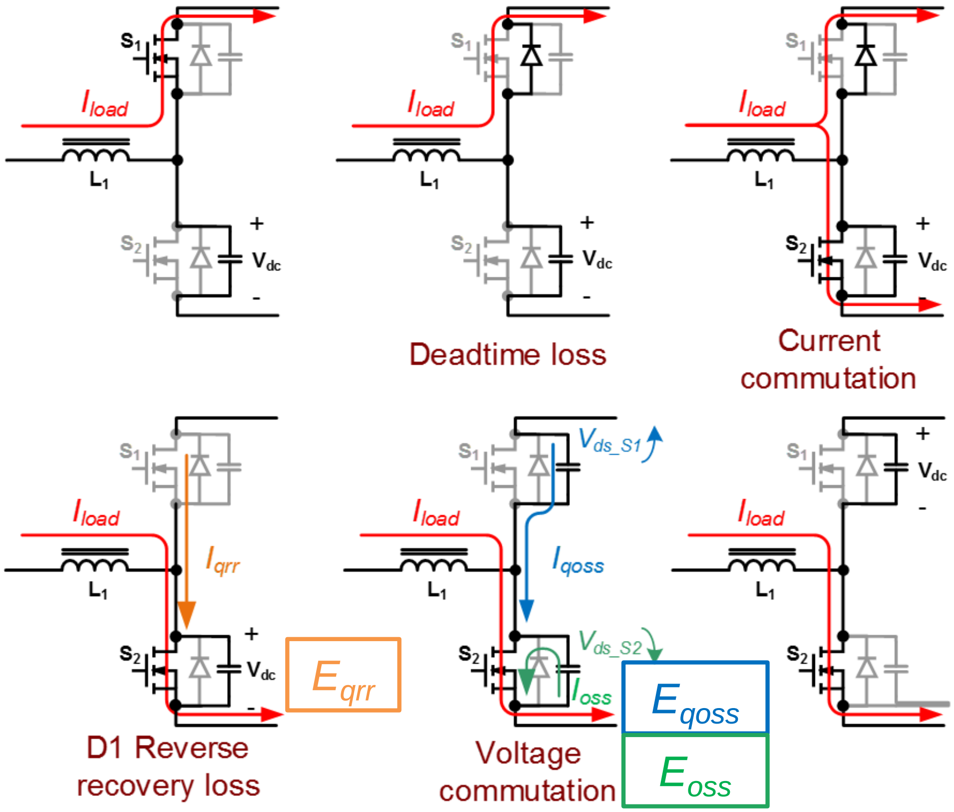


7 kW Level-2 EV onboard charger from Hella (soft-switching)

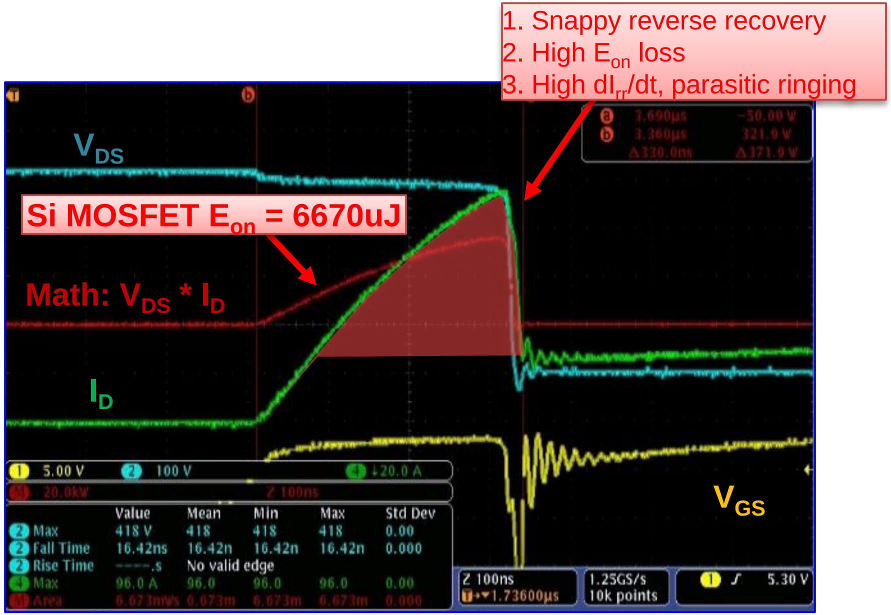
3 kW CCM Totem-pole PFC from GaN Systems (hard-switching)

2. E_{qoss} loss mechanism

Hard-switching transition of Si MOSFET



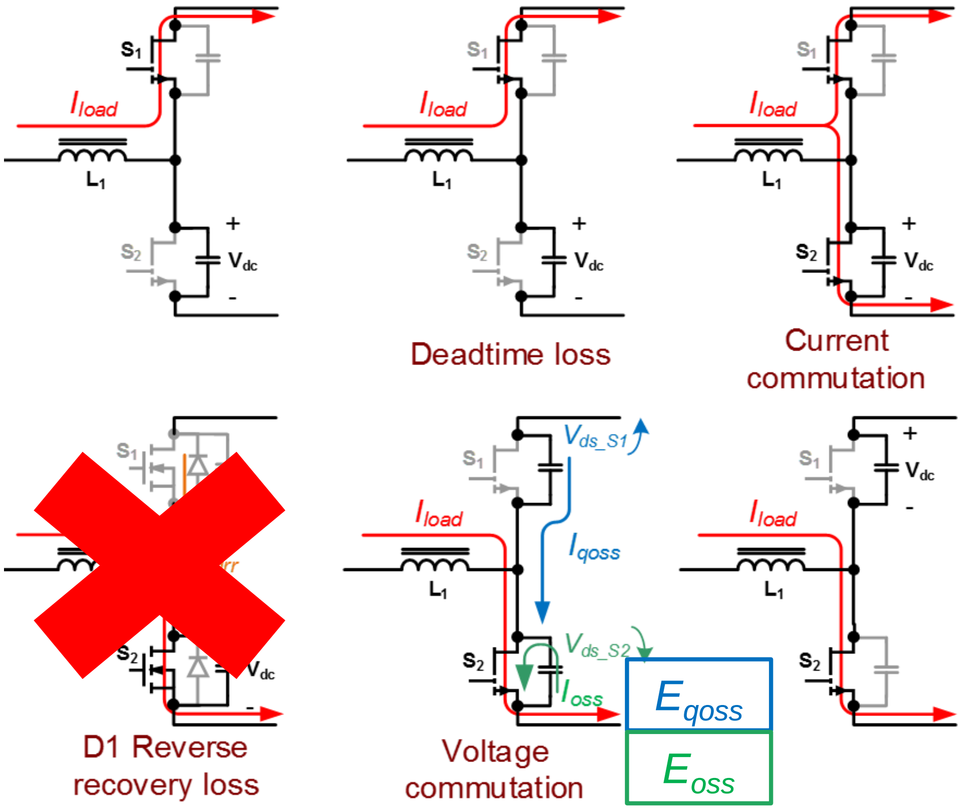
Switch commutation operating principle of Si MOSFET



Hard switching turn-on of a Si SJ MOSFET @ 400V/22A

2. E_{qoss} loss mechanism

Hard-switching transition of GaN E-HEMT



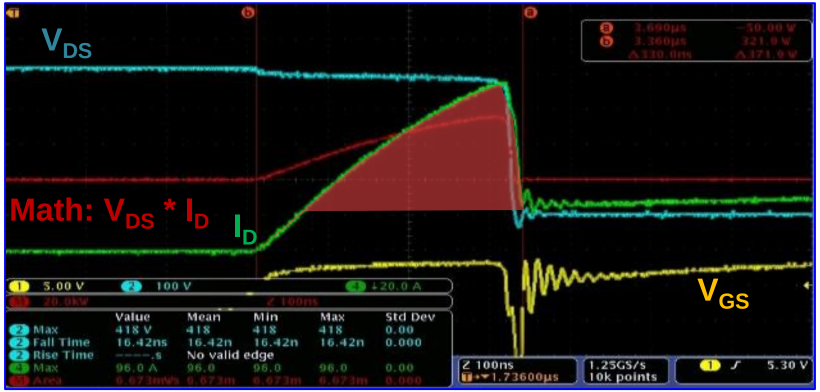
Switch commutation operating principle of GaN HEMT

1. Much lower turn-on loss
2. No snappy recovery and uncontrolled high dI_{rr}/dt
3. Clean waveforms

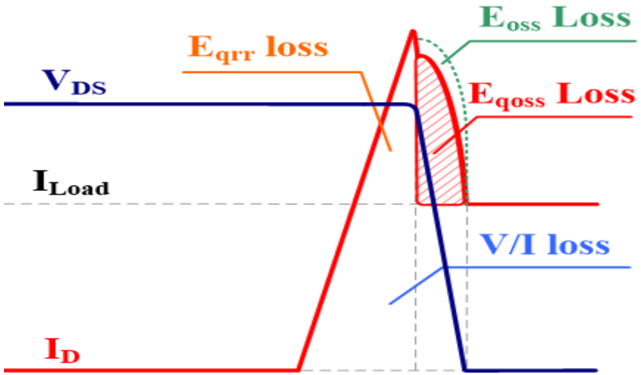
Hard switching turn-on of a GaN E-HEMT @ 400V/22A

- Zero Q_{rr} loss → **High efficiency**
- Zero Q_{rr} period → **High switching freq**

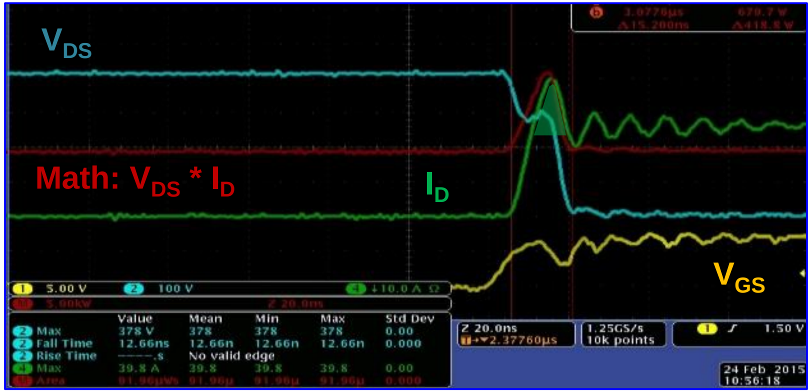
Hard-switching loss distribution



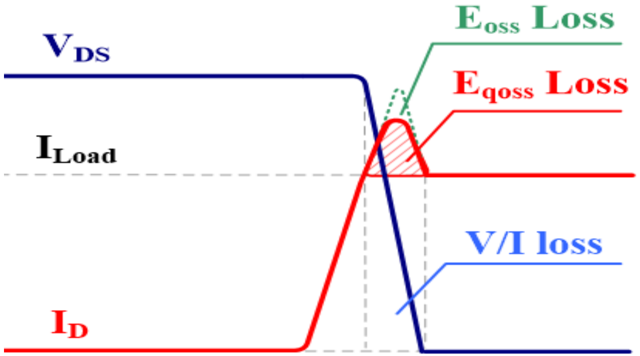
Hard switching turn-on of a Si SJ MOSFET @ 400V/22A



Hard-switching turn-on loss of Si MOSFET



Hard switching turn-on of a GaN E-HEMT @ 400V/22A



Hard-switching turn-on loss of GaN HEMT

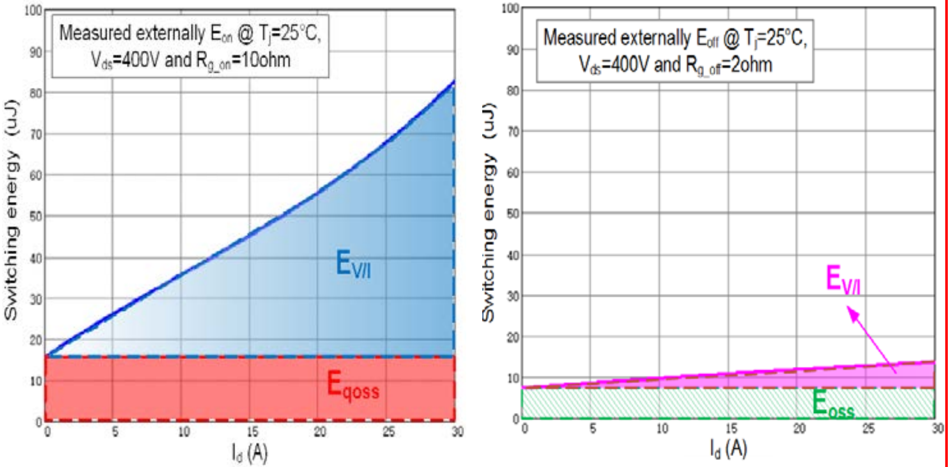
2. E_{qoss} loss mechanism

Switching loss distribution of GaN HEMT

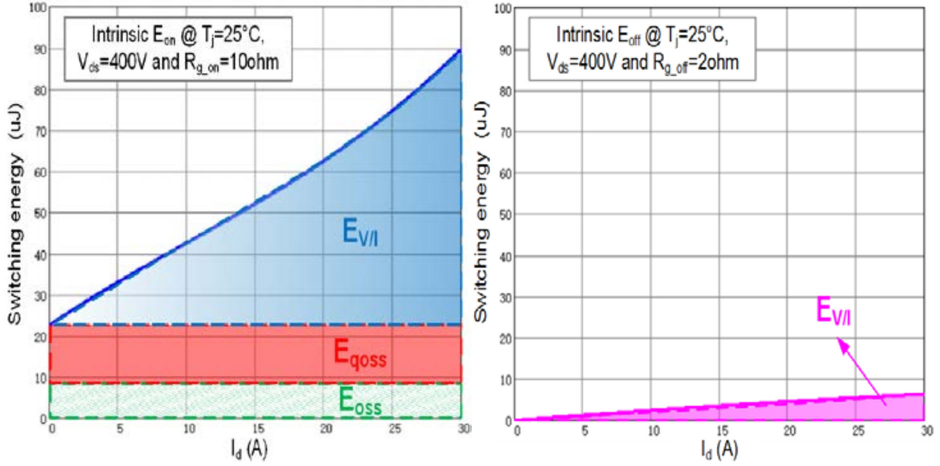
E_{on}/E_{off} loss distribution of GaN HEMT

Loss distribution	External measurement	Intrinsic
Turn-on loss E_{on}	$E_{VIon} + E_{qoss}$	$E_{VIon} + E_{qoss} + E_{oss}$
Turn-off loss E_{off}	$E_{VIoff} + E_{oss}$	E_{VIoff}

- 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.



External measured E_{on}/E_{off} switching loss distribution



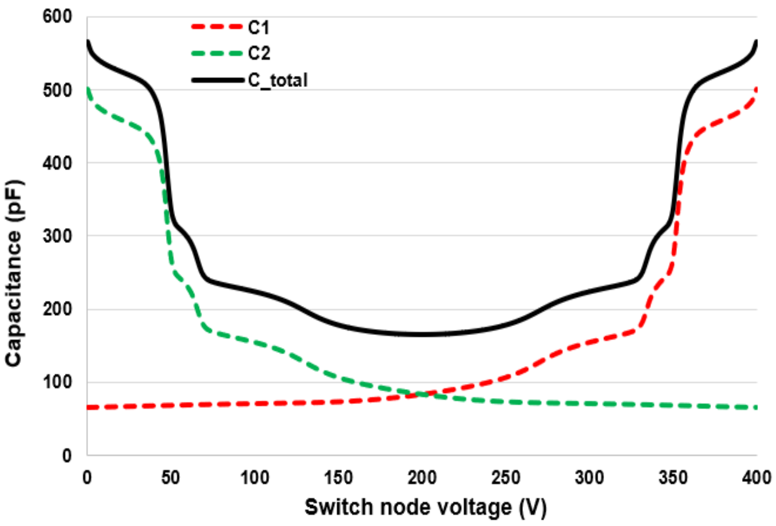
Intrinsic E_{on}/E_{off} switching loss distribution

E_{qoss} loss calculation

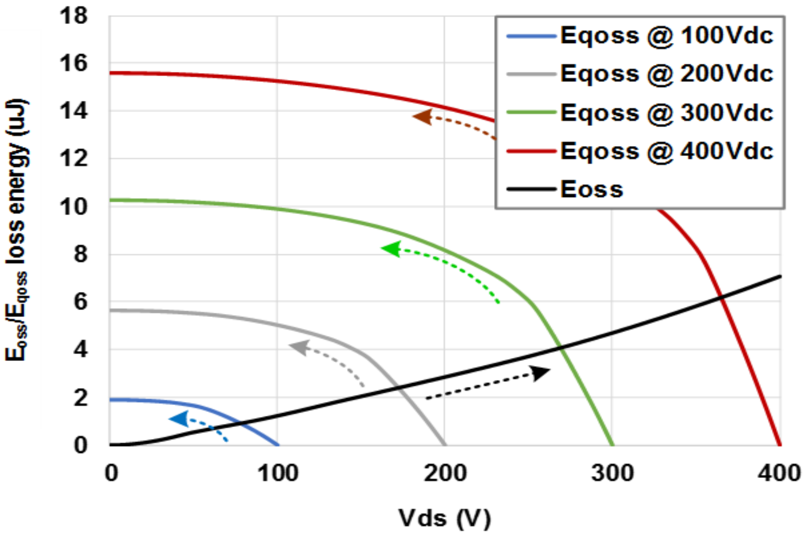
- E_{oss} loss calculation equation does not apply to E_{qoss}.

E_{oss} loss: $$E_{oss} = \int_0^{V_{dc}} V_{ds} \cdot C_{oss(V_{ds})} dV_{ds}$$

E_{qoss} loss: $$E_{qoss} = \int_0^{V_{dc}} (V_{dc} - V_{ds}) \cdot C_{oss(V_{ds})} dV_{ds}$$



Parasitic capacitance C_{oss}

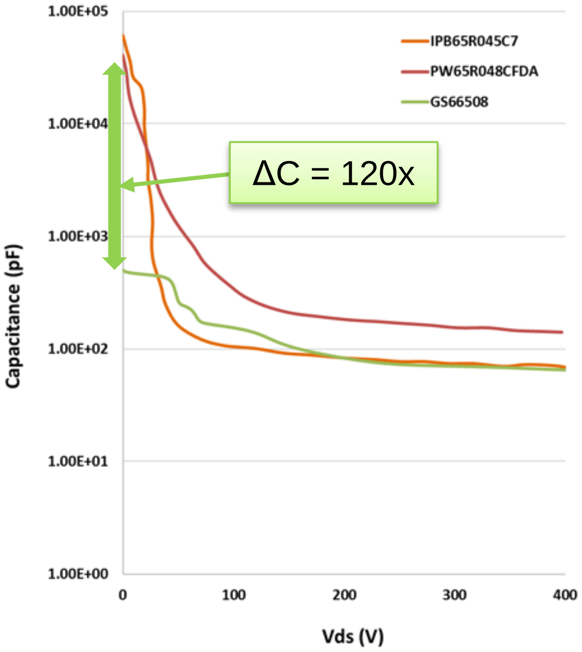


E_{oss}/E_{qoss} loss of GS66508T at different operating voltage

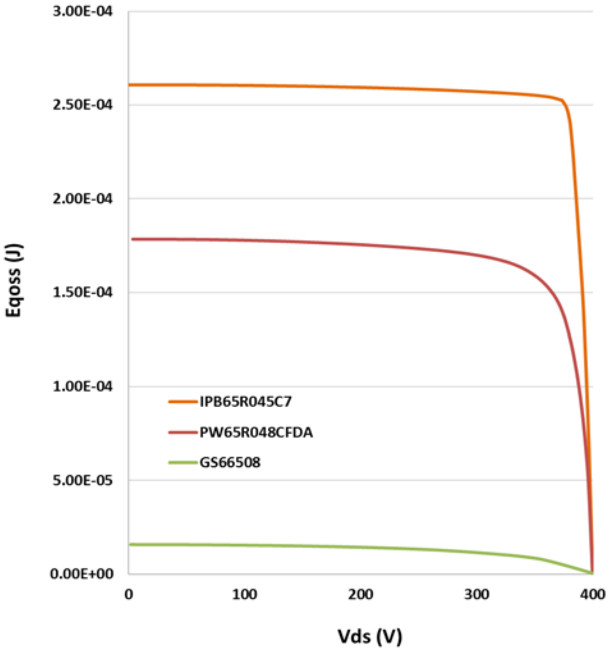
- E_{qoss} loss is higher than E_{oss} loss, as usually the C_{oss} of the device is higher at lower voltage V_{ds} region.

E_{qoss} loss comparison with Si MOSFET

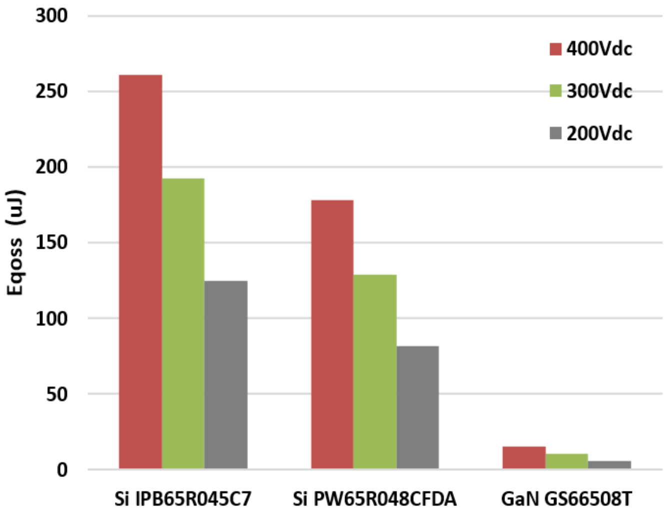
- The capacitance C_{oss} of Si MOSFET is more nonlinear than GaN's.
- Much higher C_{oss} value under low voltage region.
- E_{qoss} loss of Si MOSFET is significantly larger.



Comparison of parasitic capacitance C_{oss}



Comparison of E_{qoss} loss under 400V



Comparison of E_{qoss} loss under different V_{ds}

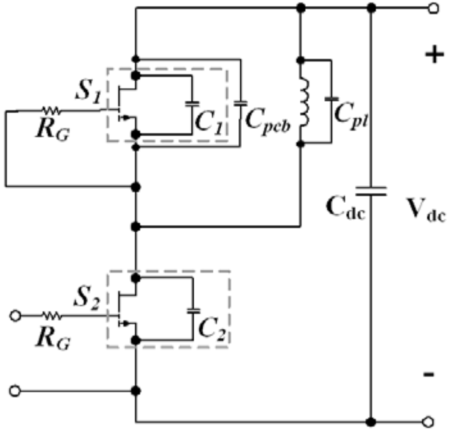
3. E_{qoss} loss calculation

Other parasitic capacitances contribute to E_{qoss} loss

- On double pulse test (DPT) circuit, the measured E_{oss}/E_{qoss} also includes the parasitic capacitances from PCB and inductor. Taking C_{pcb} and C_{pl} into account:

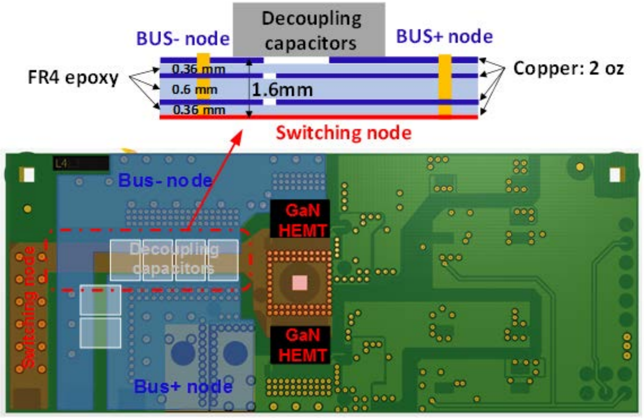
$$E_{oss} = \int_0^{V_{dc}} V_{ds} \cdot C_{oss(V_{ds})} dV_{ds} + \frac{1}{2}\left(C_{pl} + C_{pcb}\right)V_{dc}^2 \qquad E_{qoss} = \int_0^{V_{dc}} (V_{dc} - V_{ds}) \cdot C_{oss(V_{ds})} dV_{ds} + \frac{1}{2}\left(C_{pl} + C_{pcb}\right)V_{dc}^2$$

- A Q3D simulation has been performed on the GS66508T evaluation board.
- The total voltage-independent capacitance is about 20 pF.



Parasitic capacitances that contribute to E_{qoss} loss in DPT circuit

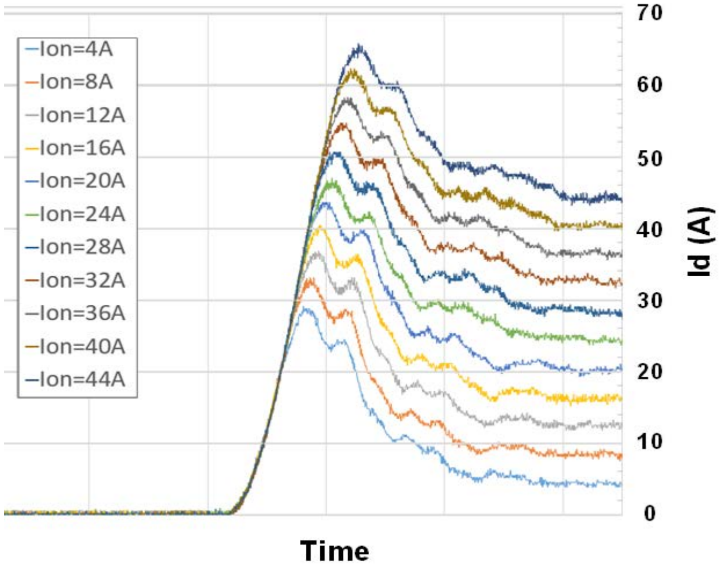
GS66508T evaluation daughter board



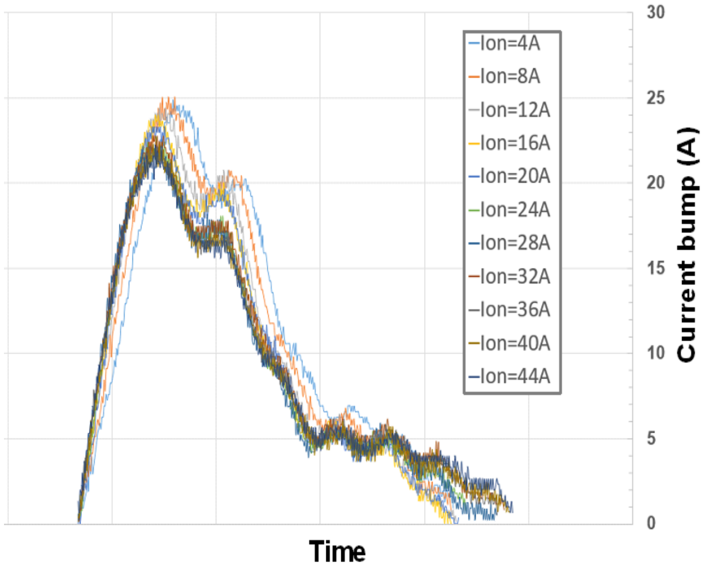
PCB parasitic capacitance from switching node to bus+/- node

A. Load current independence

- Several double pulse tests based on GS66516T under different load currents were performed.
- The load current independence of the current bump also indicates the absence of body diode.



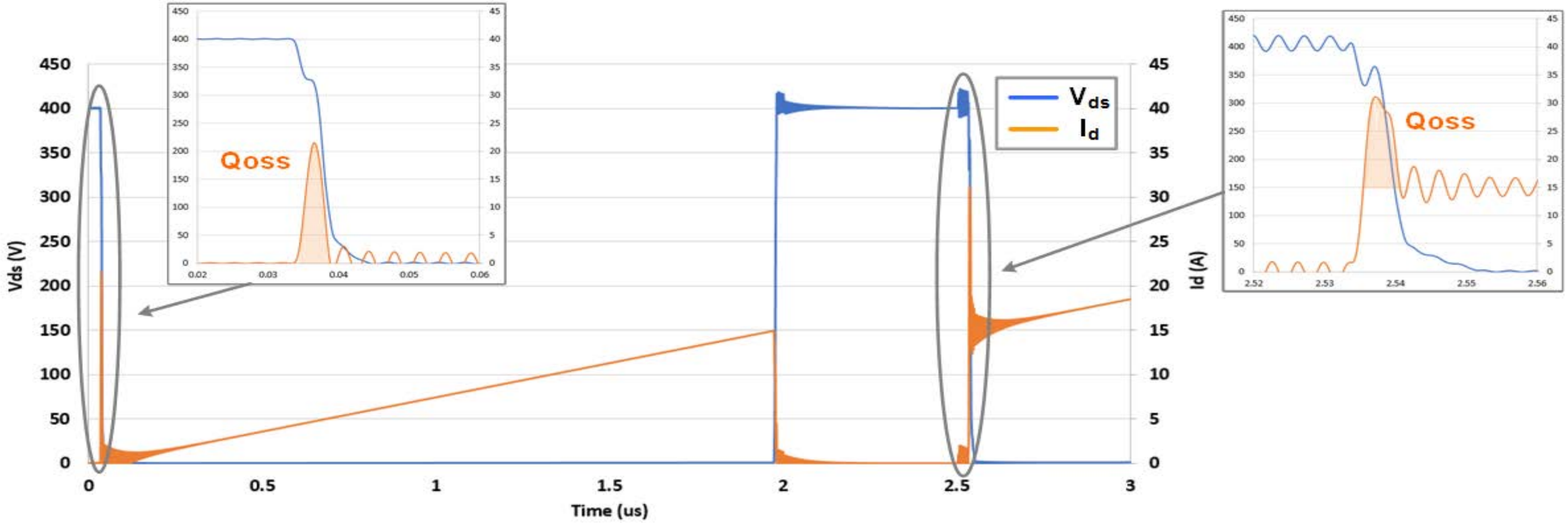
Measured drain current waveforms of GS66516T under different load currents



Zoomed current bump comparison of GS66516T under different load currents

B. E_{qoss} loss measurement method

- During the DPT, the E_{qoss} can be measured either upon turn-on of the first pulse or on the turn-on of the second pulse.
- In order to simplify the E_{qoss} loss measurement, the loss is measured at the turn-on of the first pulse which the V/I loss is zero.

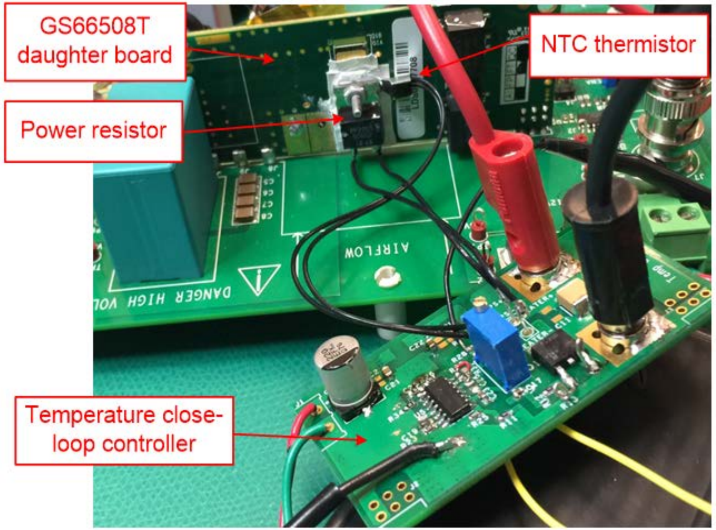


Simulated double pulse testing waveform

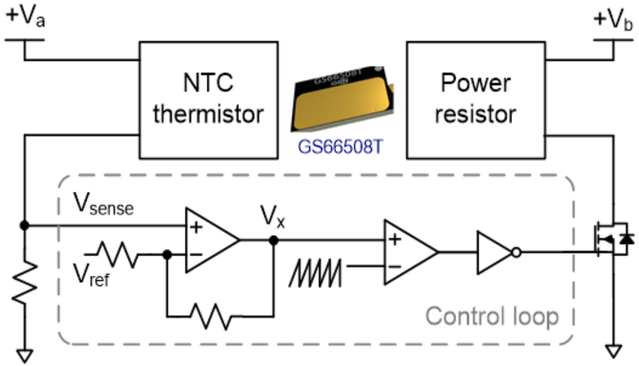
4. E_{qoss} loss measurement method

C. E_{qoss} loss measurement setup

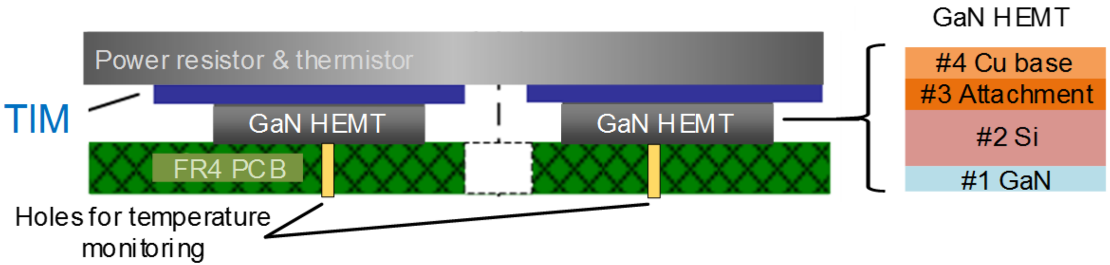
- To verify the impact factor and also the value of the loss, the DPT platform with closed-loop temperature control is applied.



DPT setup with junction temperature control



Close-loop temperature control block diagram.

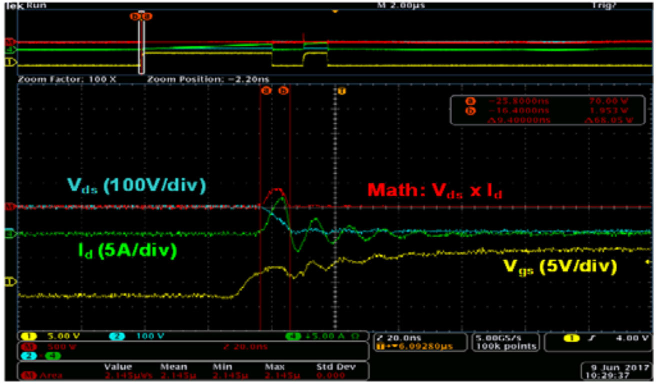


Monitored temperature thru thermal holes

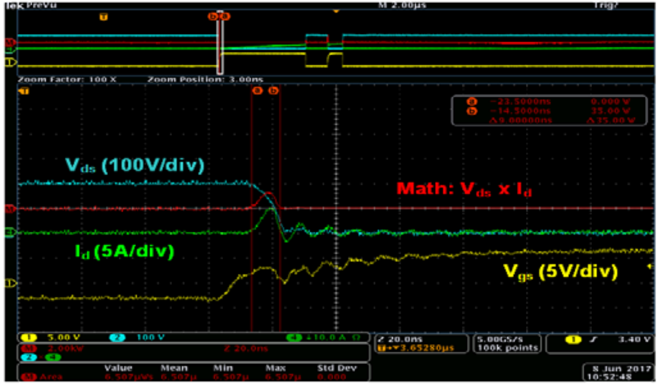
4. E_{qoss} loss measurement method

D. Junction temperature and switching speed independence

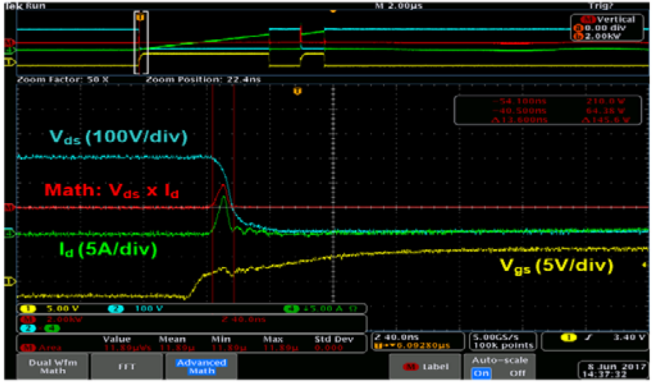
- R_{g_on} is chosen as 30 ohm and 50 ohm, as the purpose of the test is to prove the switching speed independence and also measure the E_{qoss} energy loss as accurate as possible.



100 V_{dc} with T_j=75°C and R_{g_on}=30 ohm



200 V_{dc} with T_j=25°C and R_{g_on}=30 ohm



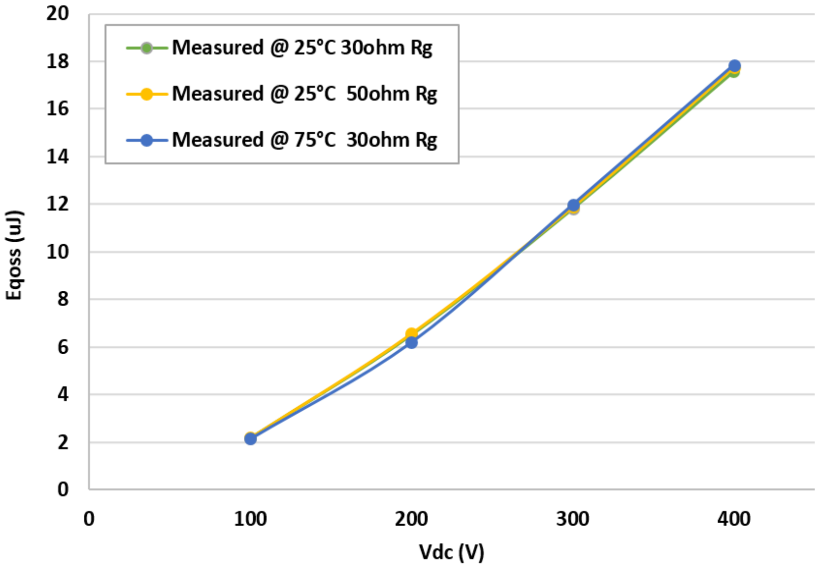
300 V_{dc} with T_j=25°C and R_{g_on}=50 ohm

400 V_{dc} with T_j=75°C and R_{g_on}=30 ohm

4. E_{qoss} loss measurement method

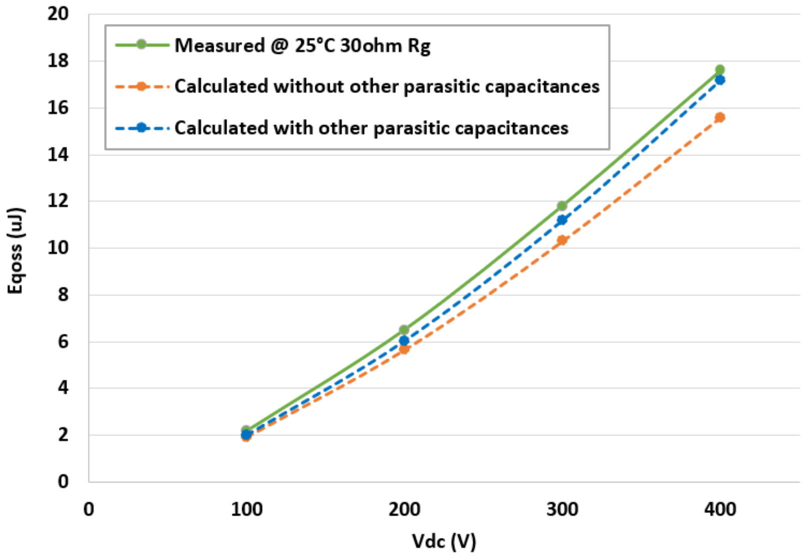
Summary on E_{qoss} loss measurement

- Test results are consistent which indicates E_{qoss} is also independent on the junction temperature and switching speed.



Measured results with different T_j and R_g

- By considering the other parasitic capacitances, the discrepancy between the theoretical values and measured values is relatively small, verifying the calculation method.



Comparison between measurement and calculation results

5. Conclusions

- Detailed E_{qoss} loss mechanism, calculation and measurement method for GaN HEMTs are presented.
- The E_{qoss} loss of GaN HEMT is significantly lower compared with Si MOSFET.
- Experimental results verify the E_{qoss} loss calculation method and also prove that the loss is only a function of voltage and the corresponding capacitances.
- The accurate E_{qoss} loss calculation yields a more accurate E_{on} loss estimation, especially under light load condition.