High-Performance SiC Power Module Development

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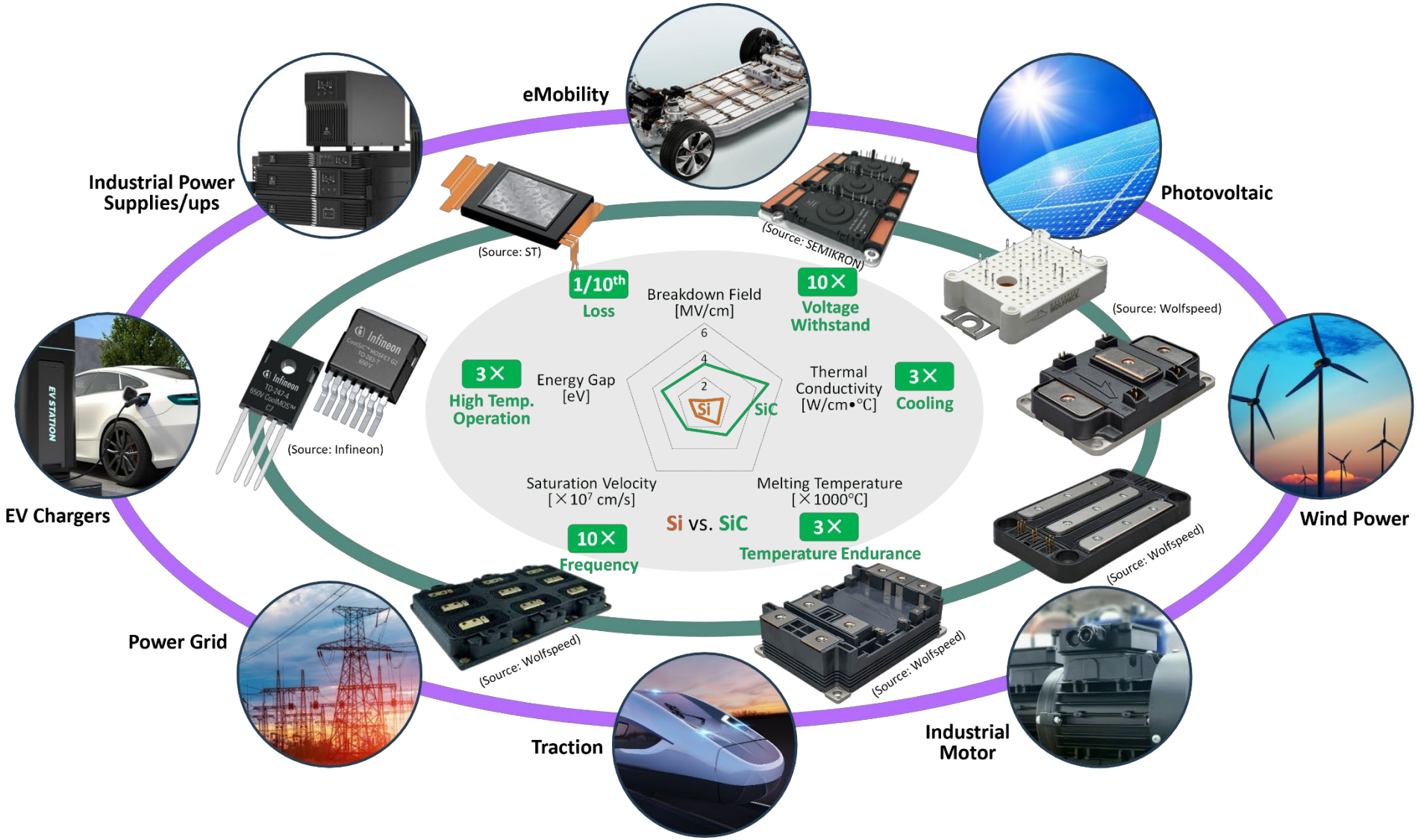
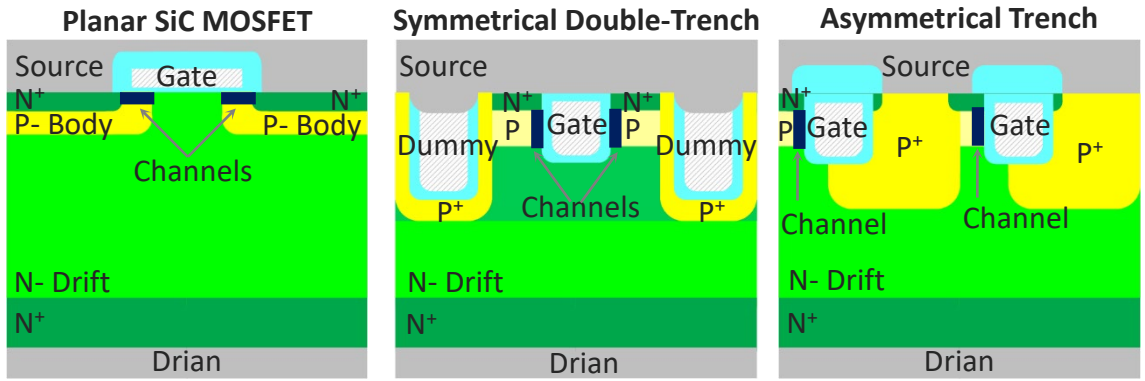
Silicon Carbide Power Device: Opportunities



* Power SiC device market is forecast to grow nearly to $9B with continuing penetration of SiC in automotive, along with industrial applications. (Source: Power SiC 2023, YOLE)

More efficient, smaller, and lighter than Si-Based System

Silicon Carbide Power Device: Challenges



3.3 kV SiC devices become a commercial reality

GeneSiC SEMICONDUCTOR

Wolfspeed

MICROCHIP

Wolfspeed Gen 4

Gen 3

life.augmented

onsemi M3e

ROHM SEMICONDUCTOR Gen 4

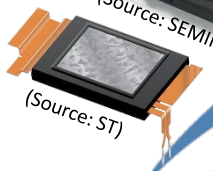
infineon Gen 2

SiC Device Technologies (Rapidly evolving)

- DSC
- SSC + Pin fin
- Epoxy molding

Automotive Modules


(Source: SEMIKRON)


(Source: ST)

SiC Power Module Packaging


(Source: wolfspeed)

Challenges on Module Packaging

High-thermal dissipation structures:
Structured baseplate
Baseplate-free structure
Double-sided cooling

High temp. & reliable materials:
AlN & Si3N4 Substrates
Silver & copper sintering
Copper wire bonding
High-temp epoxy & silicone gel

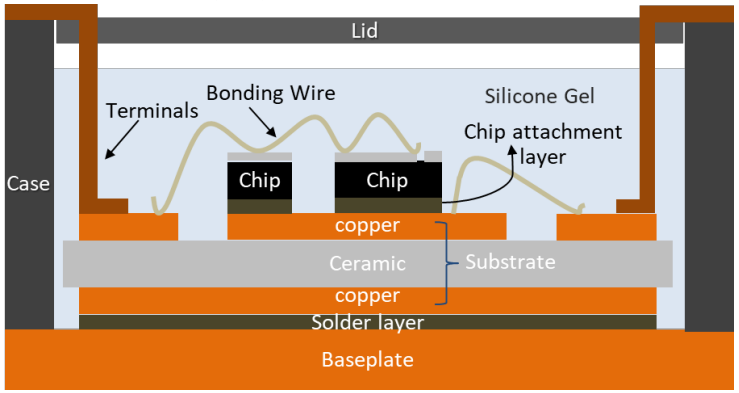
SiC chips:
High Temp
Fast Switching
High Voltage

High insulation structure & EMI reduction/optimization design:
Stacked substrates with patterned middle layer copper

Low-inductance structures & interconnections:
wire bondless techniques (clip, metal spacer, lead frame……)

More Effort Needed

Current (most available): Standard or enhanced Module Packaging based on Traditional Structure



UA's Module Progression

eMobility

Photovoltaic

Wind Power

Traction

Industrial Motor

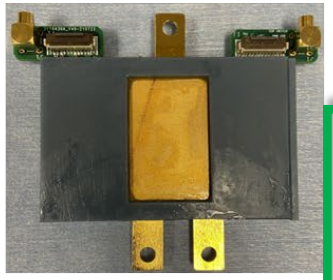
Power Grid

1.2 kV

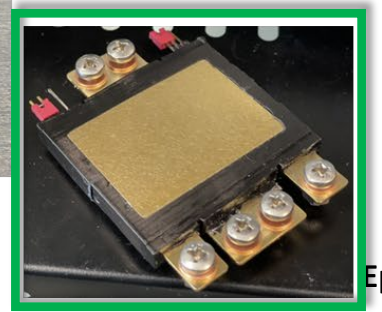
1.7 kV

3.3 kV

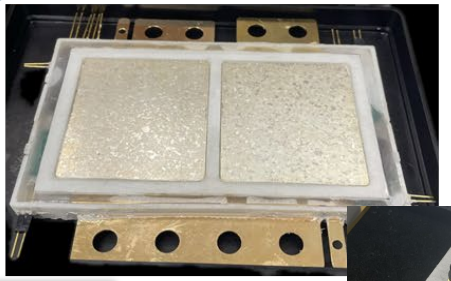
10 kV



1.2 kV DSC + Integrated Gate Driver

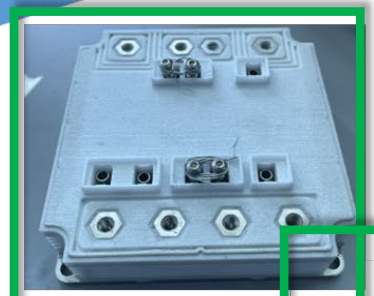


1.2 kV DSC + Epoxy Resin-Molded



1.7 kV/1.6 kA DSC + Integrated Gate Driver

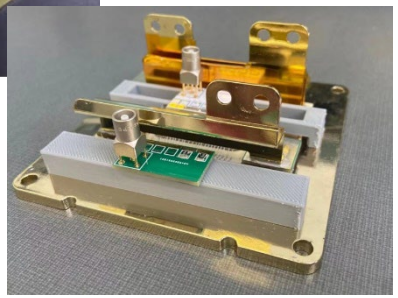
1.7 kV H-bridge with Integrated Decoupling caps. and Cooler



3.3 kV

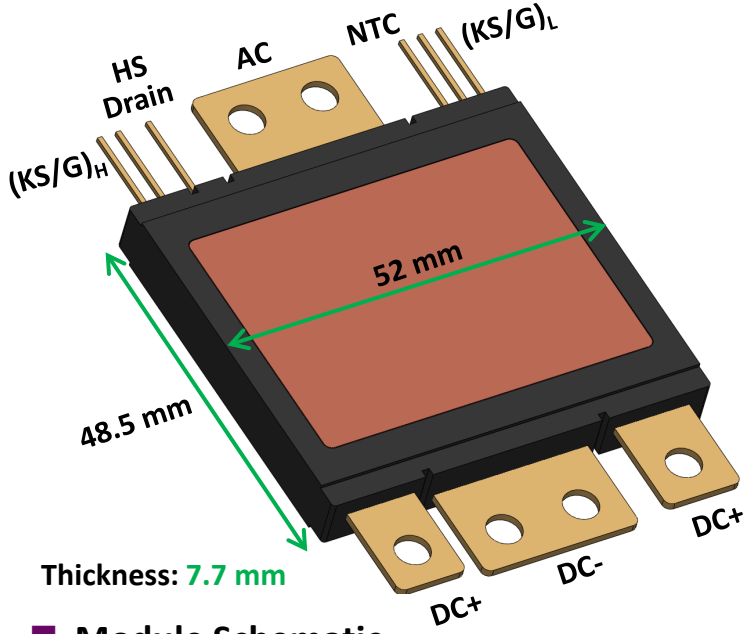
3.3 kV + Integrated Gate Driver

10 kV + Embedded Decoupling Cap.

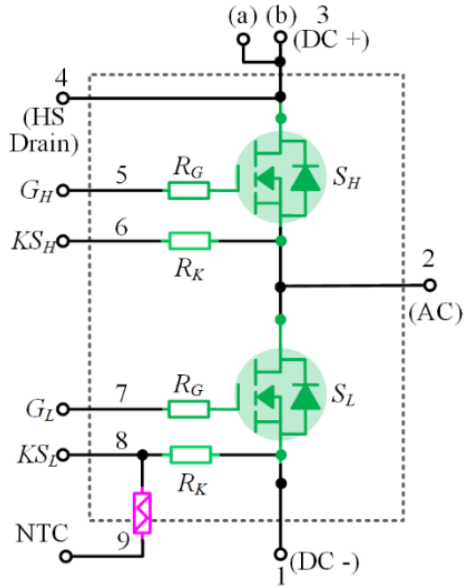


1.2 kV Double-sided cooled (DSC) SiC-based Half-Bridge Module Development

Module Specifications & Features



Module Schematic



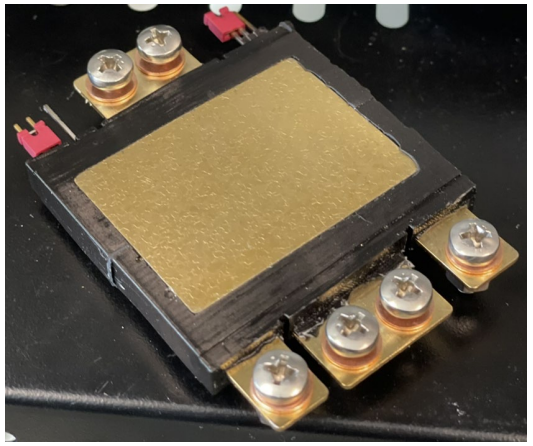
Main Specifications

Rating		1.2 kV/400 A (@T_C = 25°C) (DC)
Configuration		Half-Bridge Module
Dimensions		52 × 48.5× 7.7 (mm) (= **19.4 cm³**)
Clearance & Creepage distances	**Between terminals**	Mini. 3 mm and 4 mm
	To grounded heatsink	Mini. 7.5 mm and 7.5 mm

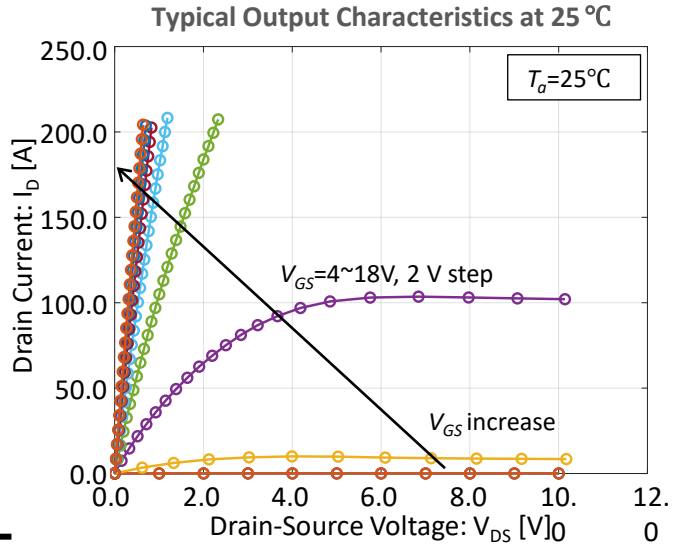
Technical Features

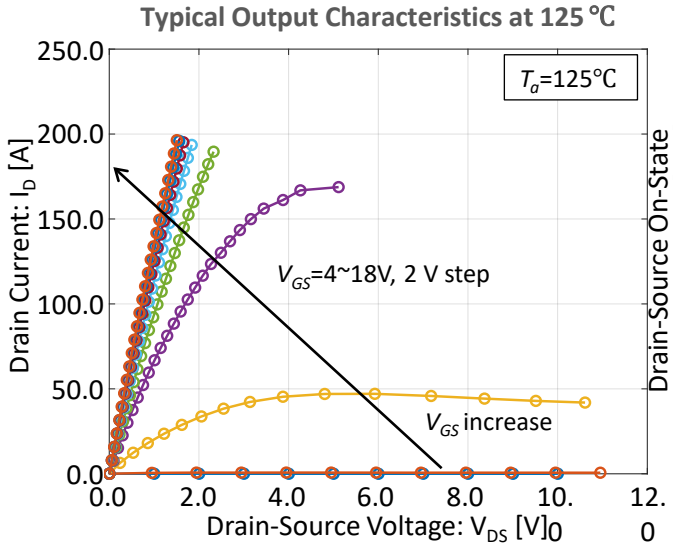
- **Full** SiC MOSFET Module, 4 die per switch position
- **Cu-Mo metal spacers** for chip topside power connections and **compact sandwich structure** enable low commutation-loop inductance design (Estimated **2.53 nH** @ 10 MHz)
- **Double-sided cooled structure** to achieve better thermal performance
- Combination of SiC device + **Si_3N_4 AMB** Substrate (good CTE matching) for high reliability
- **Molding process using epoxy resin** as encapsulant to deliver high reliability and high mechanical robustness
- **Integrated gate** & **Kelvin source resistors** to reduce high peak currents that may flow in gate loop as well as help to improve dynamic sharing in gate loop
- **Embedded temperature sensing** enables system-level temperature protection

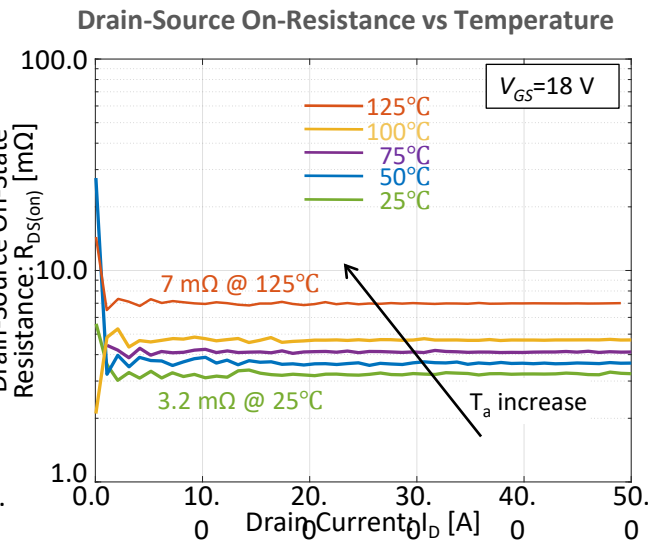
Typical Static Characteristics of Modules

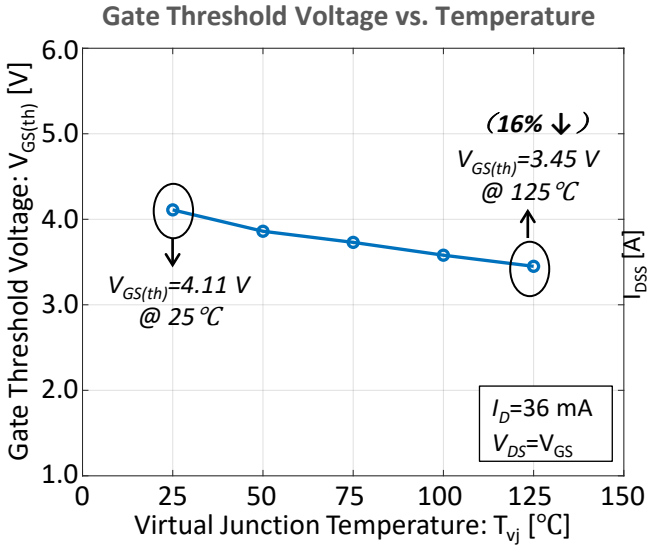


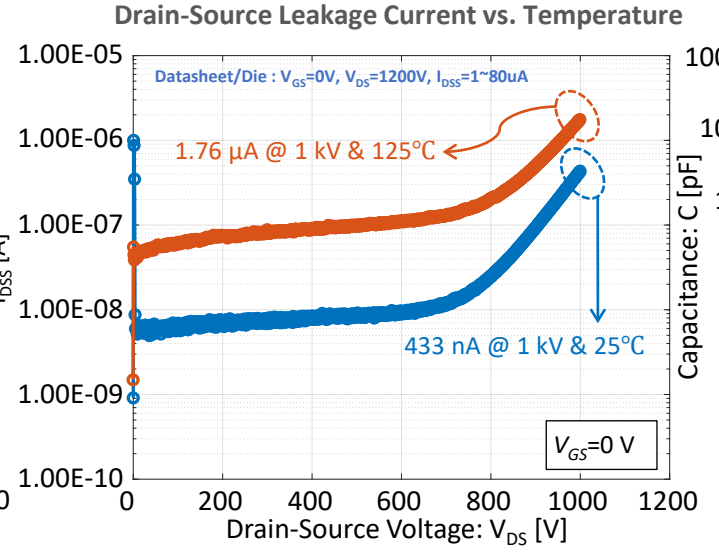
Drain-source voltage @25°C	1200 V	
Gate threshold voltage @25°C	4.1 V~4.2 V @I_D=36 mA	
Drain-source on-state resistance @25°C	3 mΩ~5 mΩ	
Drain-source leakage current @25°C	<1 uA @V_{DS}=1 kV	
Input capacitance	30 nF	V_{GS}=0 V V_{DC}=800 V f=100 kHz V_{AC}=25 mV
Output capacitance	960 pF	
Reverse transfer capacitance	20 pF	

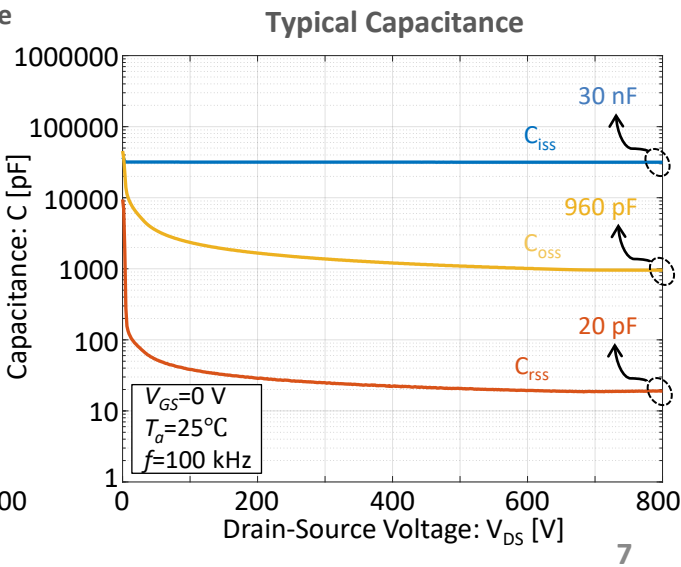






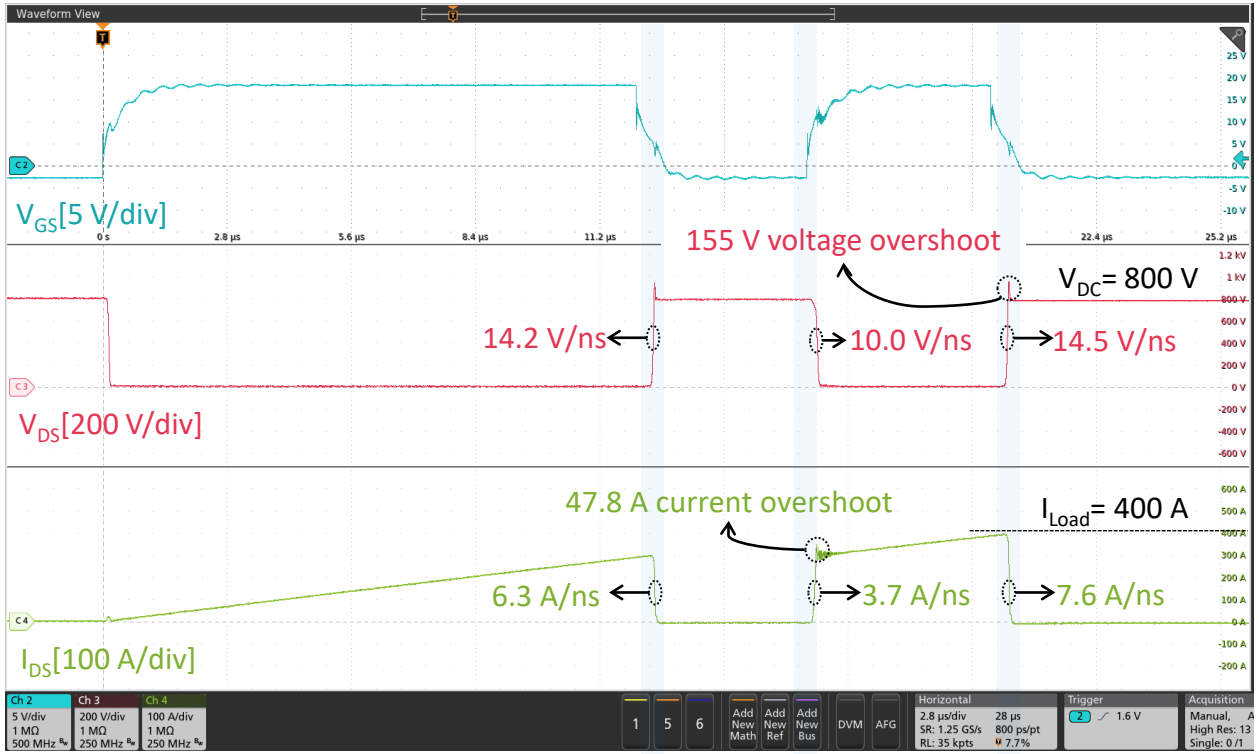






Typical Dynamic Performance of Modules (1)

Example Waveform of LS: 800 V, 400 A, 5 Ω, 25℃

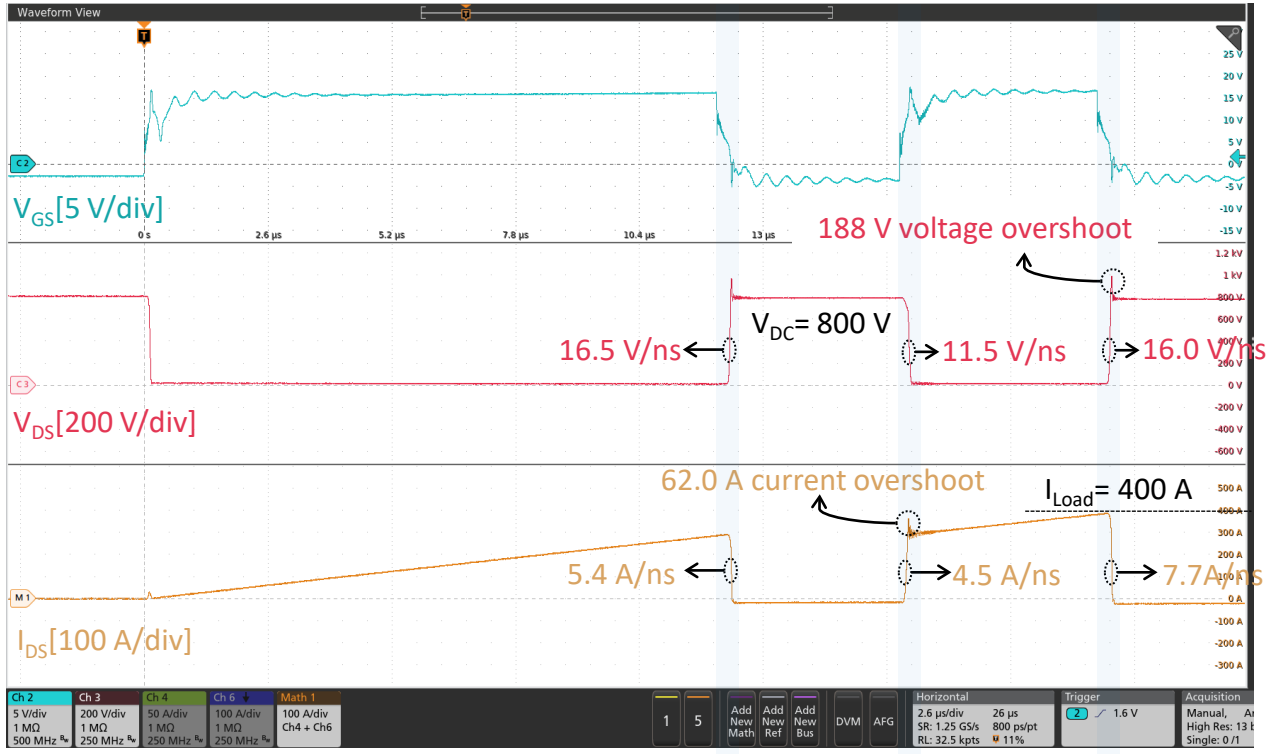


E_{off} @ 300 A= 9.5 mJ

E_{off} @ 400 A= 14.1 mJ

E_{on} @ 300 A= 14.4 mJ

Example Waveform of HS: 800 V, 400 A, 5 Ω, 25℃

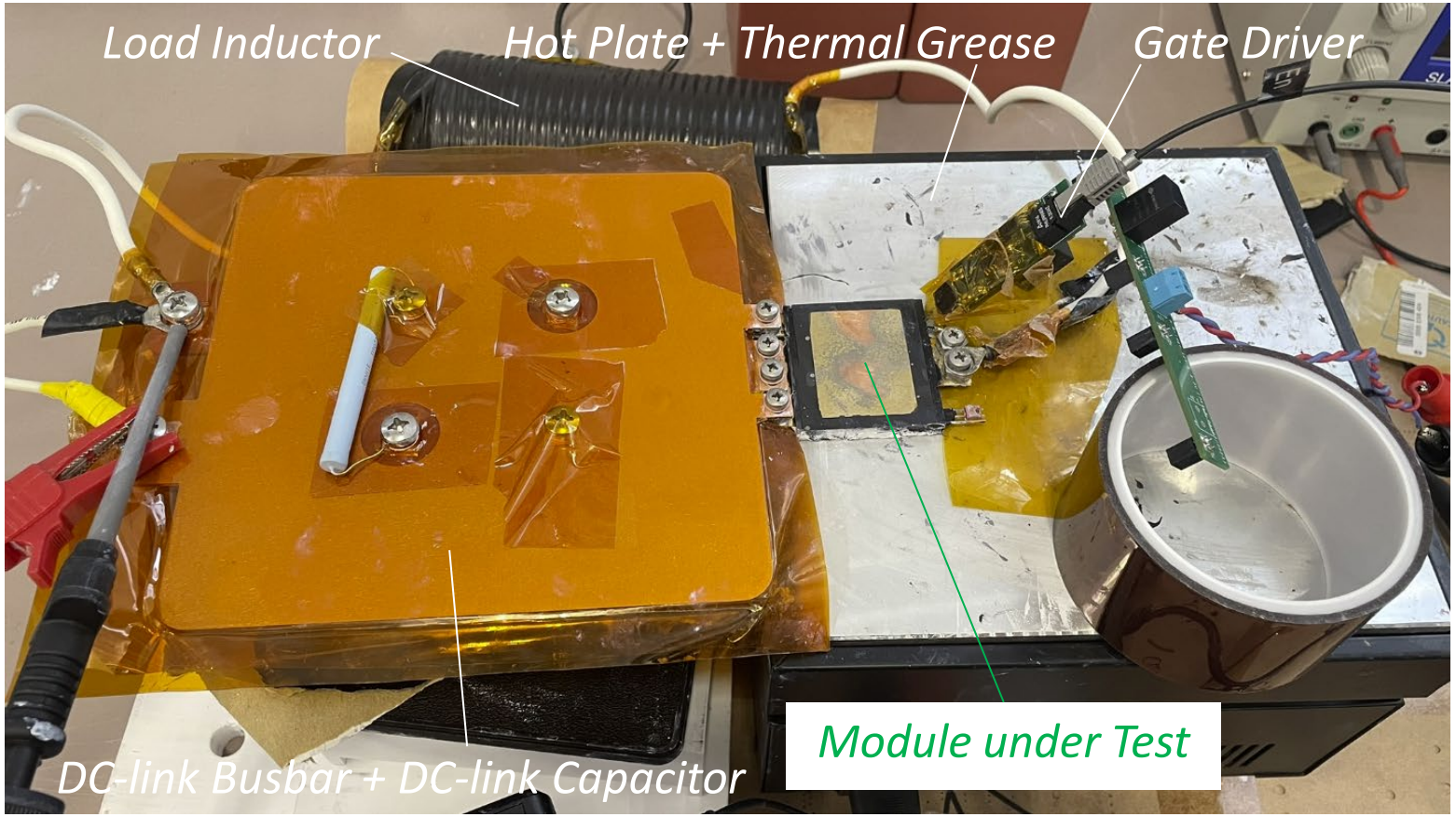


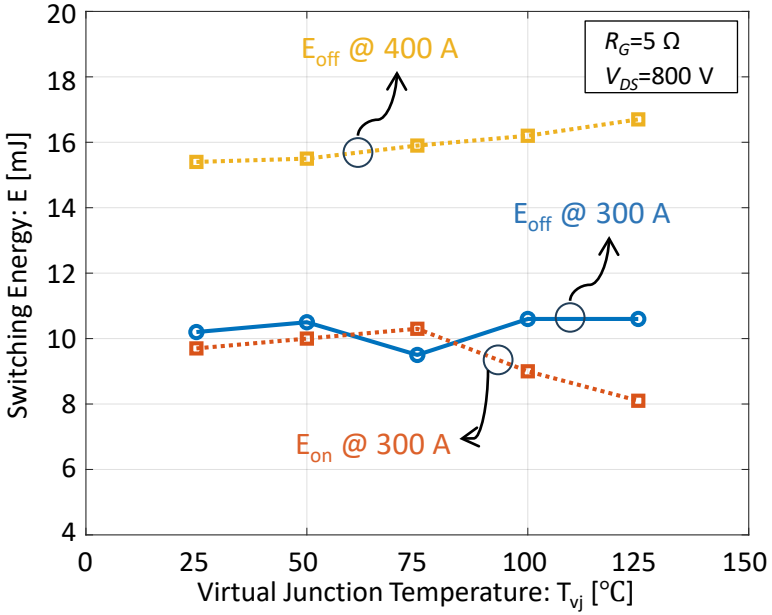
E_{off} @ 300 A= 7.7 mJ

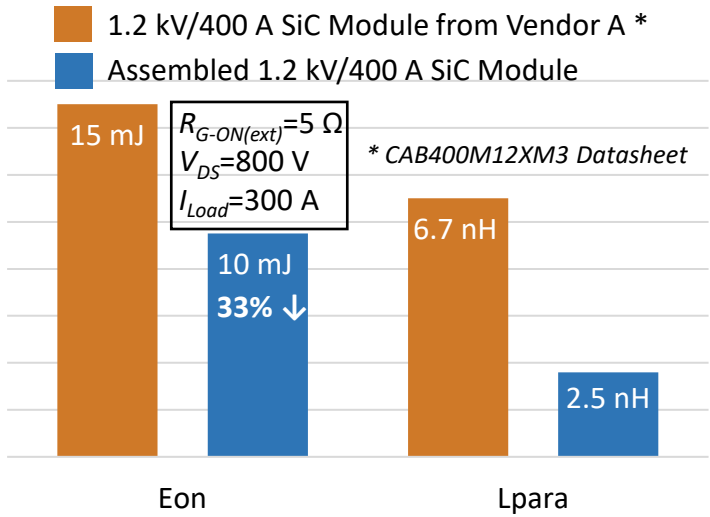
E_{off} @ 400 A= 11.4 mJ

E_{on} @ 300 A= 12.8 mJ

Typical Dynamic Performance of Modules (2)







Designed module packaging structure has the potential to utilize chip capabilities better

For the assembled modules :

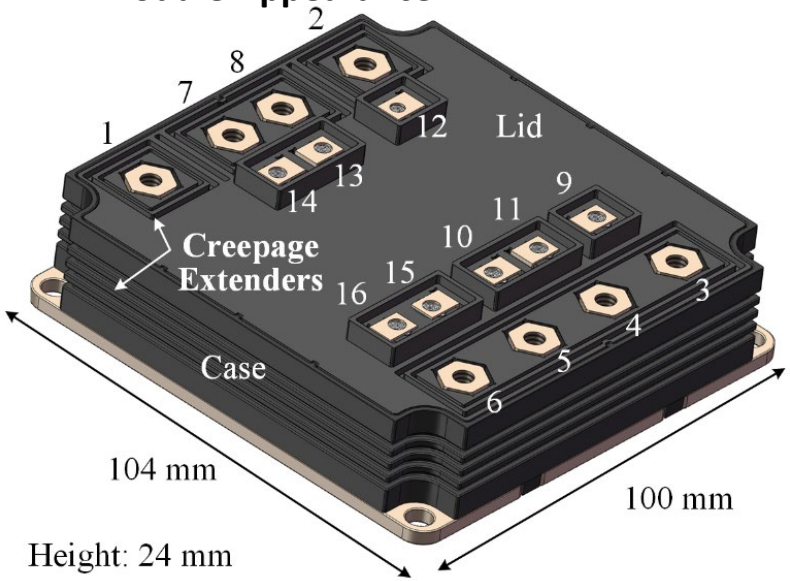
- ***With V_{GS}=-2 V/+ 18 V, L_{load}= 30 µH, $R_{G\text{-}ON\ (ext)}$=$R_{G\text{-}OFF(ext)}$= 5 Ω, the turn-off energy E_{off} and turn-on energy E_{on} show a slight temperature dependency over the entire temperature range***

3.3 kV/200 A SiC Half-Bridge Power Module

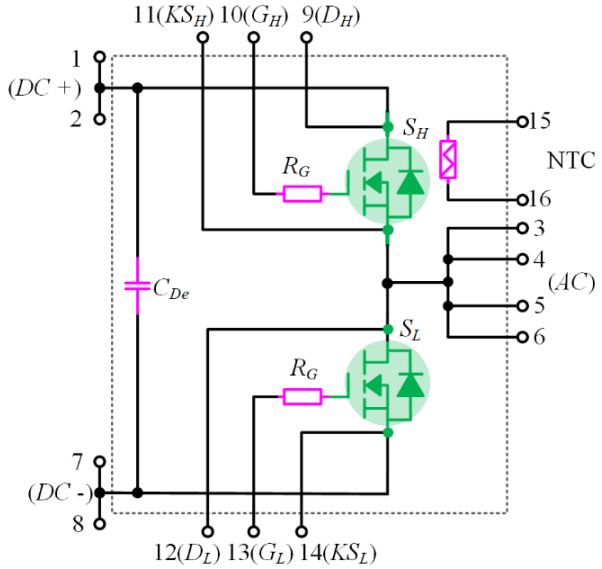
-Pushing Boundaries of Single-Sided Structure with Functional Integration

Functional Integration: Decoupling Caps.

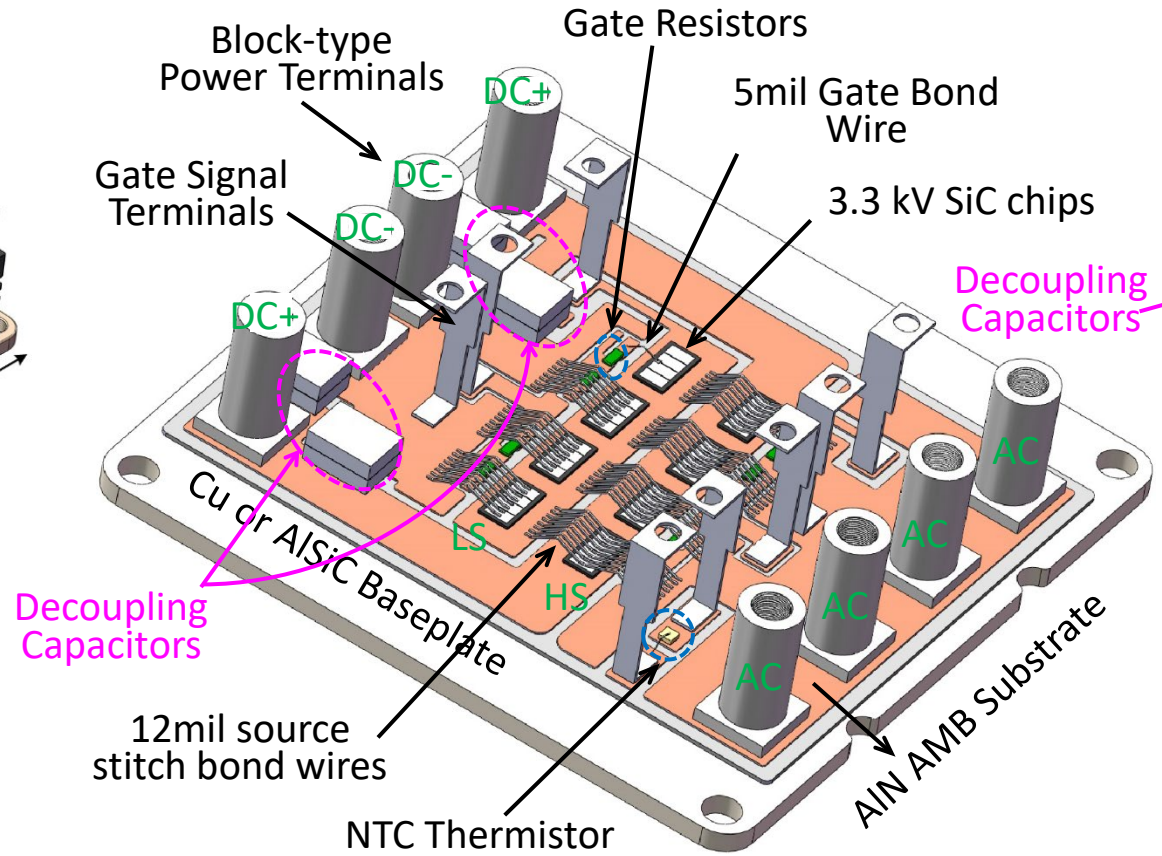
Module Appearance

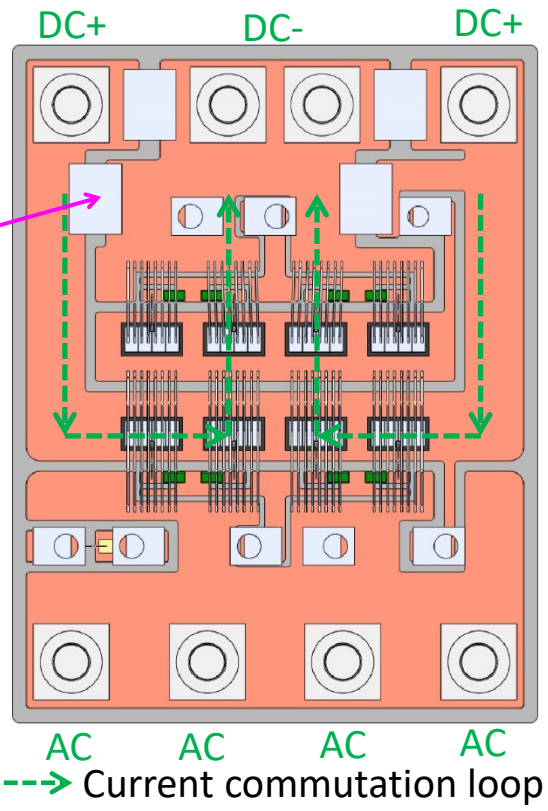


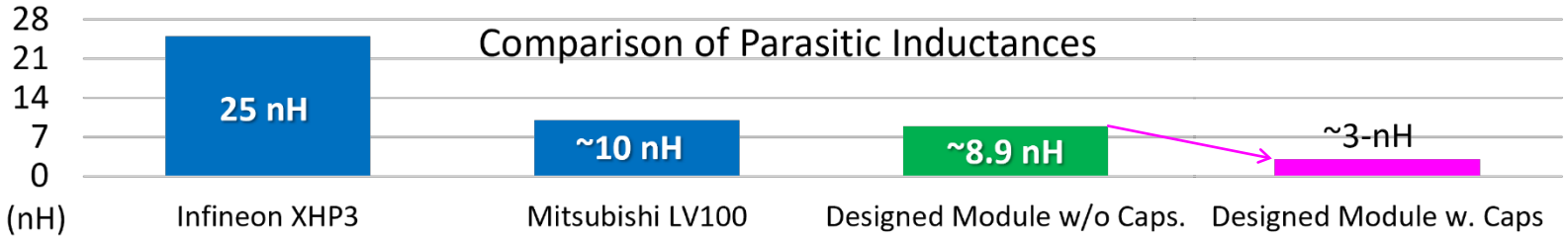
Module Schematic



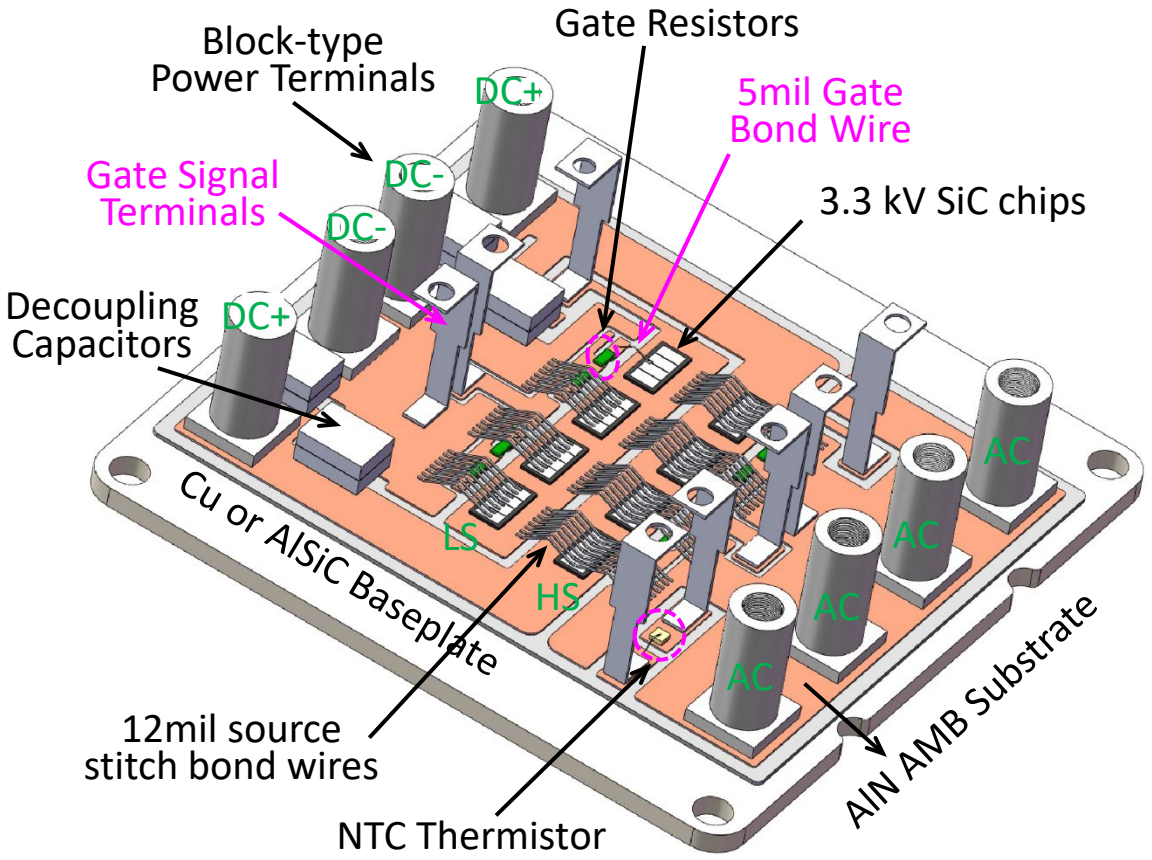
Internal Layout



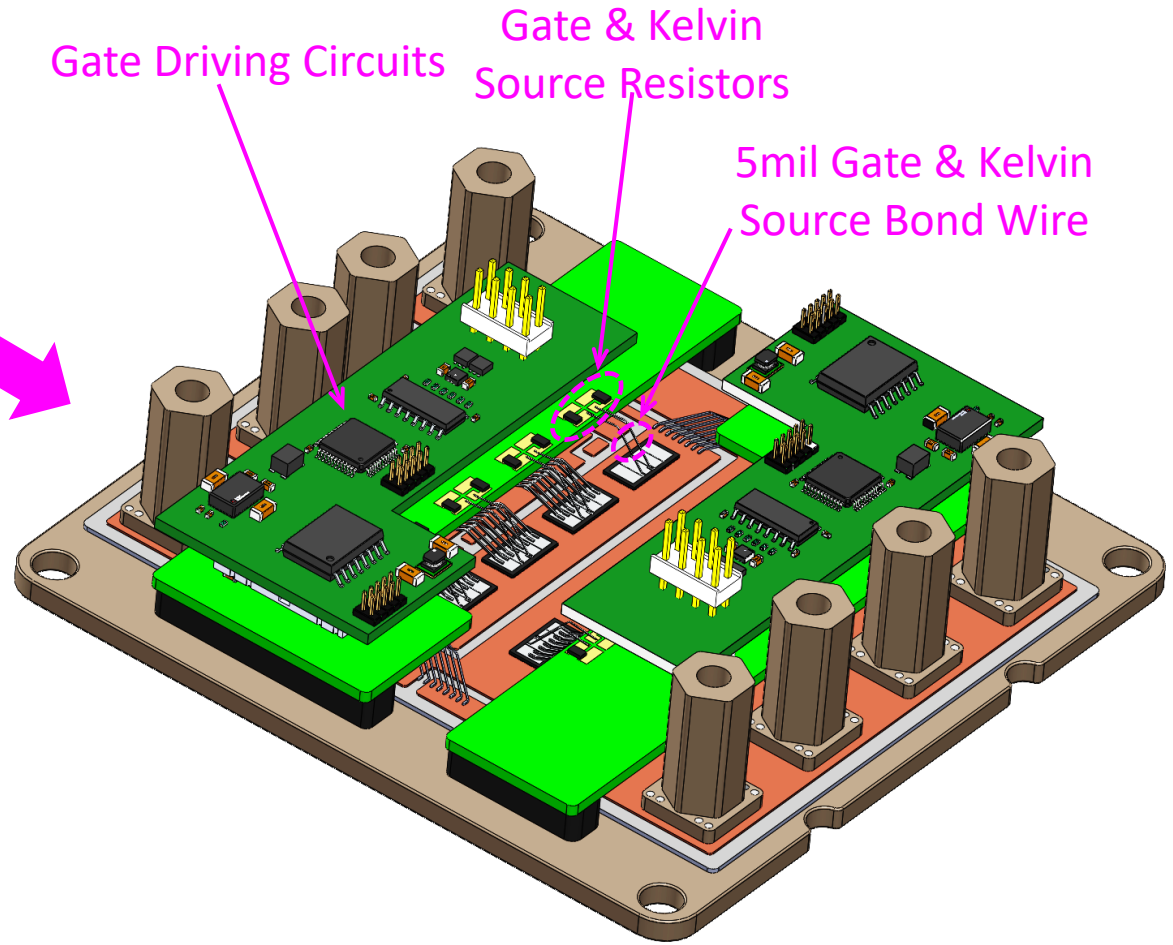




Functional Integration: Gate Drivers



Built-in gate drivers: Minimize gate-loop inductance and Maximize device performance

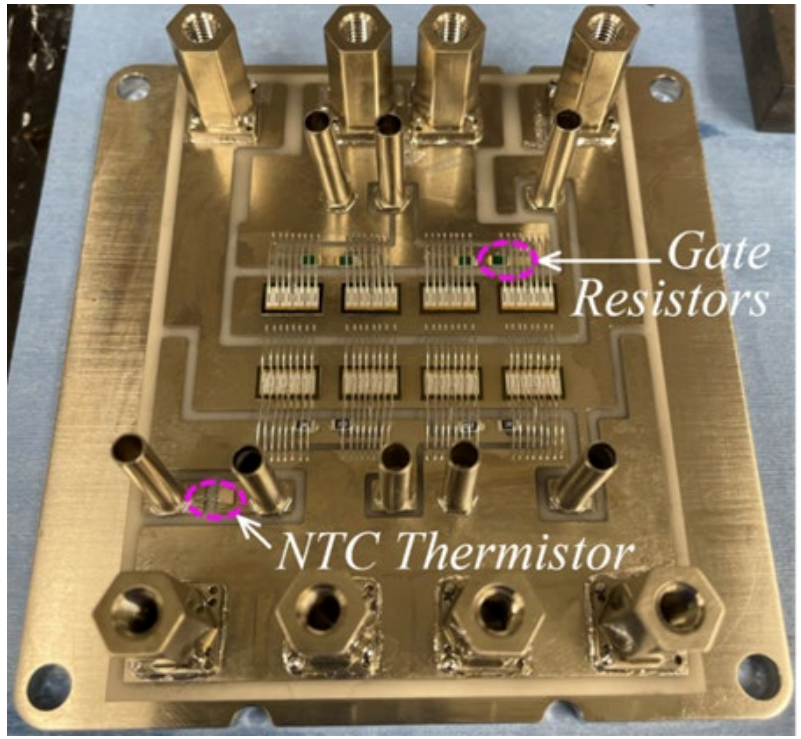


■ **Designed Module Stray Inductances (Q3D)**

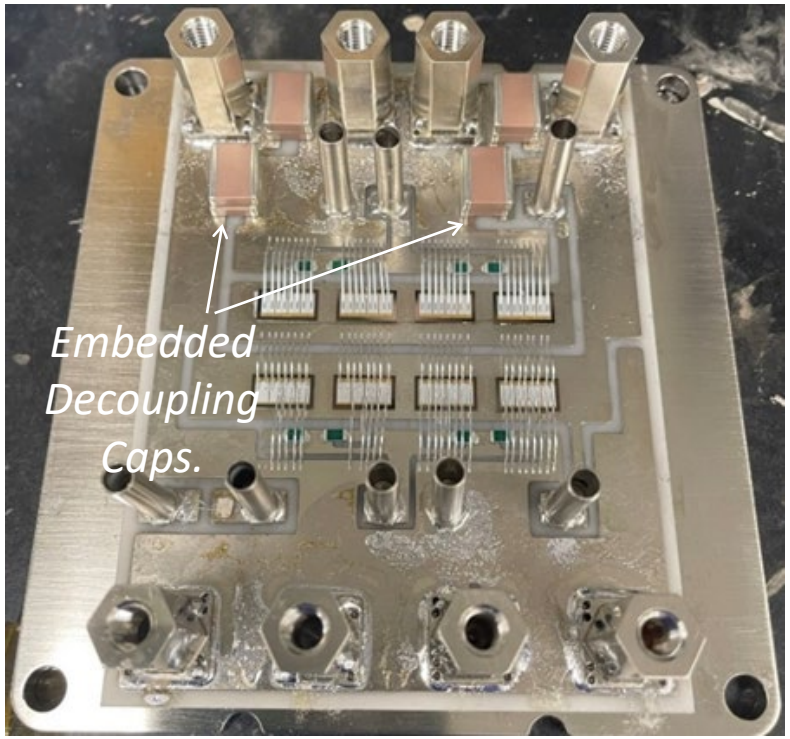
Gate Loop	15 nH
Commutation Loop	8.9 nH w/o decoupling caps. 3 nH w. decoupling caps.

Assembled 3.3 kV/200 A Prototype Modules

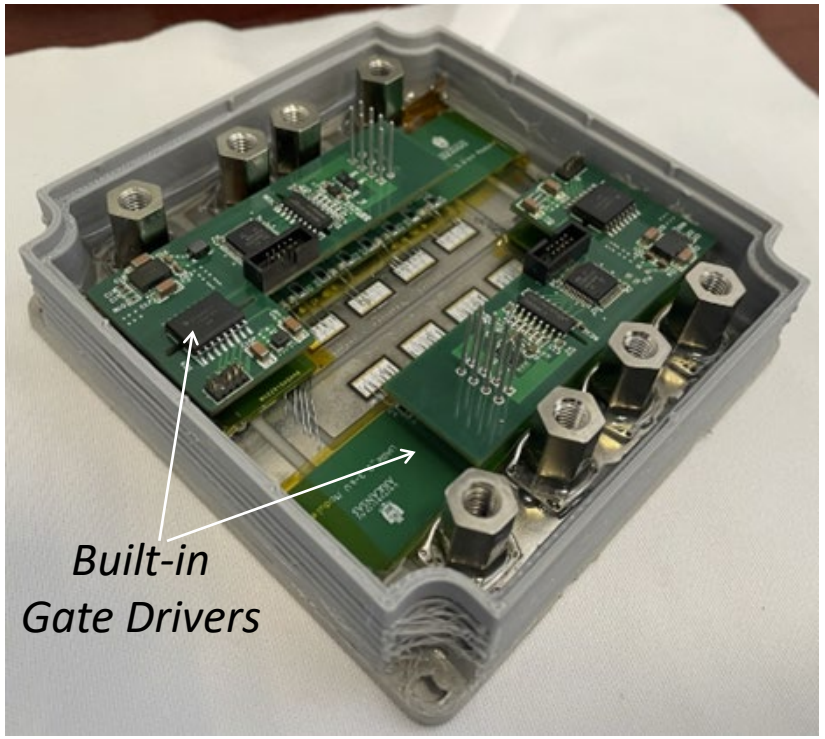
- **Baseline Module**



- **Module with Embedded Caps.**



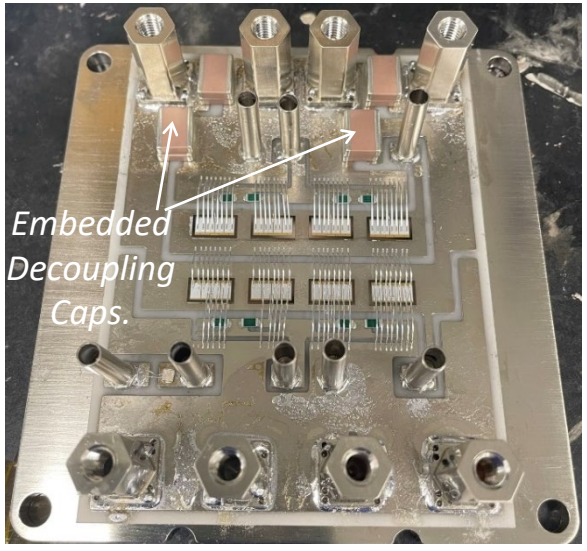
- **Module with Built-in Gate Driver**

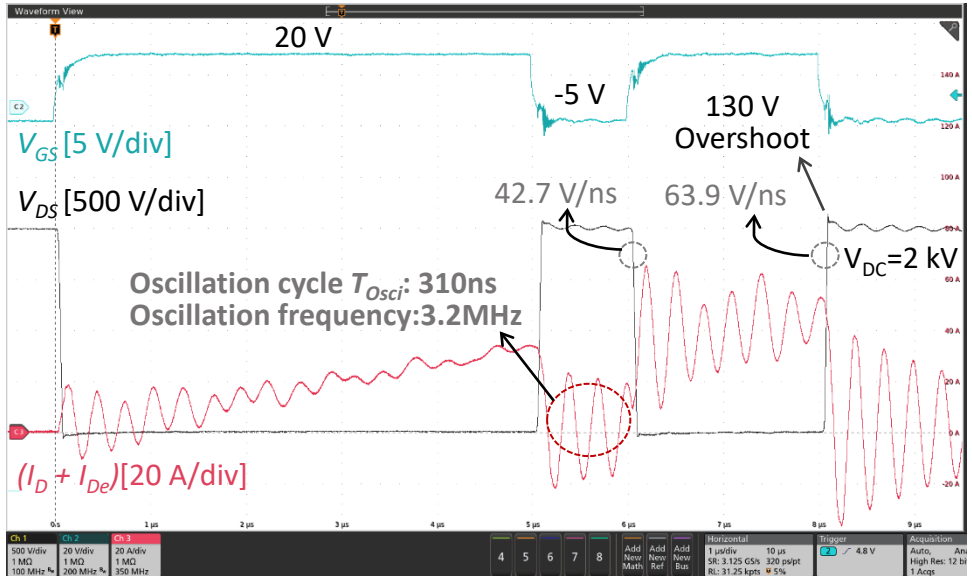


Performance Comparison and Demonstration

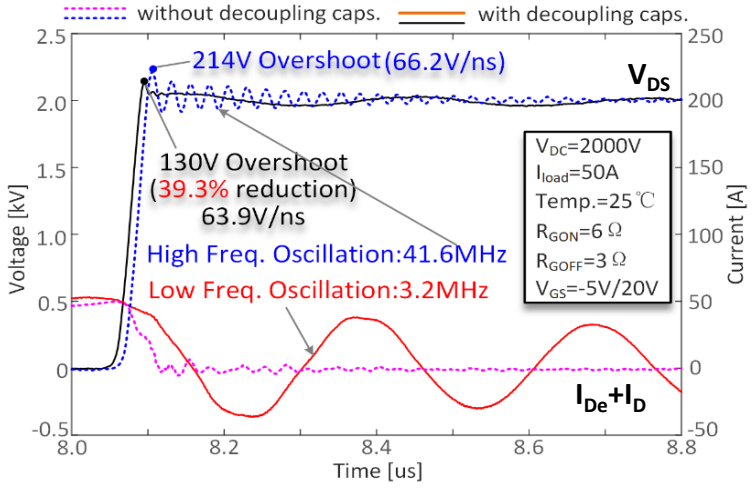
Module with Embedded Decoupling Capacitors

(Example Waveform: 2 kV, 50 A, 25 ℃)





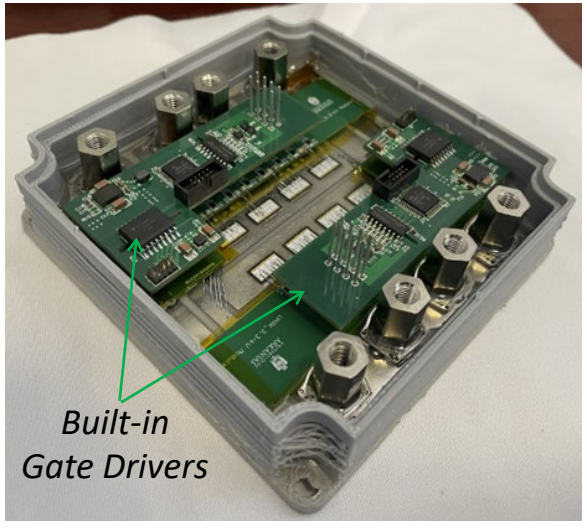
Comparison

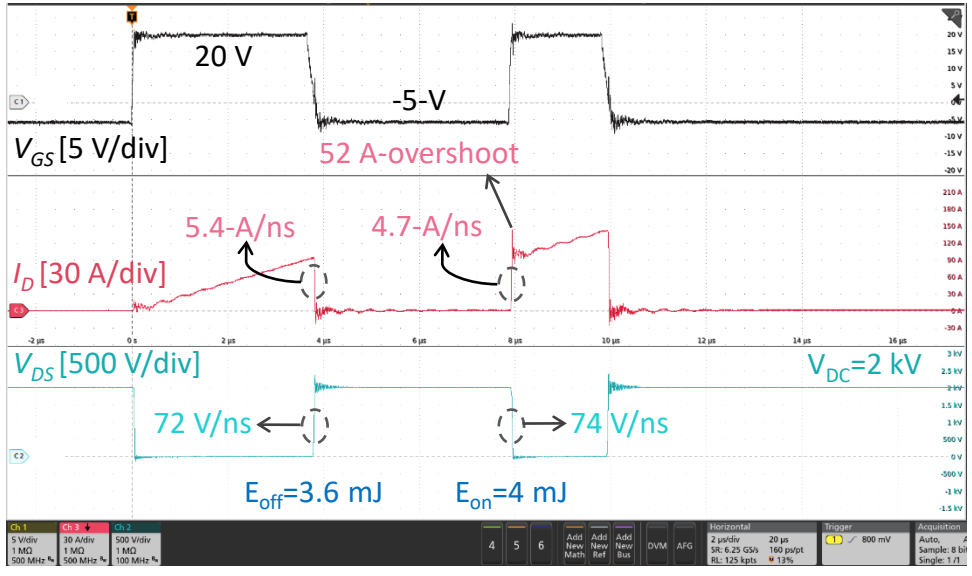


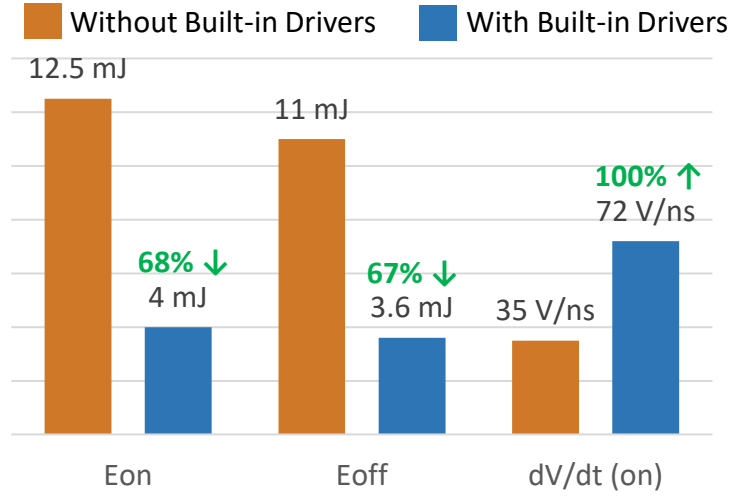
Embedded decoupling Caps.: Suppress voltage overshoot, difficult to directly measure the current flow through chips

Module with Built-in Gate Drivers

(Example Waveform: 2 kV, 150 A, 25 ℃)







Built-in gate driver: can maximize device performance

Conclusions

- More research should be extended from WBG device technology to **WBG power module packaging development**, encompassing all necessary technologies and supply steps along the value chain of WBG power electronics.
- To **maximize** SiC device performance,
  - **Advanced structures**: wire bondless, double-sided cooled…
  - **Functional integration** to push the boundaries of traditional single sided structures

Thank you !