The University of Edinburgh

Exploiting SiC-MOSFET Modules in High Current Applications

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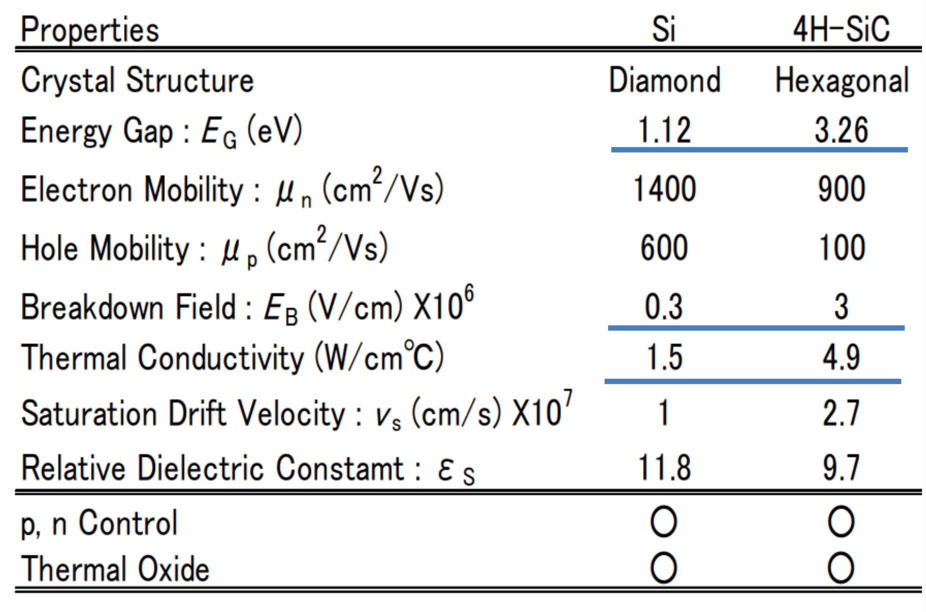
Silicon Carbide (4H-SiC) vs Silicon for Power Semiconductor



Properties	Si	4H-SiC	
Crystal Structure	Diamond	Hexagonal	
Energy Gap : E_G (eV)	1.12	3.26	A
Electron Mobility : μ_n (cm^2/Vs)	1400	900	
Hole Mobility : μ_p (cm^2/Vs)	600	100	
Breakdown Field : E_B (V/cm) X10^6	0.3	3	B
Thermal Conductivity (W/cm°C)	1.5	4.9	C
Saturation Drift Velocity : v_s (cm/s) X10^7	1	2.7	
Relative Dielectric Constamt : ε_S	11.8	9.7	
p, n Control	○	○	
Thermal Oxide	○	○	

A	Can operate at higher temperatures
B	Thinner drift layer and/or doping concentration required for a given voltage blocking capability - Results in lower resistance relative to Si - Higher blocking voltages achievable
C	Easier to cool

Latest Commercial 1.2 kV High Power SiC MOSFETs

Wolfspeed/Cree
CAB400M12XM3

1200 V
450 A
XM3 Package

Wolfspeed/Cree
CAB760M12HM3

1200 V
765 A
HM High Performance 62 mm

ROHM Semiconductor
BSM600D12P3G001

1200 V
586 A
EconoDUAL 3 Package

Latest Experimental/Commercial 3.3 kV SiC MOSFETS

Experimental

Wolfspeed/Cree
XHV-7

3300 V
541 A
XHP3 Package

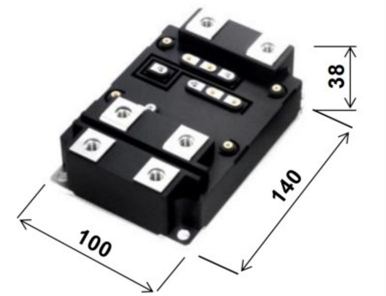
Mitsubishi
Name not given [1]

3300 V
1500 A
HiPak Package

Commercial

Mitsubishi
FMF750DC-66A

3300 V
750 A
XHV7 Package



Hitachi
MSM800FS33ALT

3300 V
800 A
nHPD^2 Package

[1] Hamada, Kenji, et al. "3.3 kV/1500 A power modules for the world's first all-SiC traction inverter." *Japanese Journal of Applied Physics* 54.4S (2015): 04DP07.

1.2 kV 400 A IGBT vs 1.2 kV 400 A SiC MOSFET

	Full SiC Module	Si IGBT	Performance Gain
Module Code	CAB400M12XM3	FF400R12KE3	
On-state Voltage (25 C)	2.3	1.7	
On-state Voltage (150 C)	3.6	2	
Turn On Energy	5 mJ	25 mJ	**80% Reduction**
Turn Off Energy	4.2 mJ	62 mJ	**93% Reduction**
Reverse Recovery	1 mJ	35 mJ	**97% Reduction**
Stray Inductance Module	6.7 nH	20 nH	
Stray Test Inductance	Not Given	30 nH	
Overall Switching Energy	10.2 mJ	122 mJ	**~91.6% Reduction**

1.2 kV 400 A IGBT vs 1.2 kV 400 A SiC MOSFET

	Full SiC Module	Si IGBT	Performance Gain
Module Code	WAB400M12BM3	FF400R12KE3	
On-state Voltage (25 C)	1.3	1.7	
On-state Voltage (150 C)	2.1	2	
Turn On Energy	12.9 mJ	25 mJ	**48% Reduction**
Turn Off Energy	12.0 mJ	62 mJ	**80% Reduction**
Reverse Recovery	1.33 mJ	35 mJ	**96% Reduction**
Stray Inductance Module	10.2 nH	20 nH	
Stray Test Inductance	Not Given	30 nH	
Overall Switching Energy	26.23 mJ	122 mJ	**79% Reduction**

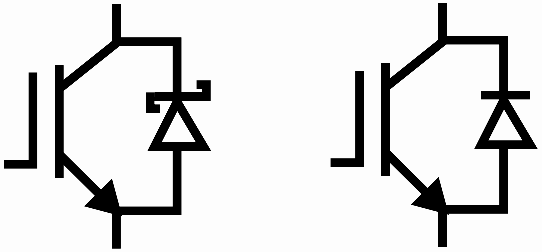
1.7 kV 300 A IGBT vs 1.7 kV 300 A SiC MOSFET

	Full SiC Module	Si IGBT	Performance Gain
Module Code	CAS300M17BM2	SEMiX303GB17E4p	
Drain Source on-state Voltage (25 C)	2.4	1.9	**26% Increase**
Drain Source on-state Voltage (150 C)	4.8	2.29	**110% Increase**
Turn On Energy	13 mJ	76 mJ	**82% Reduction**
Turn Off Energy	10.0 mJ	99 mJ	**90% Reduction**
Reverse Recovery	Not Given	56 mJ	
Stray Inductance Module	15 nH	20 nH	
Stray Test Inductance	Not Given	30 nH	
Overall Switching Energy (Excluding E_{rr})	23 mJ	175 mJ	**86% Reduction (Excluding E_{rr})**

3.3 kV 800 A IGBT vs 3.3 kV 800 A SiC MOSFET

	Full SiC Module	Si IGBT	Performance Gain
Module Code	MSM800FS33ALT	MBN800E33E	
Drain Source/Collector Emitter on-state Voltage (25 C)	2.3	3.5 (125 C)	
Drain Source on-state Voltage (150 C)	3.6		
Turn On Energy	0.96 J	1.2 J	**25% Reduction**
Turn Off Energy	0.37 J	1.3 J	**71.5% Reduction**
Reverse Recovery	0.06 J	1 J	**94% Reduction**
Stray Inductance Module	10 nH	18 nH	
Stray Test Inductance	30 nH	30 nH	
Overall Switching Energy	1.39 J	3.5 J	**~60% Reduction**

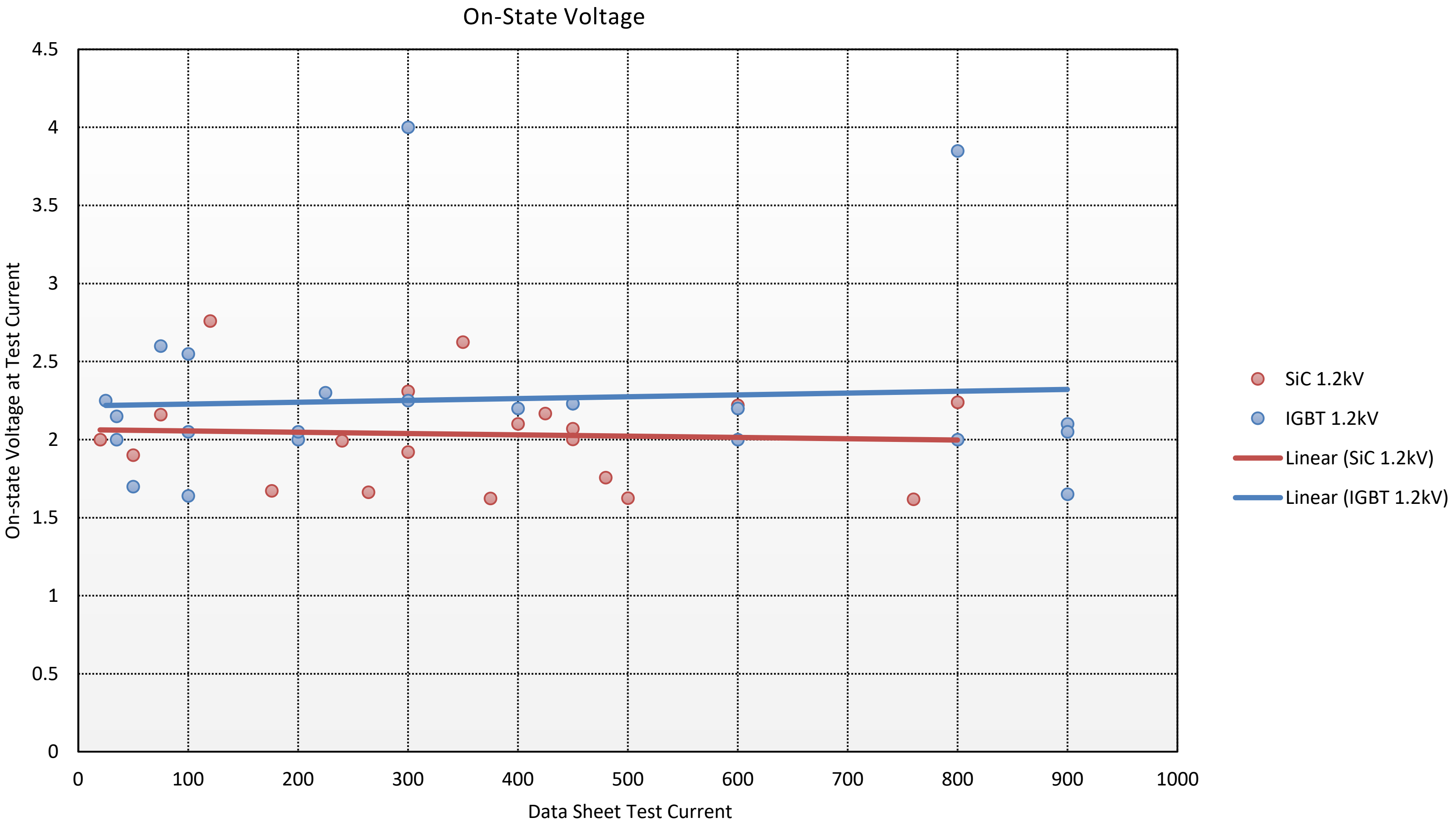
3.3 kV 1200 A IGBT vs 3.3 kV 1200 A IGBT w. SiC Schottky Diode



	Si IGBT w. SiC Schottky Diode	Si IGBT	Performance Gain
	MBN1200F33F -C3	MBN1200F33F	
Turn On Energy	1.4 J	2.6 J	**46.1% Reduction**
Turn Off Energy	2.2 J	2.2 J	**0% Reduction**
Reverse Recovery	0.1 J	1.7 J	**94% Reduction**
Stray Inductance Module	10 nH	10 nH	
Overall Switching Energy	3.7 J	6.5 J	**43% Energy Reduction**

Si IGBT vs. SiC MOSFET

Date Sheet Comparison of On-State Voltage Drop for 1.2kV Power Devices/Modules

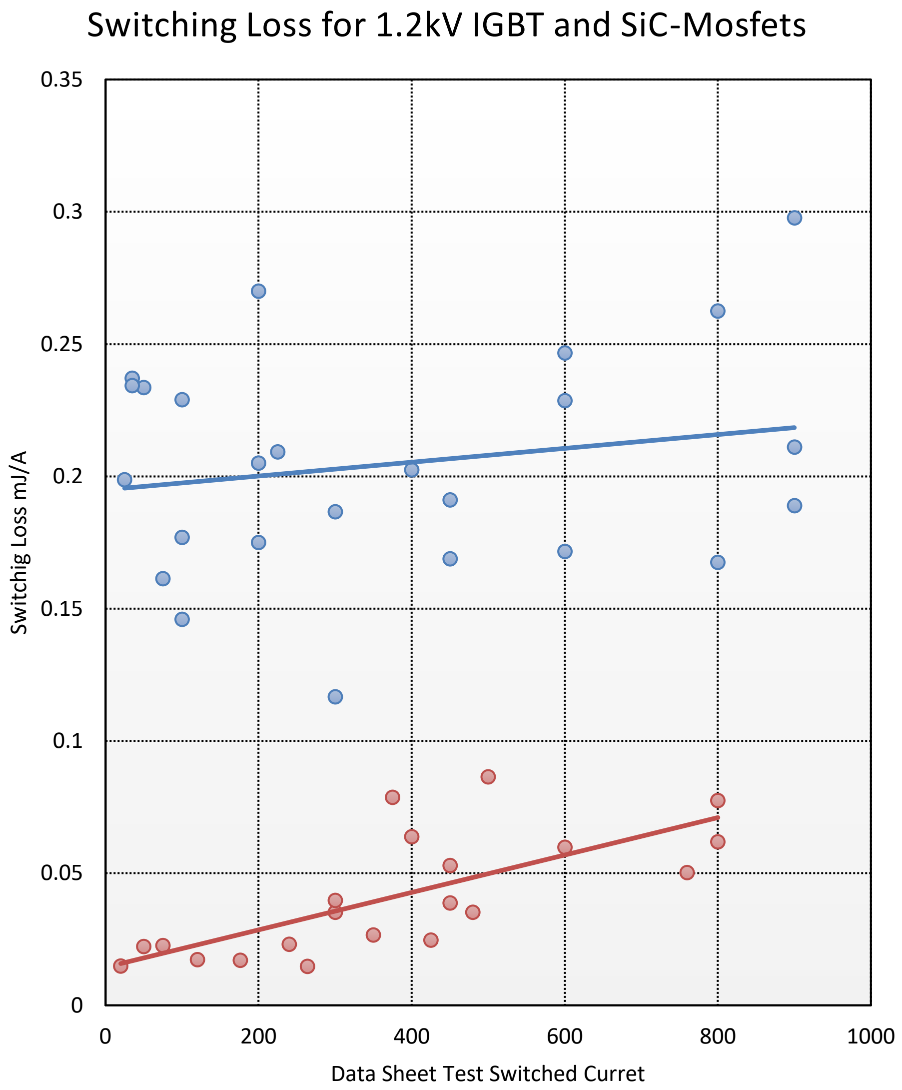


Manufacturers data indicates that:

- SiC devices/Modules can match on-state voltage of equivalently rated IGBTs
- SiC implementations should deliver similar (or slightly improved) conduction losses than IGBTs

Si IGBT vs. SiC MOSFET

Date Sheet Comparison of Switching Energies for 1.2kV Power Devices/Modules

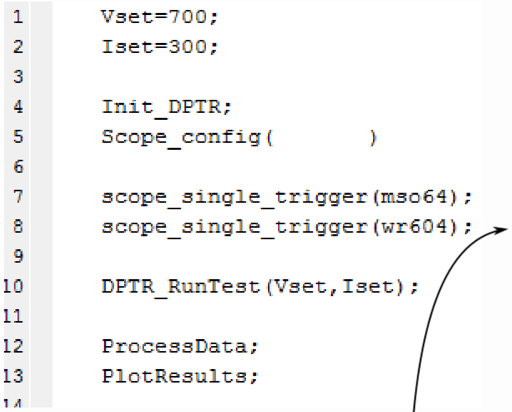


Comparison of manufacturers data for E_{on}+E_{off}) indicates that:

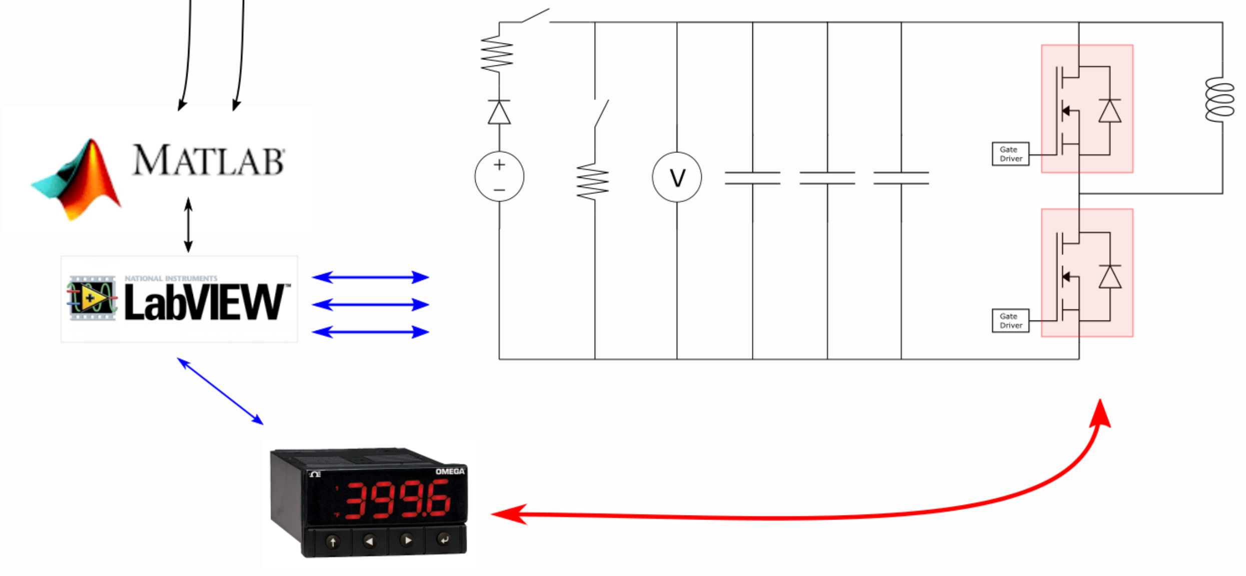
- SiC devices can achieve lower relative switching energies (mJ/A) than IGBTs with equivalent current rating.
- Relative switching energies increase with device/module current rating.
- This effect is more significant for SiC-Mosfets. Decreasing the benefits of SiC in high current applications.

Experimental Testing of High-Power Semiconductors

Double Pulse Test Rig

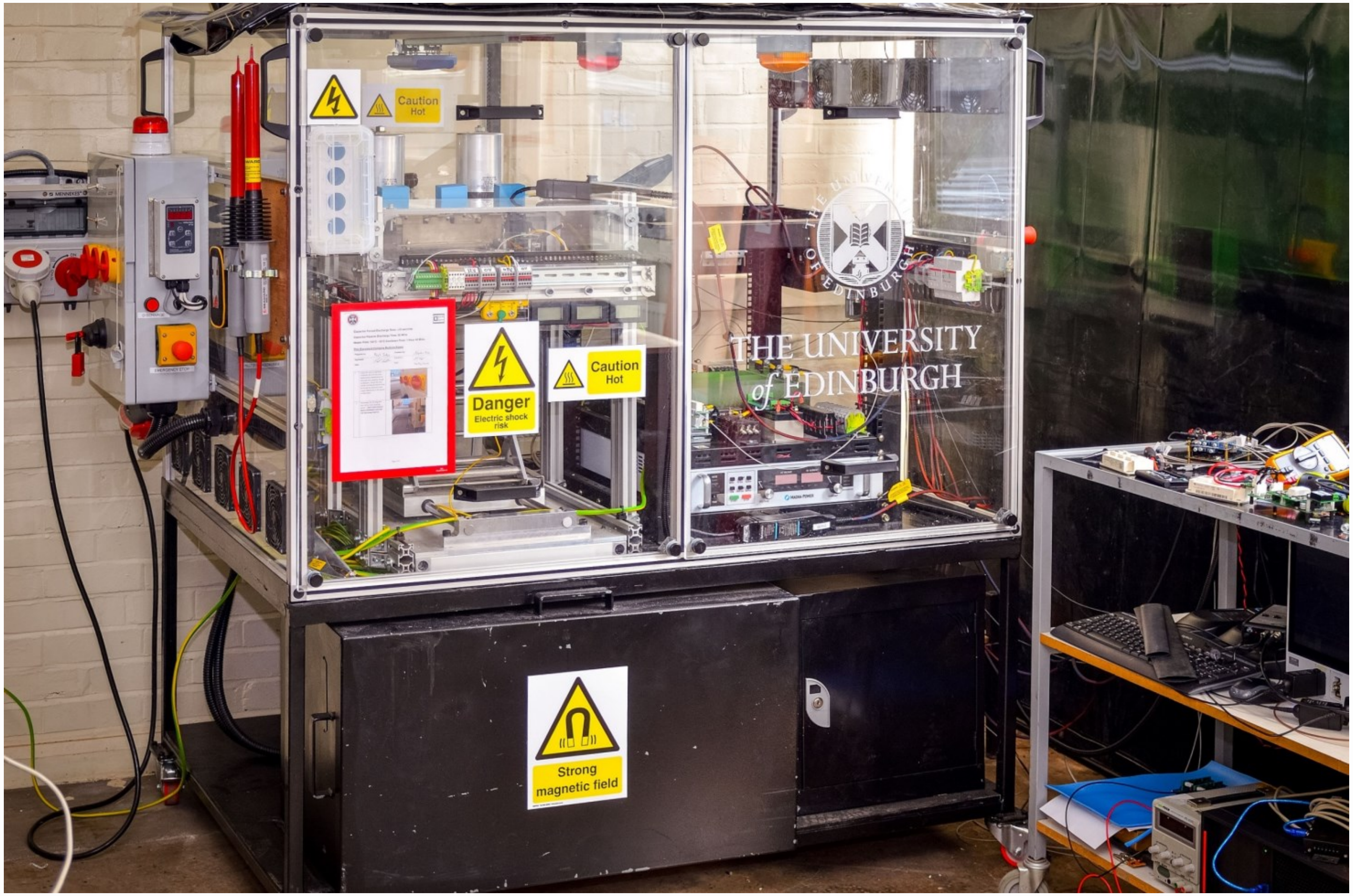


```
Vset=700;
Iset=300;

Init_DPTR;
Scope_config(        )

scope_single_trigger(mso64);
scope_single_trigger(wr604);

DPTR_RunTest(Vset,Iset);

ProcessData;
PlotResults;
```

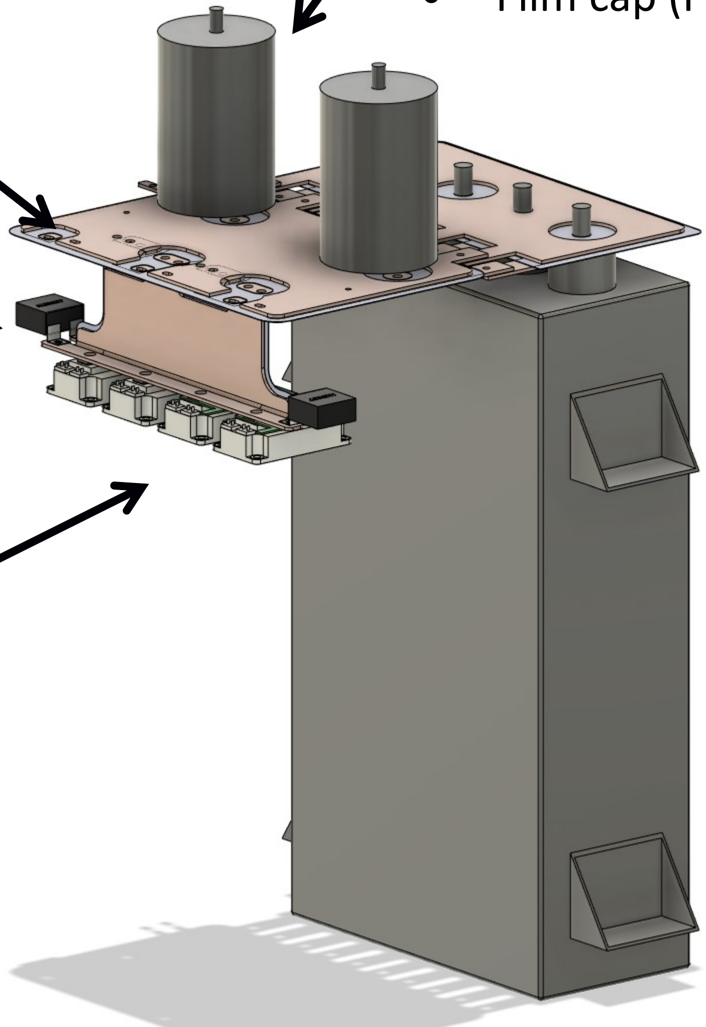


Double Pulse Test Rig

The DPTR lets us subject Power Electronic Semiconductor Devices to voltages/currents that they would see in full scale power converters. We can test up to 2000 V and 1500 A at 150^{o}C.



Power Circuit – Busbar & Capacitors



Low Inductance BUSBAR

- 3mm Copper
- Tinned to stop oxidisation
- 16.1nH

Decoupling Capacitor

- 430µF, 1.8kV
- Film cap (PP)

Decoupling Capacitor

- 470nF, 2.5kV
- Film Cap (PP)

Bulk Capacitor

- 5.4mF, 2.5kV
- Power film cap
- Oil-impregnated
- Rapeseed oil
- 50 kg weight
- 640 x 340 x 165mm

Semiconductor DUT

- MOSFET
- IGBT
  - Parallel
  - Single
  - Hybrid

C_{Total} = 6.26mF

Energy:

- 300V = 280J
- 1200V = 4.5kJ
- 2000V = 12.5kJ

- Shotgun = 4.4kJ

Power Circuit - Measurements

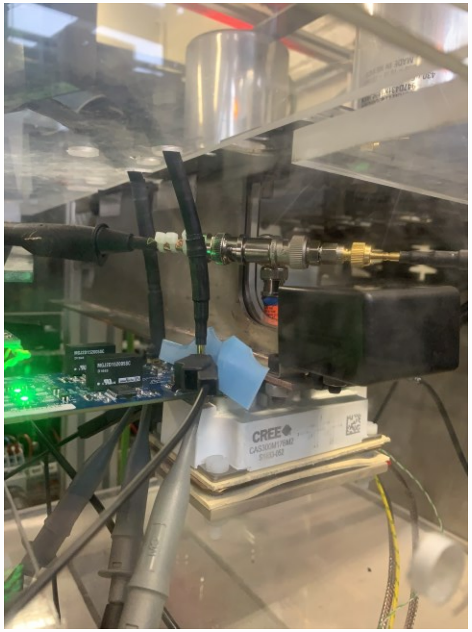
Differential Voltage Probes (HV & LV)

- Three Tektronix IsoVu Probes
    - 1 GHz bandwidth,160dB CMR, 60kV common mode, ±5V to ±2.5kV differential range
    - Capable of measuring low & high voltages (e.g gate-source and drain-source measurements)

Rogowski Coils (30 MHz & 50 MHz bandwidth)

Coaxial Current Viewing Resistors (1.2 GHz bandwidth, Emax)

Near field & far field EM probes



Experimental Measurements

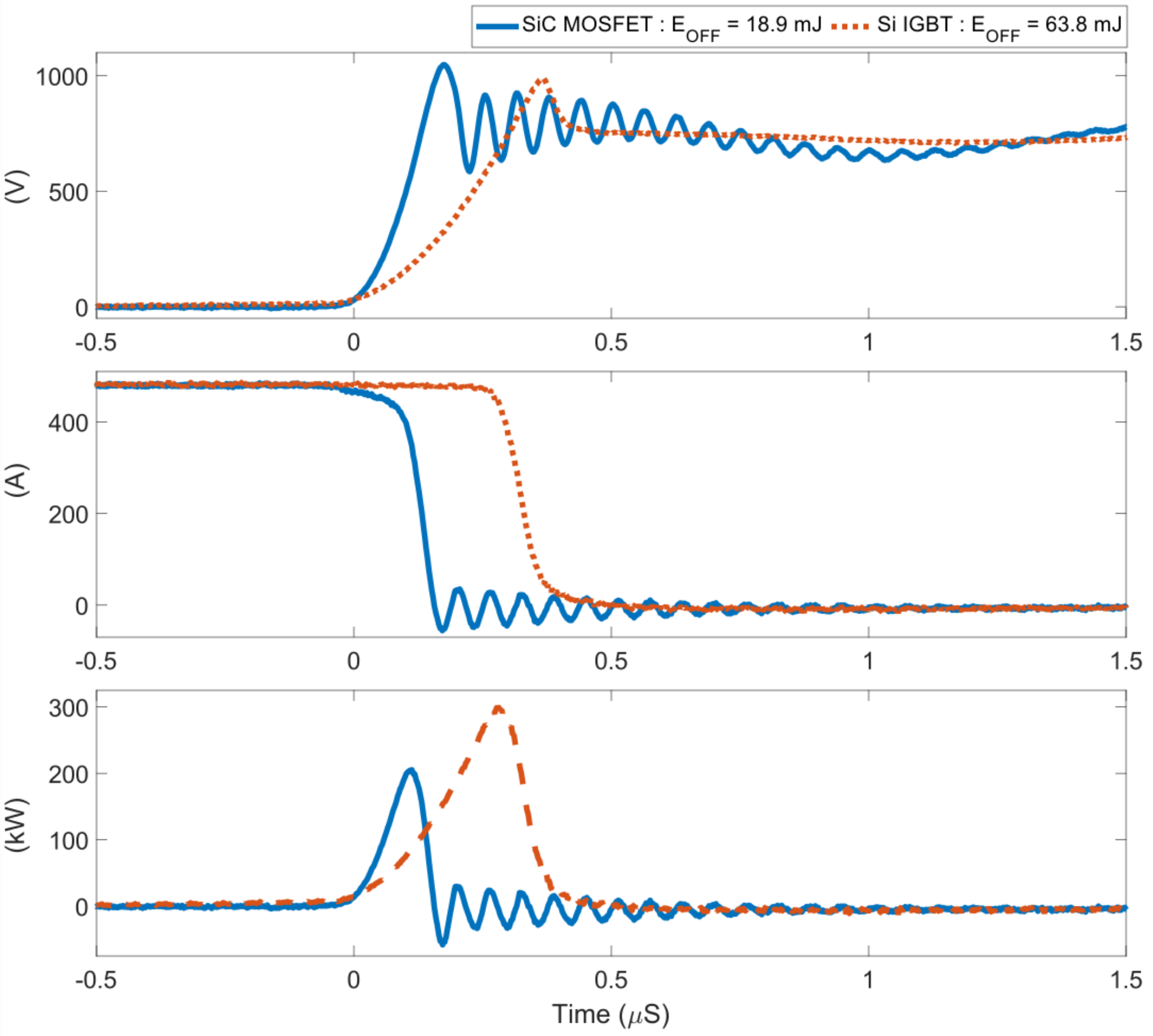
1.2 kV 600 A Devices - SiC MOSFET vs. Si IGBT Turn-Off Comparison

Si-IGBT

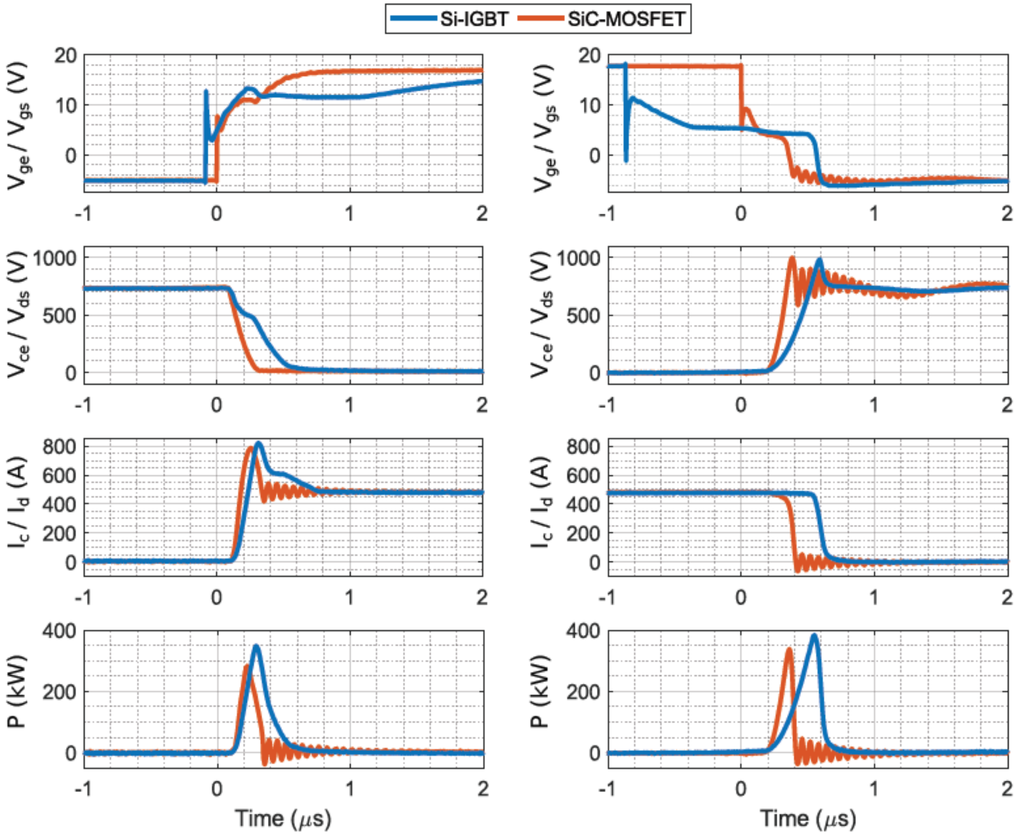
- Very good conduction
- Poor switching
  - Slow IGBT turn off due to excess minority carriers
- Negligible oscillations
- Lower dV/dt similar dI/dt

SiC-MOSFET

- Very good conduction & switching
- Expensive
- Oscillations in voltage & current a major concern due to EMI generation
- Switching performance strongly linked to stray inductance in switching loop



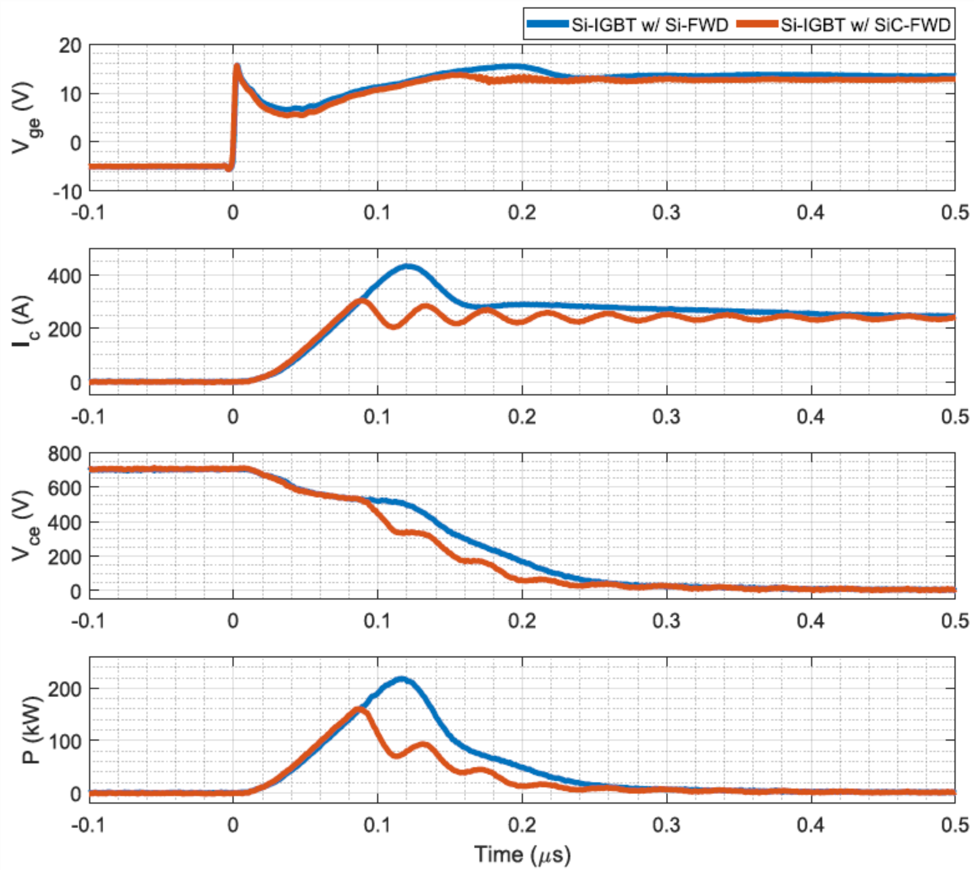
1.2 kV 600 A Devices - SiC MOSFET vs. Si IGBT Switching Comparison



(a) Turn-On. (b) Turn-Off.

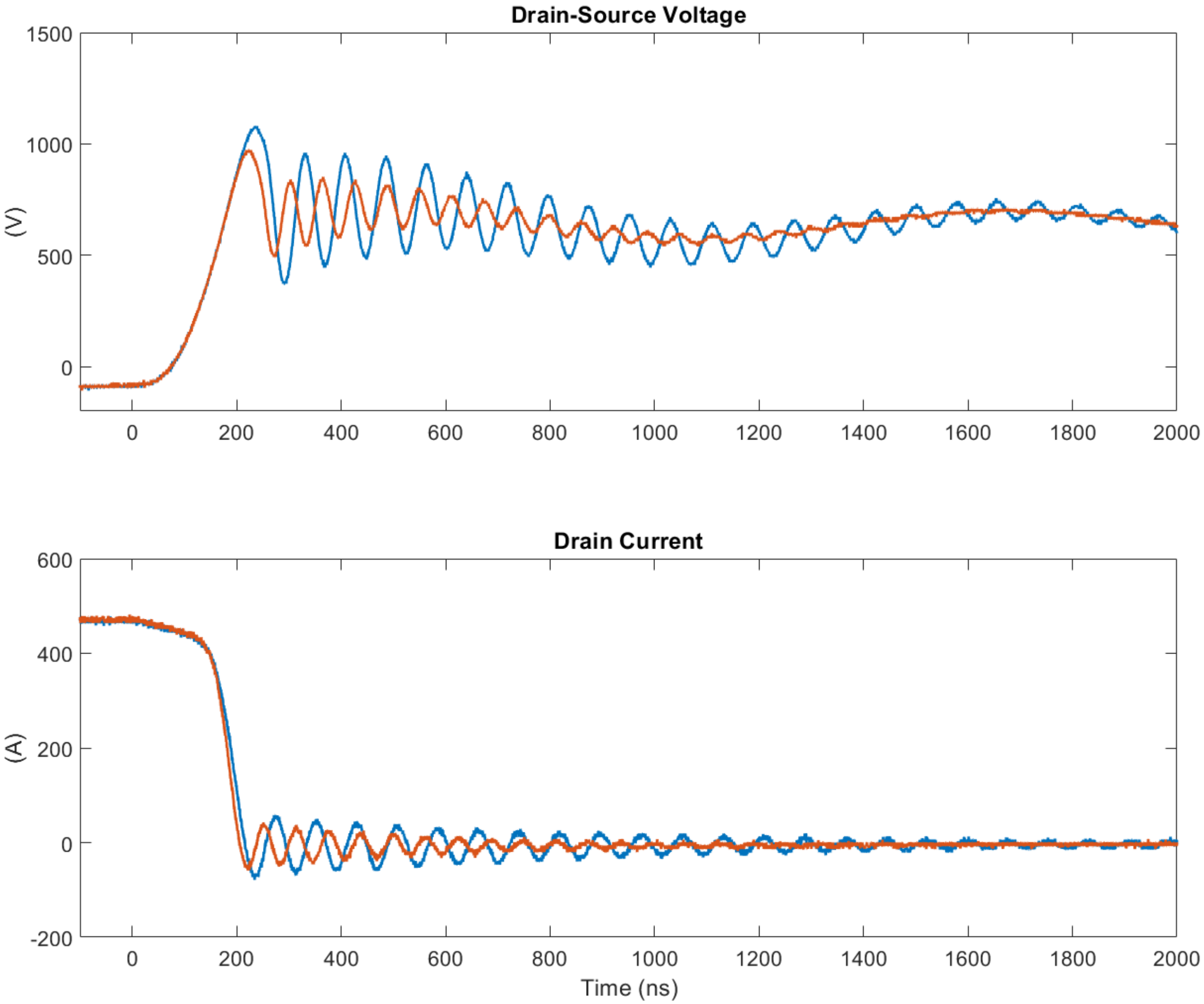
Experimental waveforms of switching transitions, Si-IGBT (FF450R12KT4) compared to SiC-MOSFET (BSM600D12P3G001). Tested at 480 A, 700 V with device baseplate set to 100 °C.

Hybrid IGBT and SiC-SDB Module



Experimental waveforms of turn-on switching transition, standard Si-IGBT with Si-FRD (SKM200GB12F4) compared to Si-IGBT with SiC-SBD (SKM200GB12F4SiC2). Tested at 250 A, 700 V with device baseplate set to 100 °C.

Influence of Stray Inductance on Switching Performance



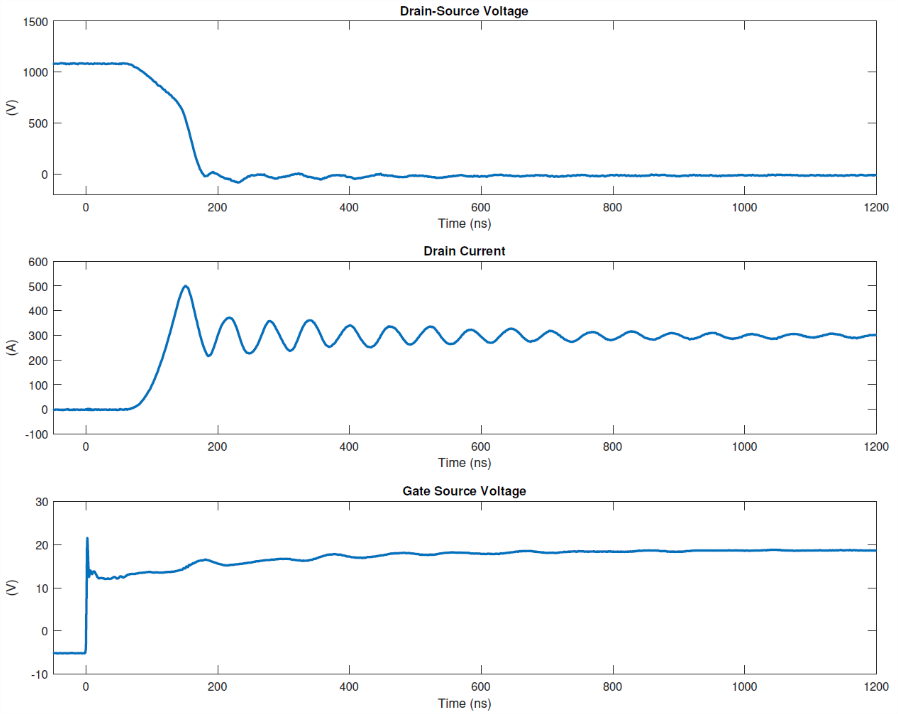
Approximately 2cm of additional commutation loop in the blue case

Significant impact on voltage overshoot (approx. 100V) and voltage/current oscillations

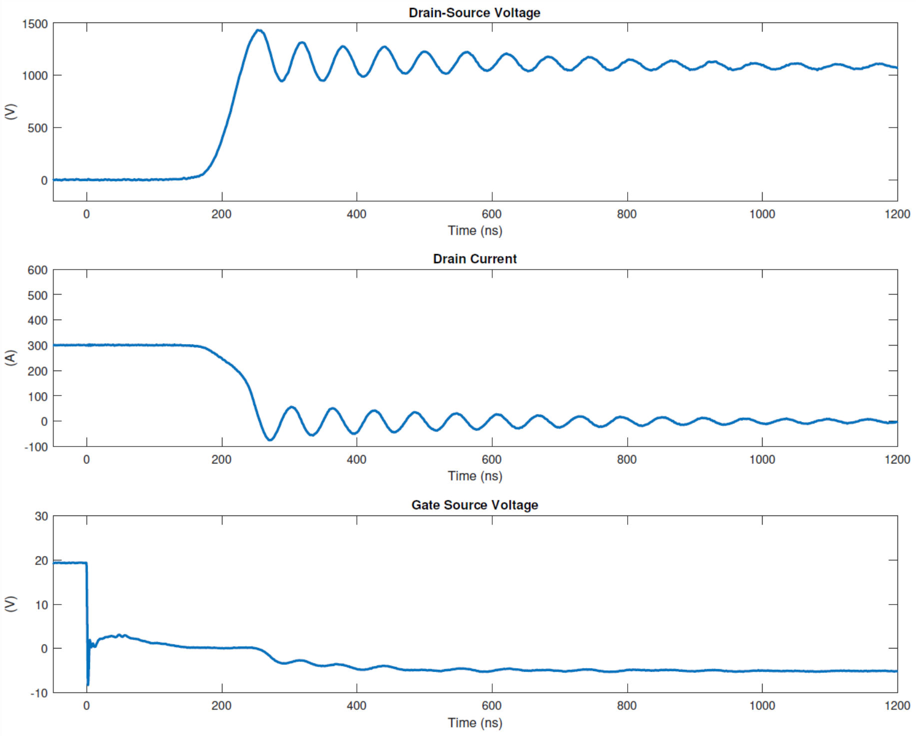
High quality busbar and de-coupling capacitors key to exploiting SiC to its full potential

Active Damping of SiC Switching Waveforms

SiC Switching Behaviour



Turn-On

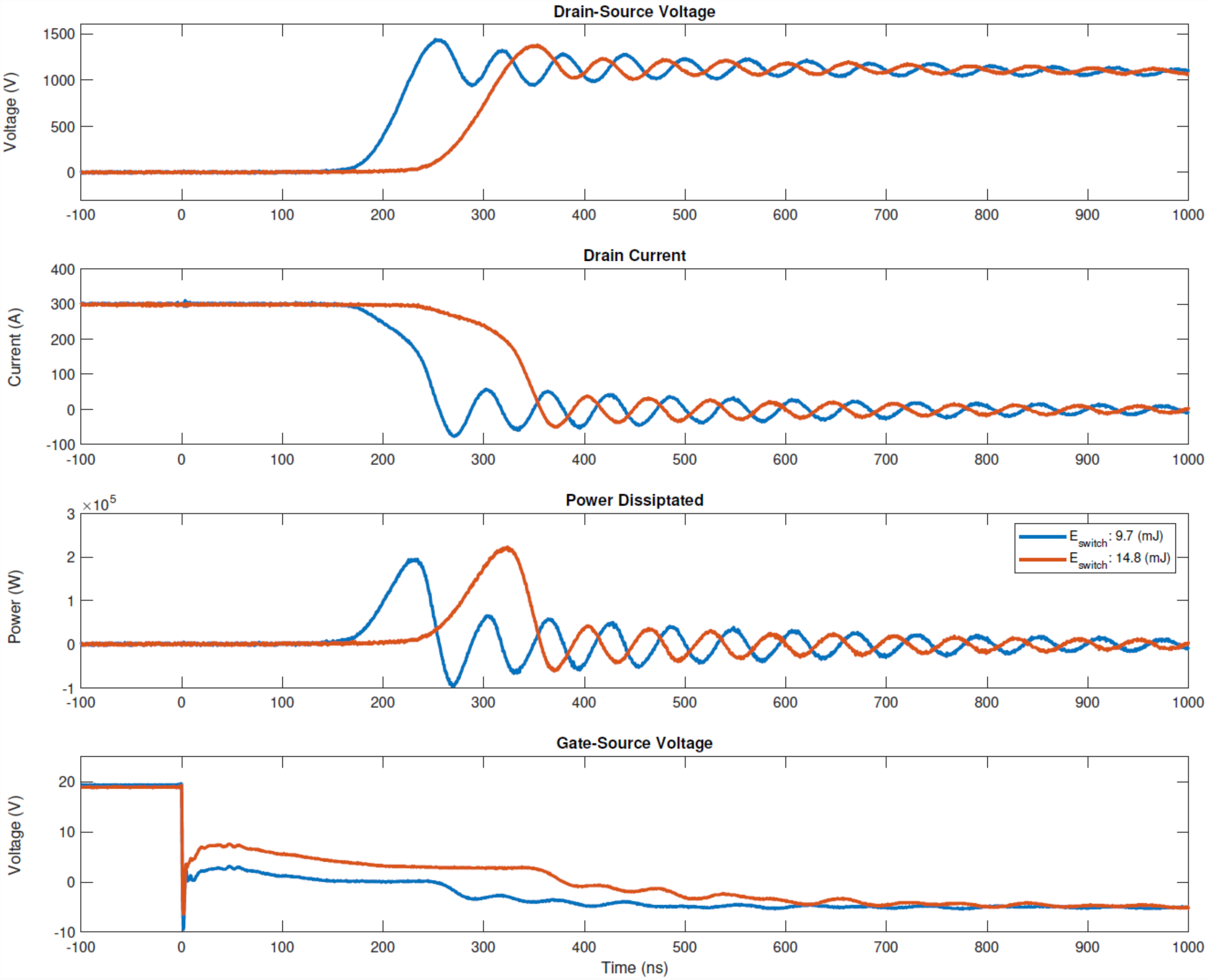


Turn-Off

SiC MOSFETS exhibit very oscillatory behaviour during switching transients

- Oscillations in both current and voltage waveforms
- Radiated emissions in both E- and H-fields
- Voltage oscillations can result in conducted emissions through the converters cabling.
- Need to pass EMC standards in order to sell commercially
- We have tested the latest XM3 1.2 kV 400 A SiC MOSFETS from Wolfspeed and gotten **200 A** oscillations at **42 MHz**

Gate Resistor Impact on Damping



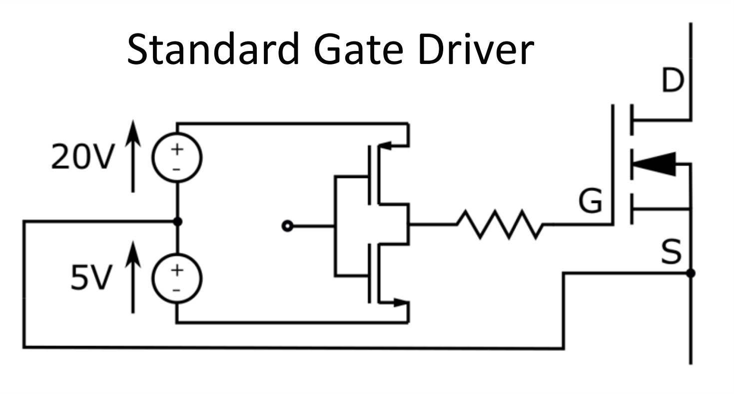
Active Gate Driving

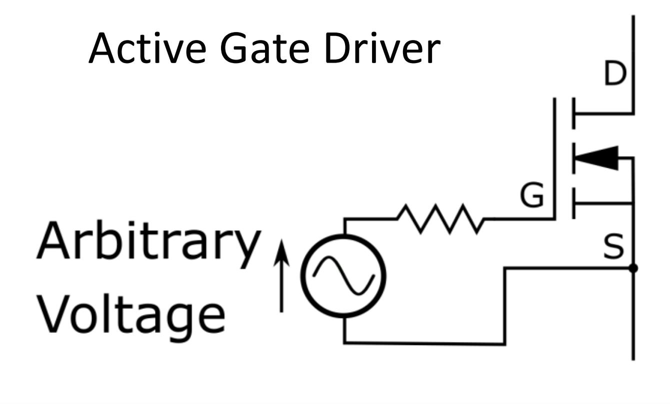
- Standard gate-drivers have fixed voltage levels
  - Drive strength changed by adjusting gate resistors – Typical to have different turn-on and turn-off resistors

- An active gate driver can attempt to influence the gate voltage of a device whilst it is switching in order to influence its switching behaviour.
  - Can either modulate the driving voltage, current or gate resistance (or a combination)

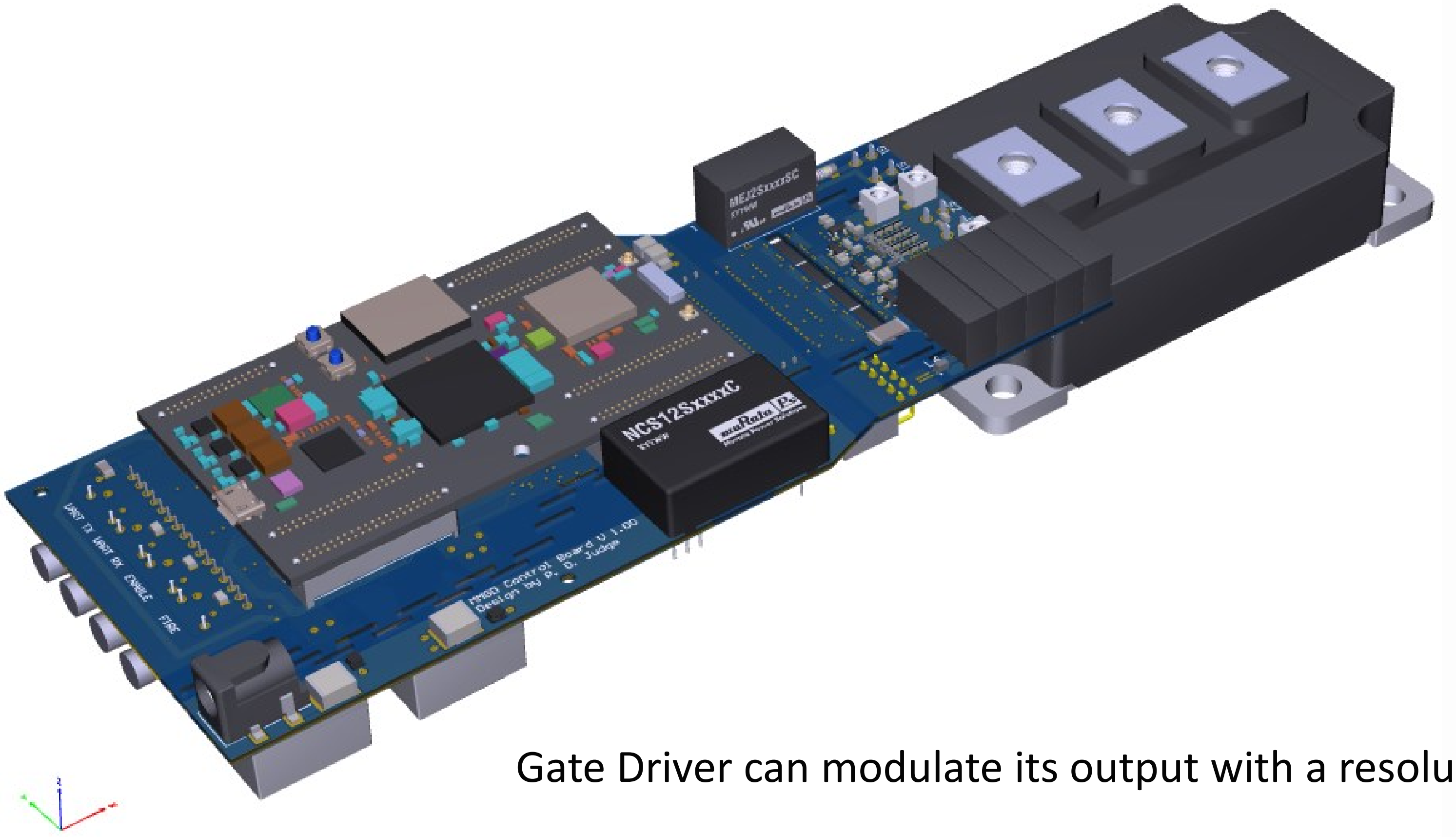
- For SiC MOSFETS this requires a circuit capable of modulating the gate-voltage in the nanosecond scale, while also driving a gate current in the region of 5 A

- Aim to add a significant amount of damping to both the voltage and current waveforms, without impacting switching losses to a large degree
  - Conventional operational amplifiers with these specifications do not exist





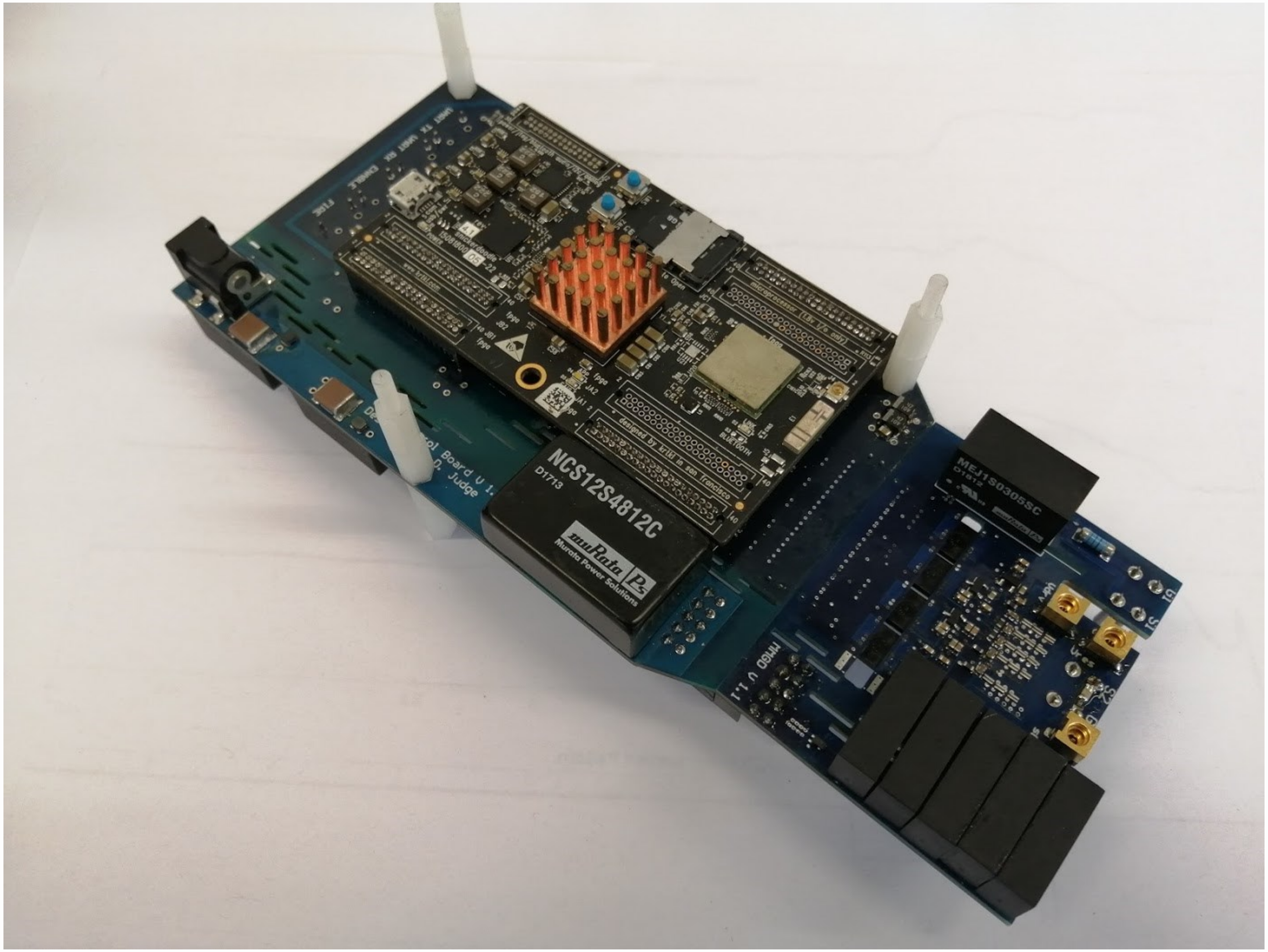
The Modular Multilevel Gate Driver



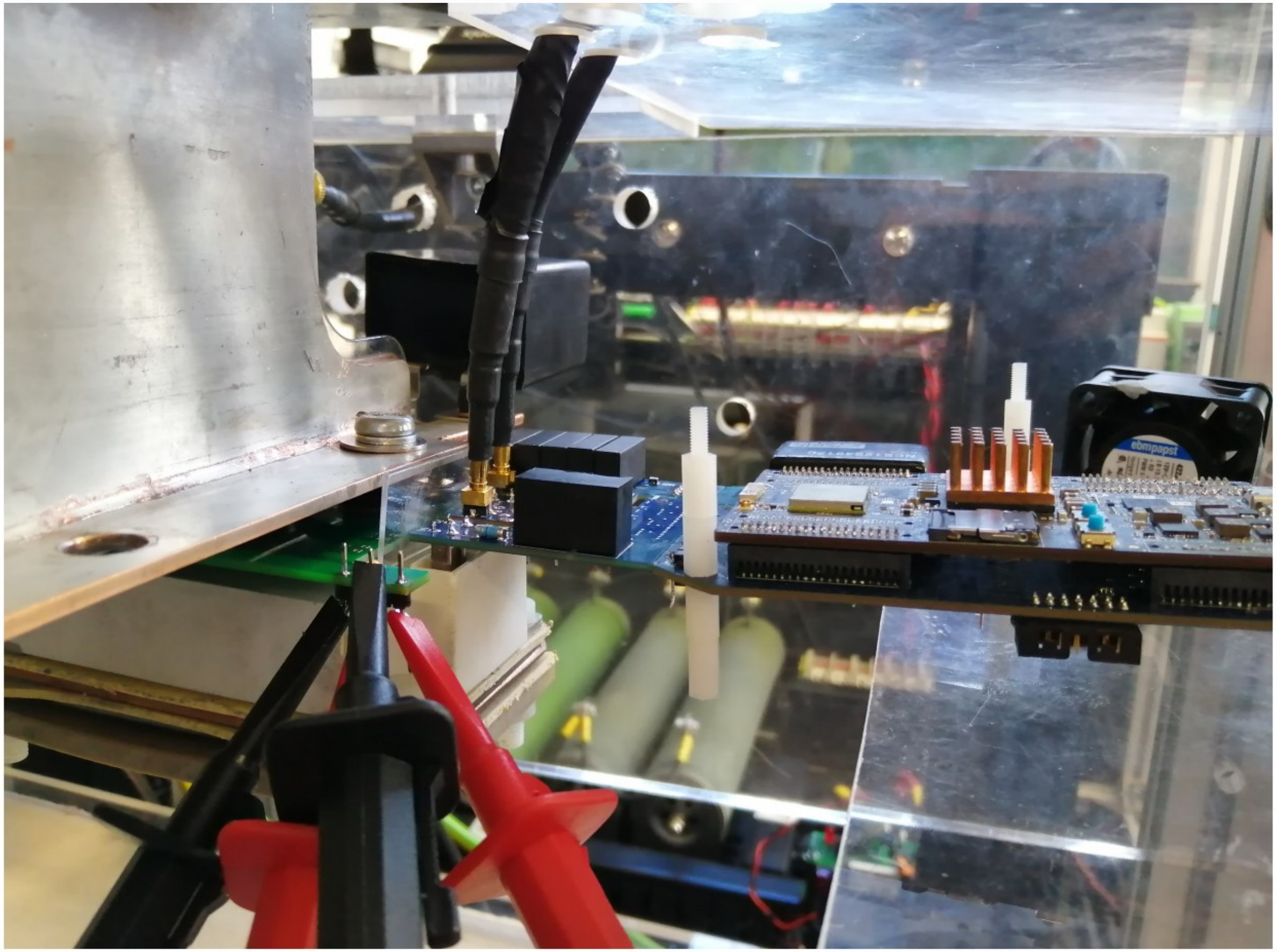
Gate Driver can modulate its output with a resolution of ~2.5 ns

- Light travels approximately 70 cm in this time
- New isolator chips should let us push down closer to 1 ns modulation

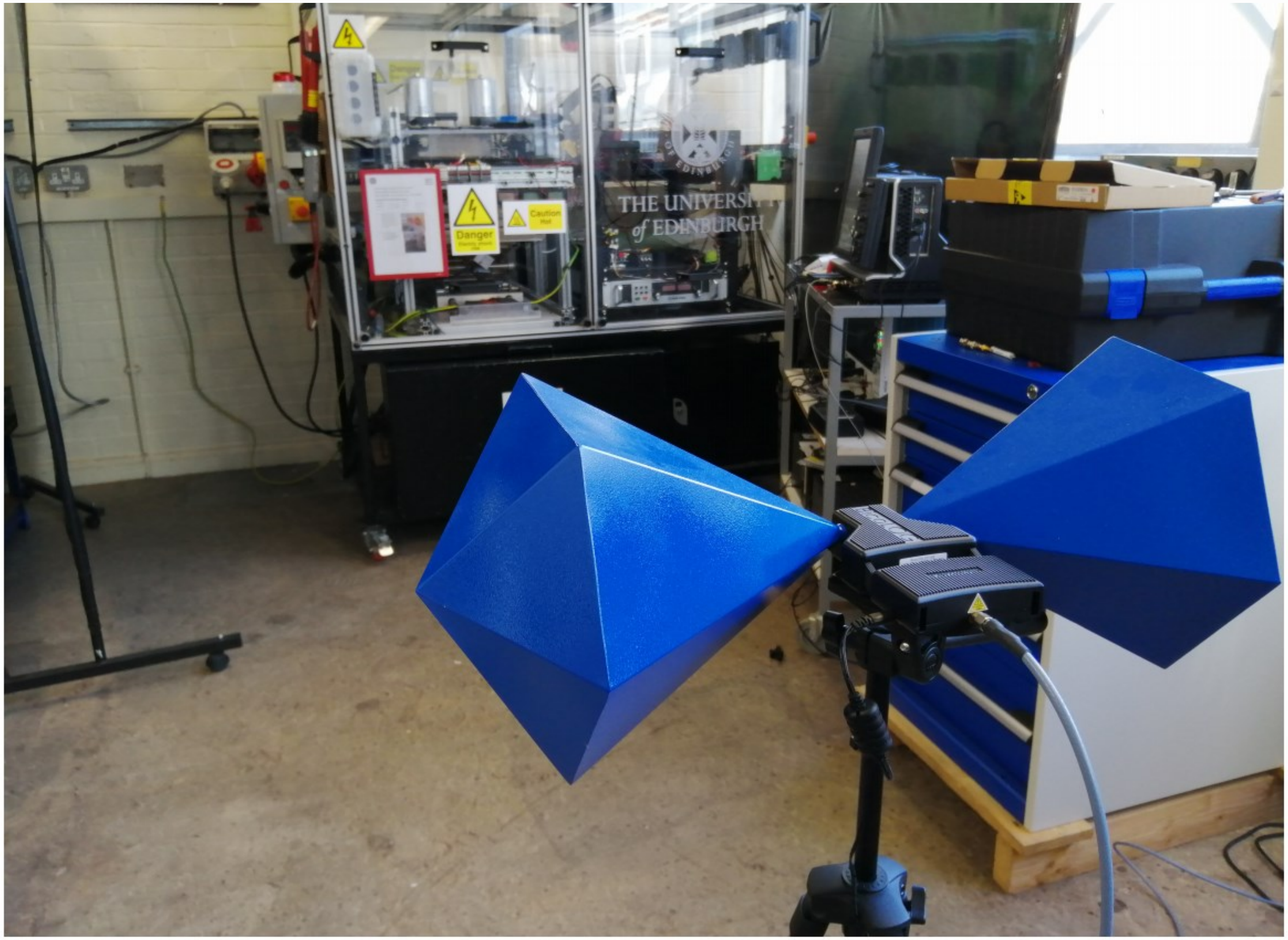
Gate Driver with Control Board Attached



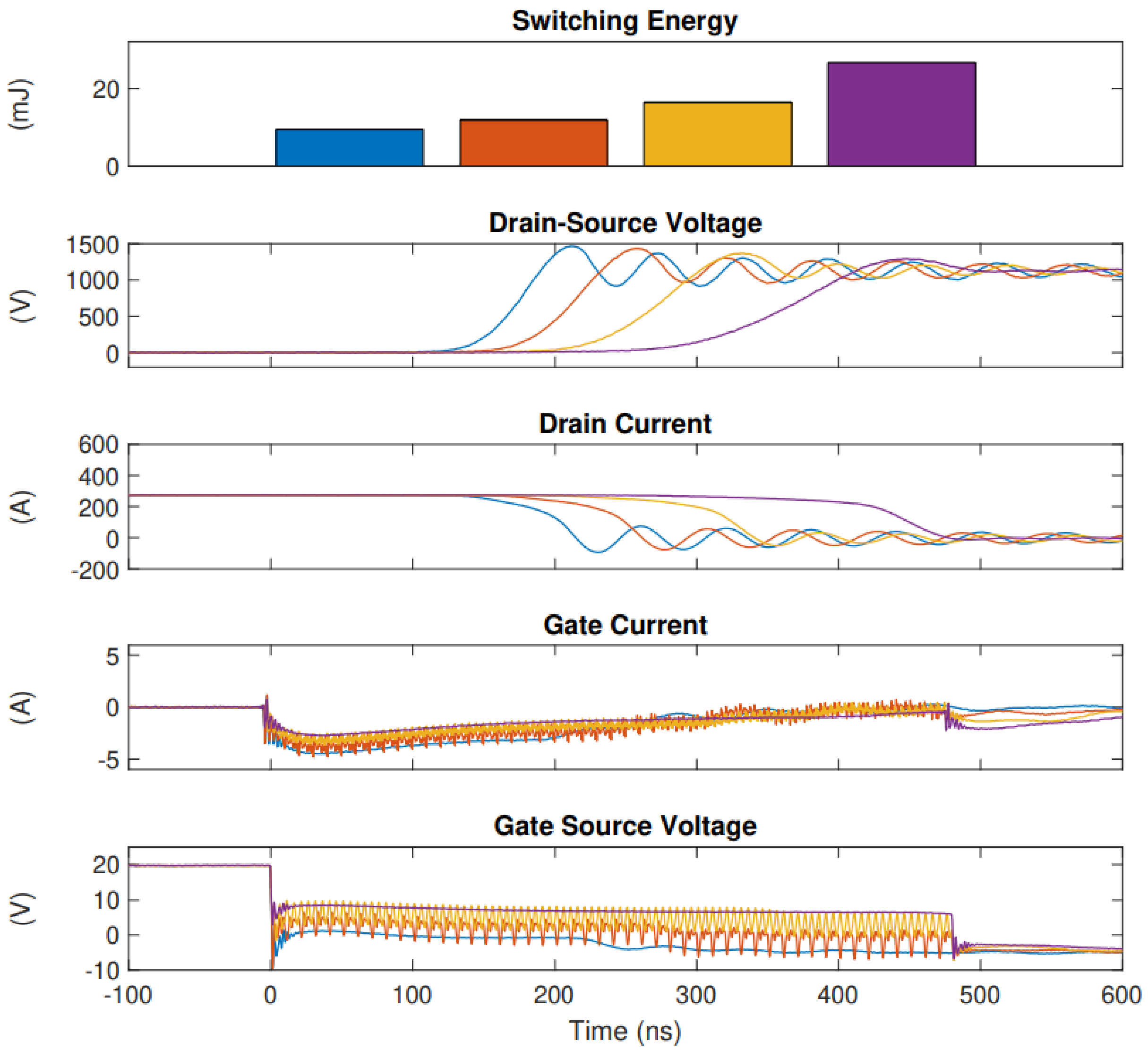
Experimental Setup



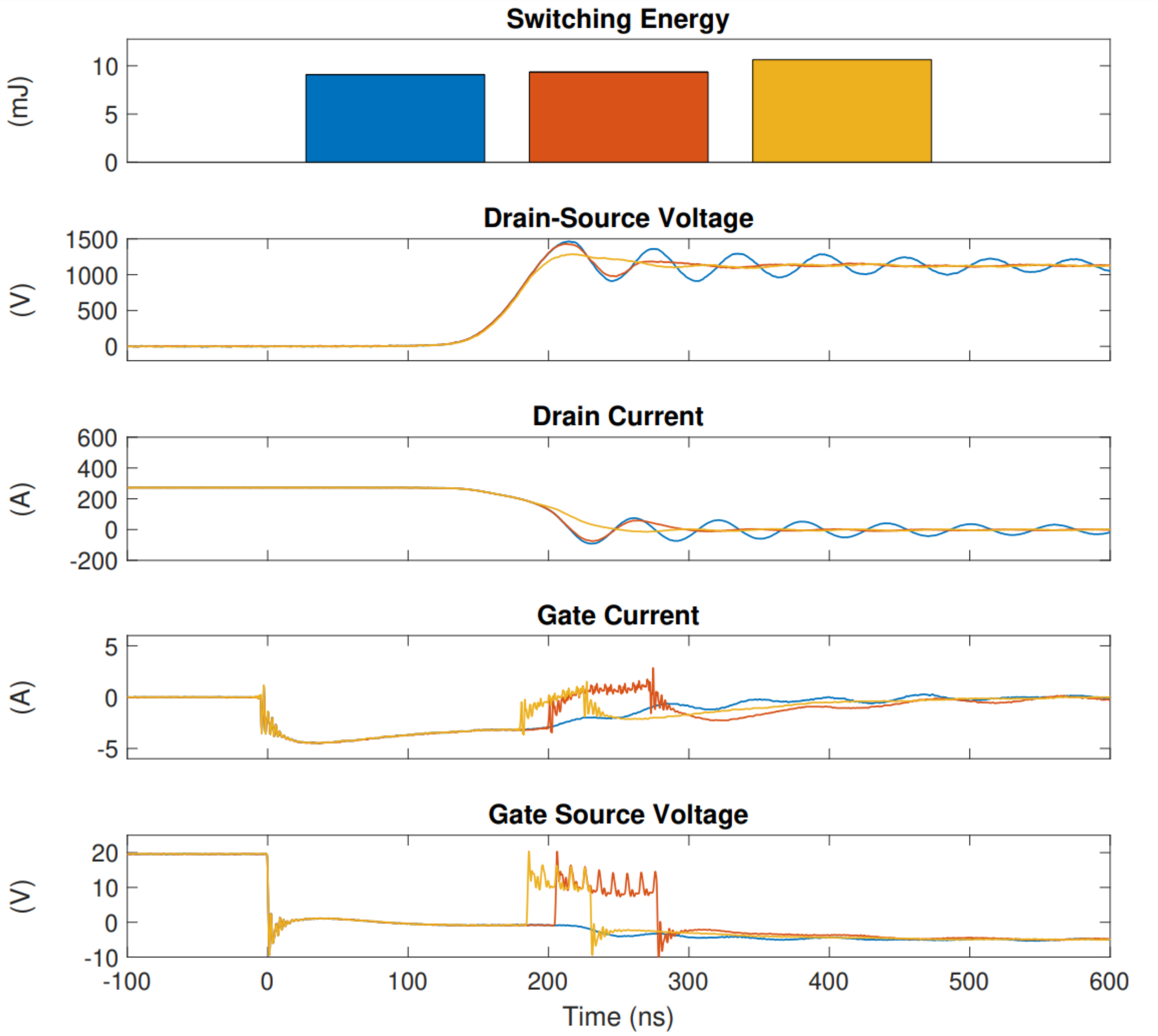
Experimental Setup



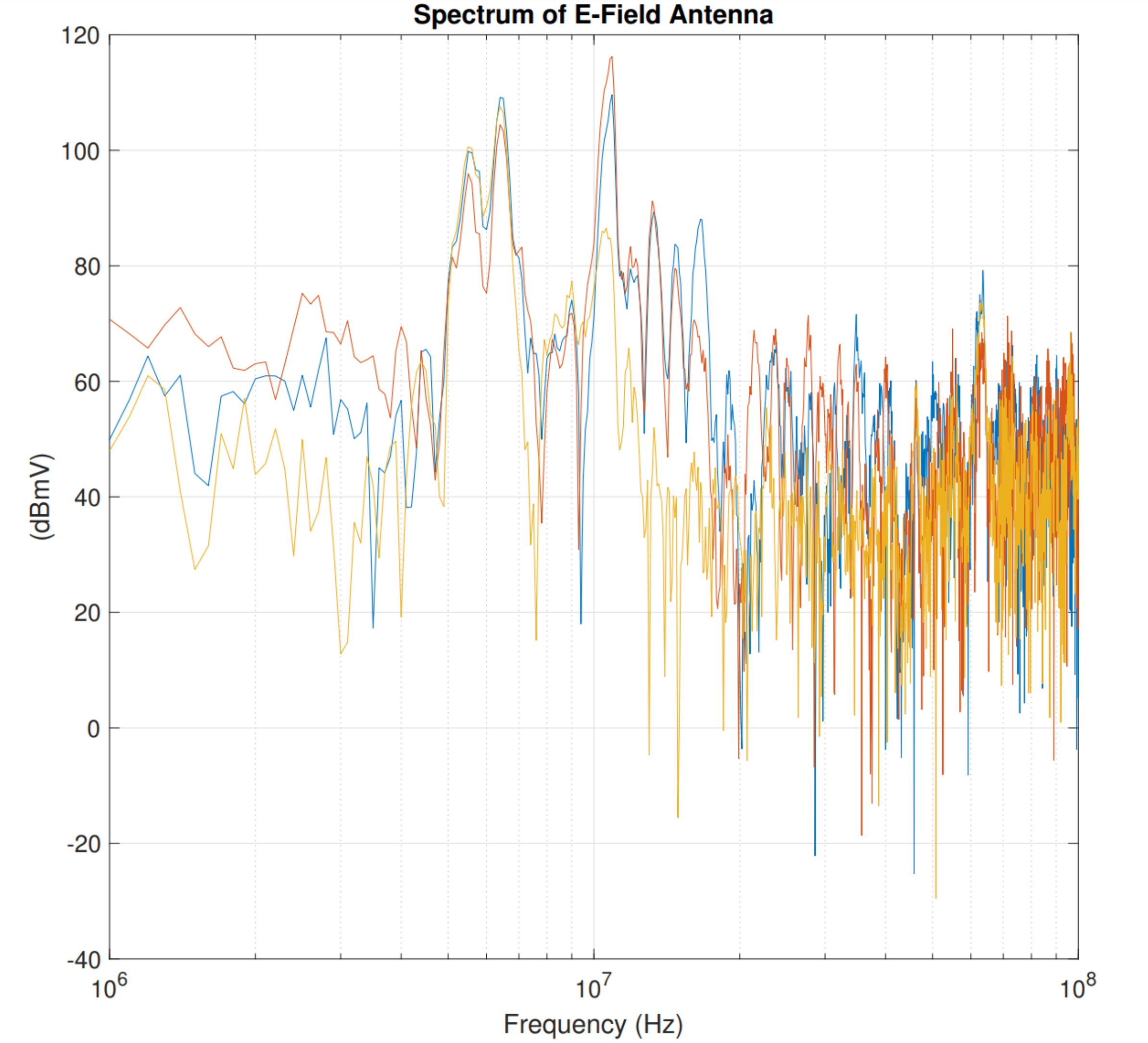
Turn-Off - Variable Pull-Down Strength



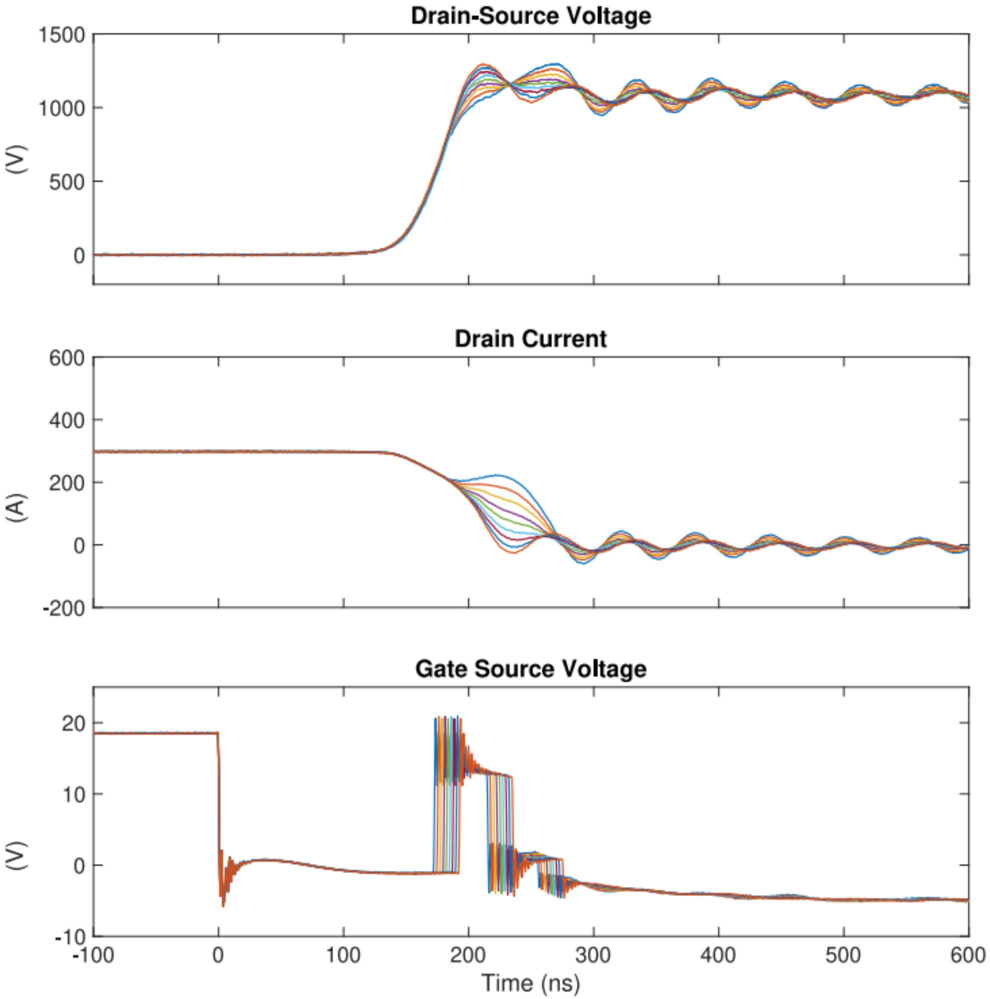
Modulated Turn-Off

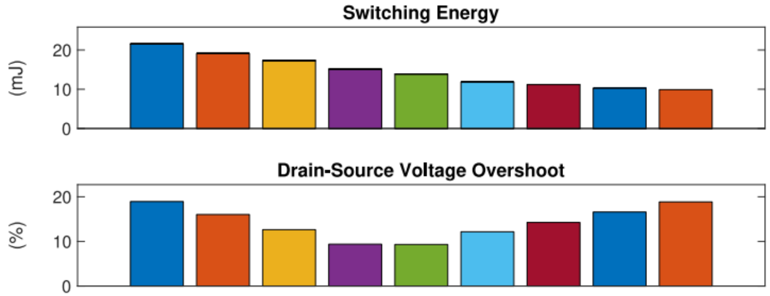


Modulated Turn-Off



Time Sensitivity





Active damping with minimal increase in switching energy loss possible

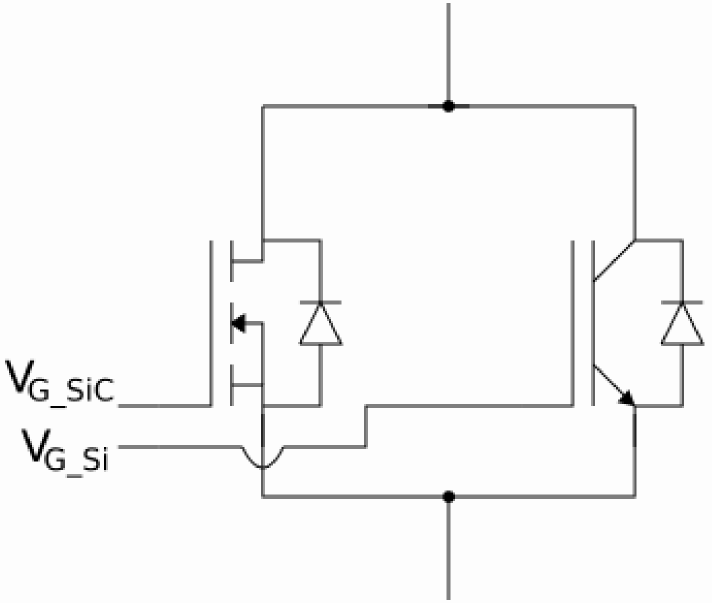
Results highly time sensitivity

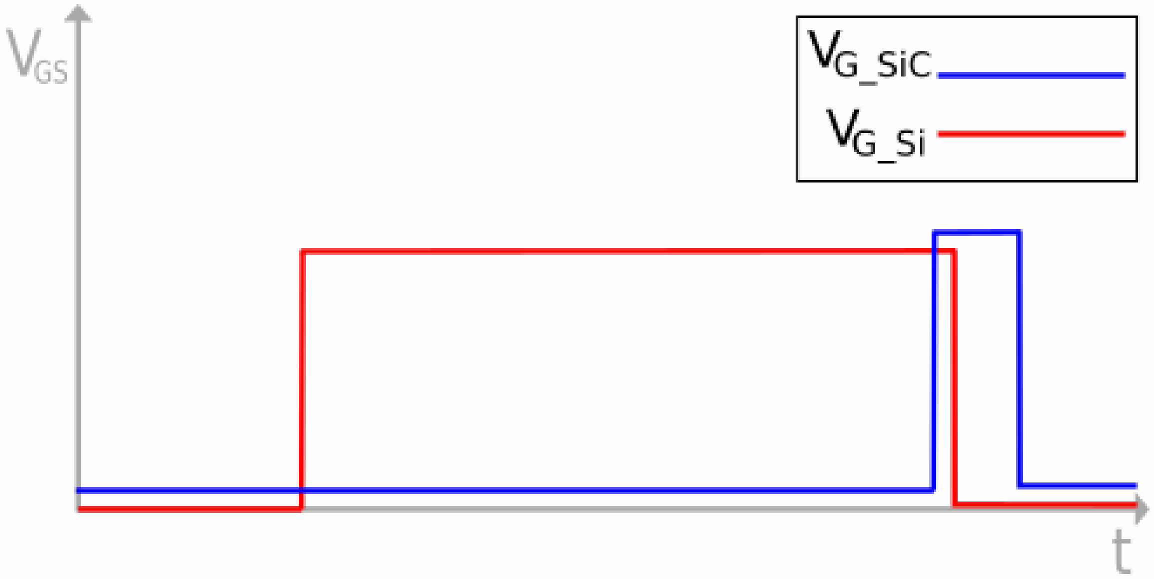
Closing the loop during inverter operation to account for varying loading conditions is a major challenge

Complimentary Switching of Si-IGBT and SiC-MOSFET Power Modules.

Hybrid Switch

- Si-IGBT and SiC-MOSFET in parallel
- Fully rated Si-IGBT used as main conduction device
- Partially rated (4:1) SiC-MOSFET used as bypass current path during turn-off
  - Faster dV/dt SiC turn-off





R. E. Mathieson, P. D. Judge and S. Finney, "Si/SiC Hybrid Switch for Improved Switching and Part-Load Performance," *2020 IEEE 21st Workshop on Control and Modeling for Power Electronics (COMPEL)*, Aalborg, Denmark, 2020, pp. 1-7

Results – 480 A / 700 V

SiC-MOSFET

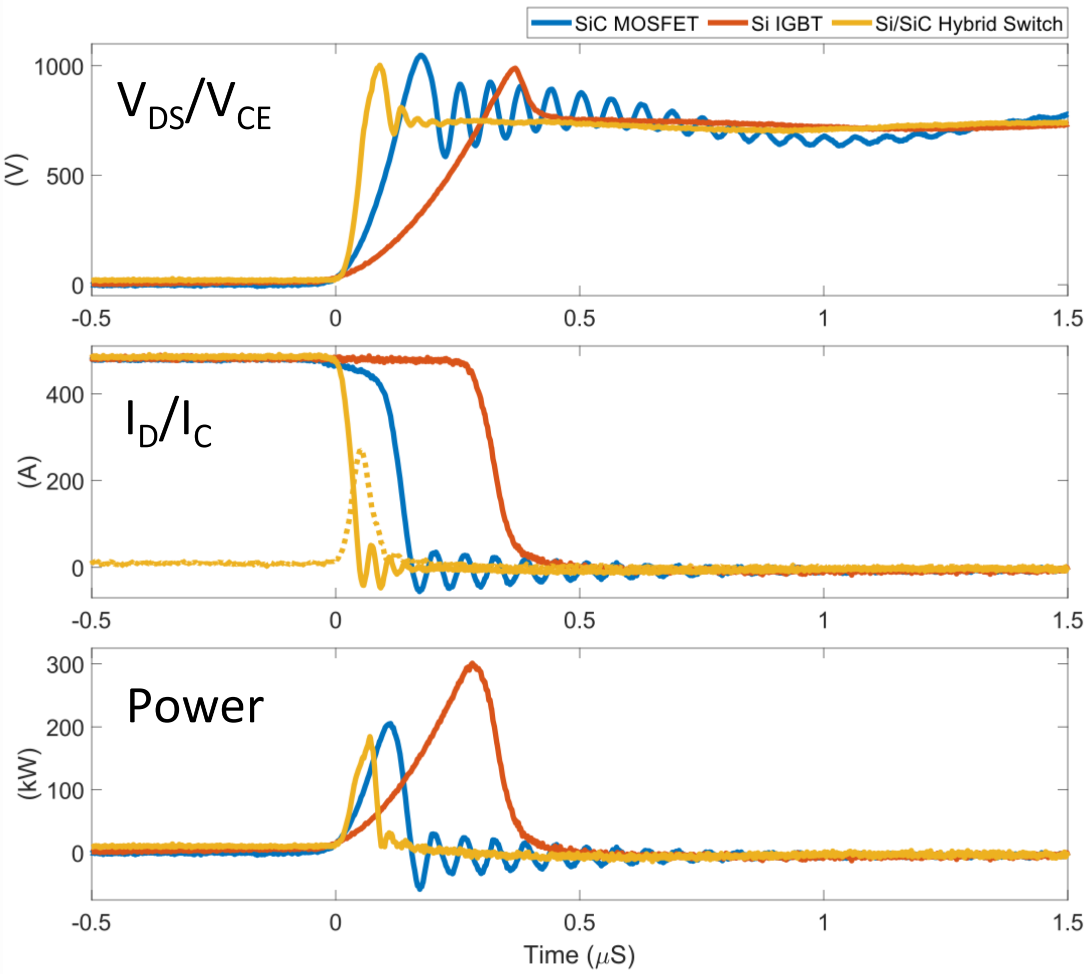
- BSM600D12P3G001
    - 1.2 kV 600 A

Si-IGBT

- FF450R12KT4
    - 1.2 kV 450 A

Hybrid Switch

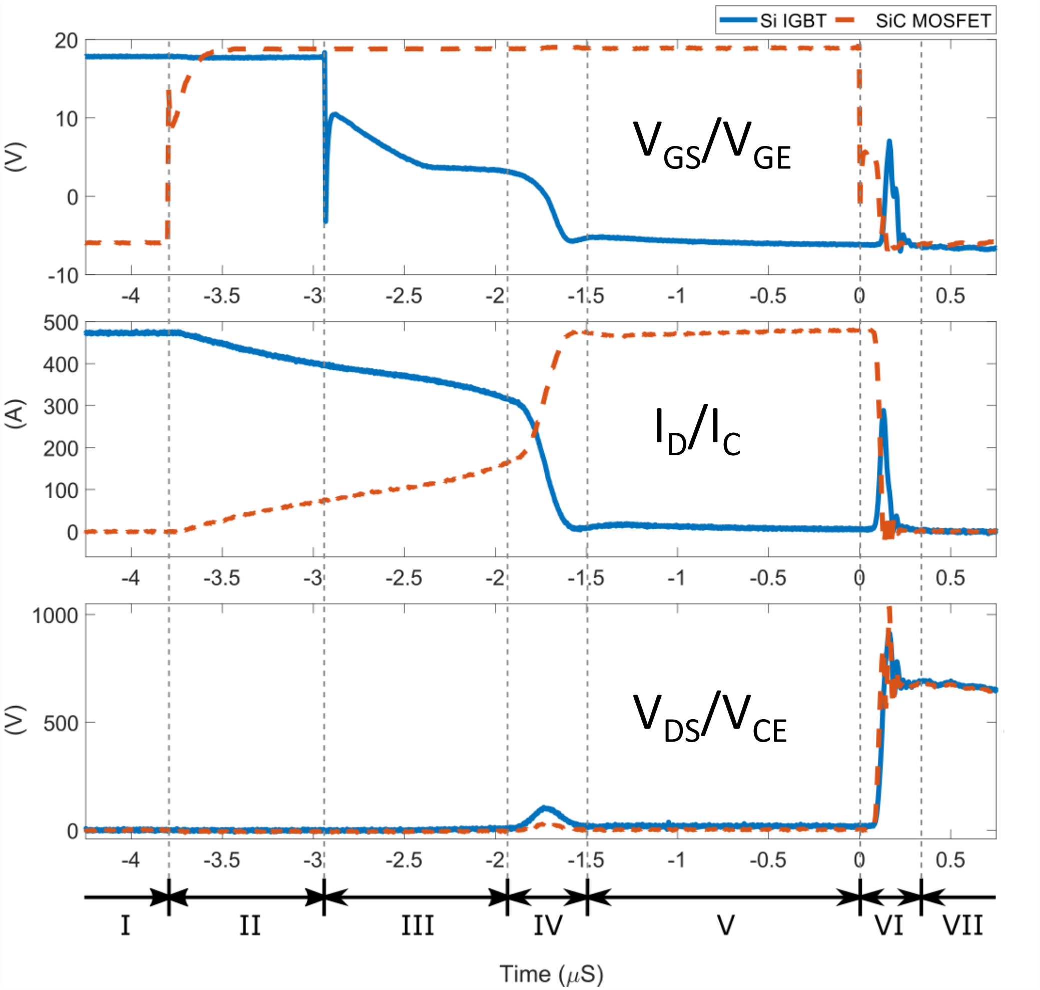
- Si: FF450R12KT4
    - 1.2 kV 450 A
- SiC: CAS120M12BM2
    - 1.2 kV 120 A



- **Hybrid Switch has significantly reduced oscillatory behaviour compared to that of the fully rated SiC-MOSFET**
- **Higher dI/dt & dV/dt values**

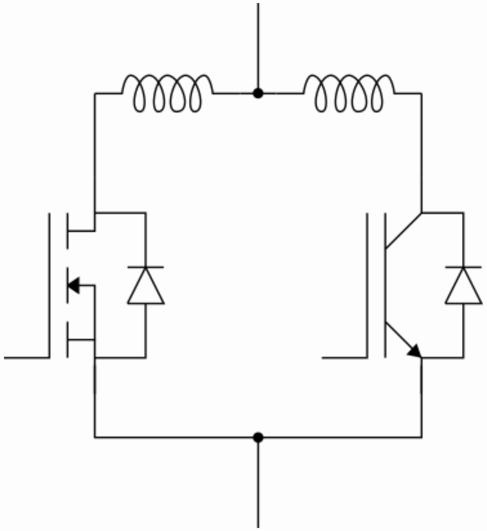
Turn-Off Switching Scheme

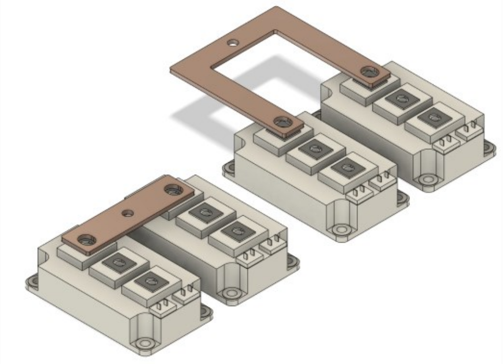
- Majority of losses incurred at final switching edge
- Large dI/dt causes induced voltages on stray inductance between devices during current commutation between devices
- Additional increased energy loss due to higher conduction loss in SiC MOSFET for the period when it conducts

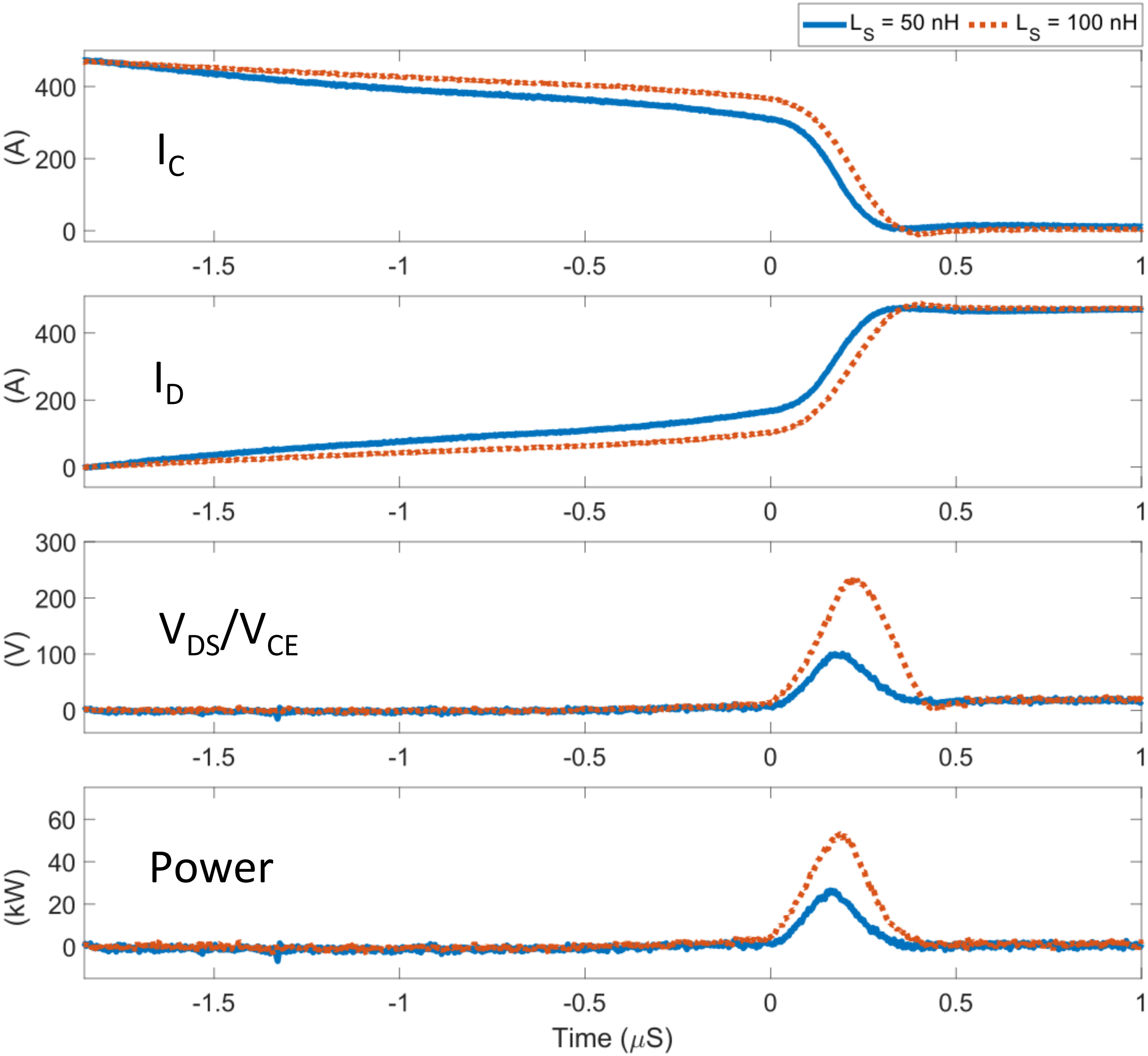


Commutation Energy Loss

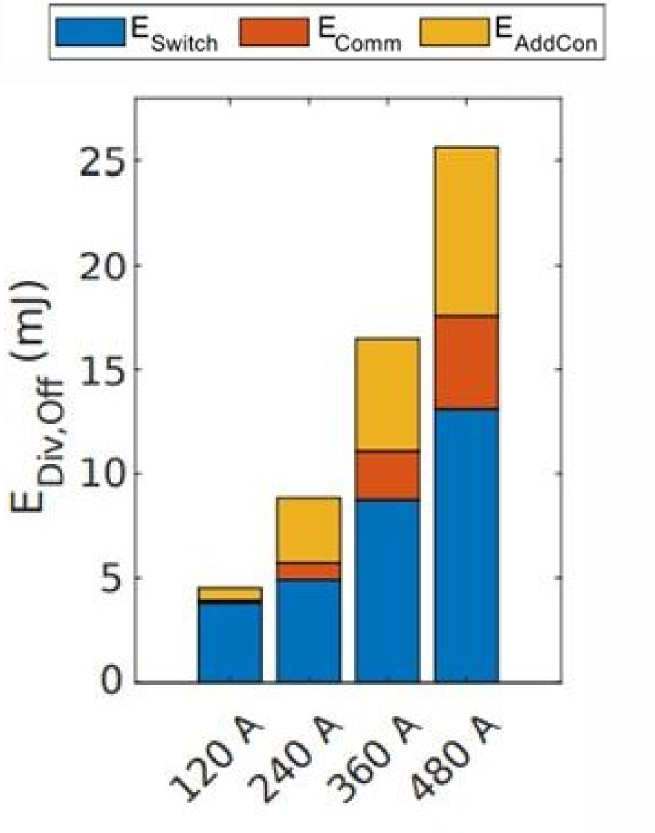
Stray Inductance

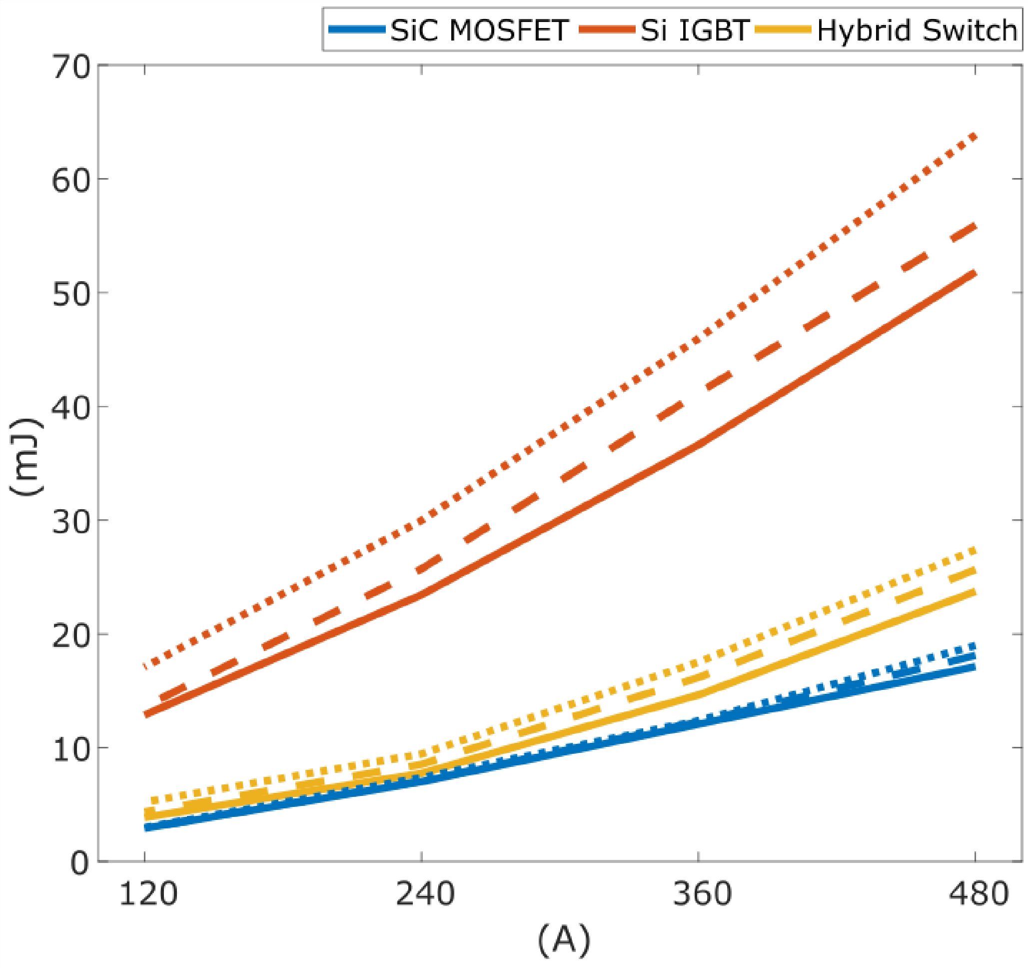






Turn-Off Loss Results





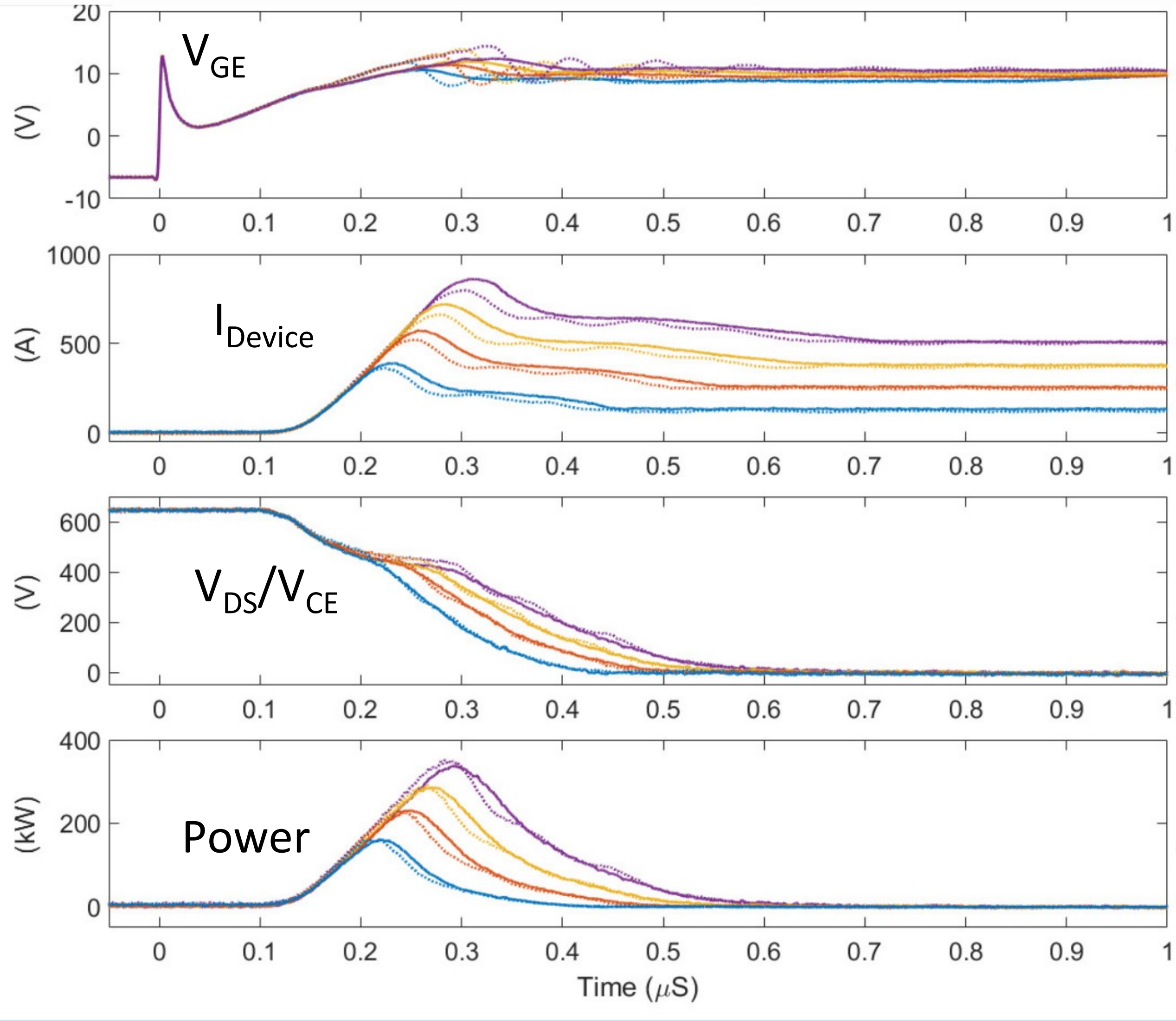
Impact on Turn-On

Negligible difference in turn-on switching loss.

- Additional output capacitance
- Lower reverse recovery in SiC diode

Solid – Just IGBT

Dashed – With SiC MOSFET In Parallel



Hybrid Switch - Conclusion

Close to **SiC performance** without a fully rated SiC device.

- 55-70% reduction in turn-off energy
- Close to switching loss of fully rated SiC-MOSFET
  - Module design would reduce commutation loss
- Damped oscillatory behaviour
- Higher dI/dt and dV/dt than either Si IGBT or fully-rated SiC MOSFET

Thank You