P / O / E / T / S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

DBC-based Embedded Micro-channel cooler for the High-Power Density Power Module

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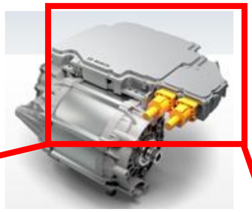
Topics covered in the presentation

- Overview of the state-of-art cooling for the power modules.
- The thermal design of the embedded micro cooler.
- The electrical design of the 6-in-1 double-sided power module.

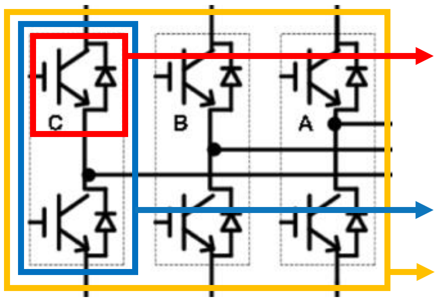
The inverter for the DC-AC conversion

Ford Mustang Mach-E Drivetrain

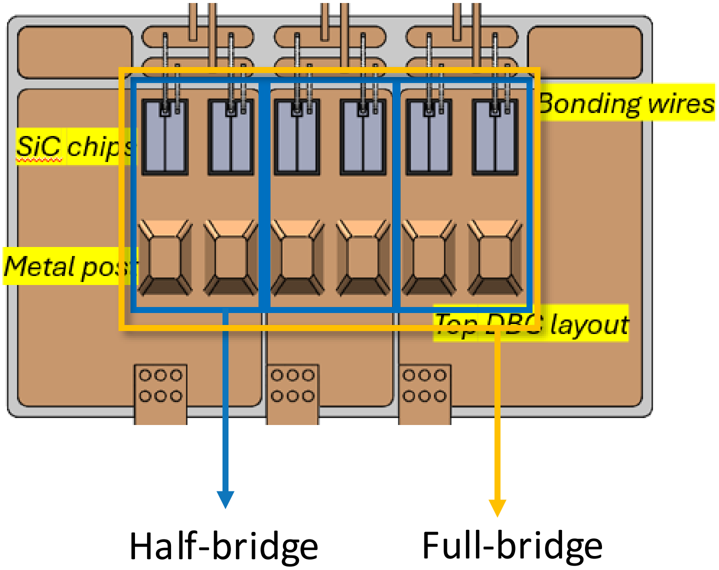
The motor is controlled by an inverter



The circuit diagram of a traction inverter



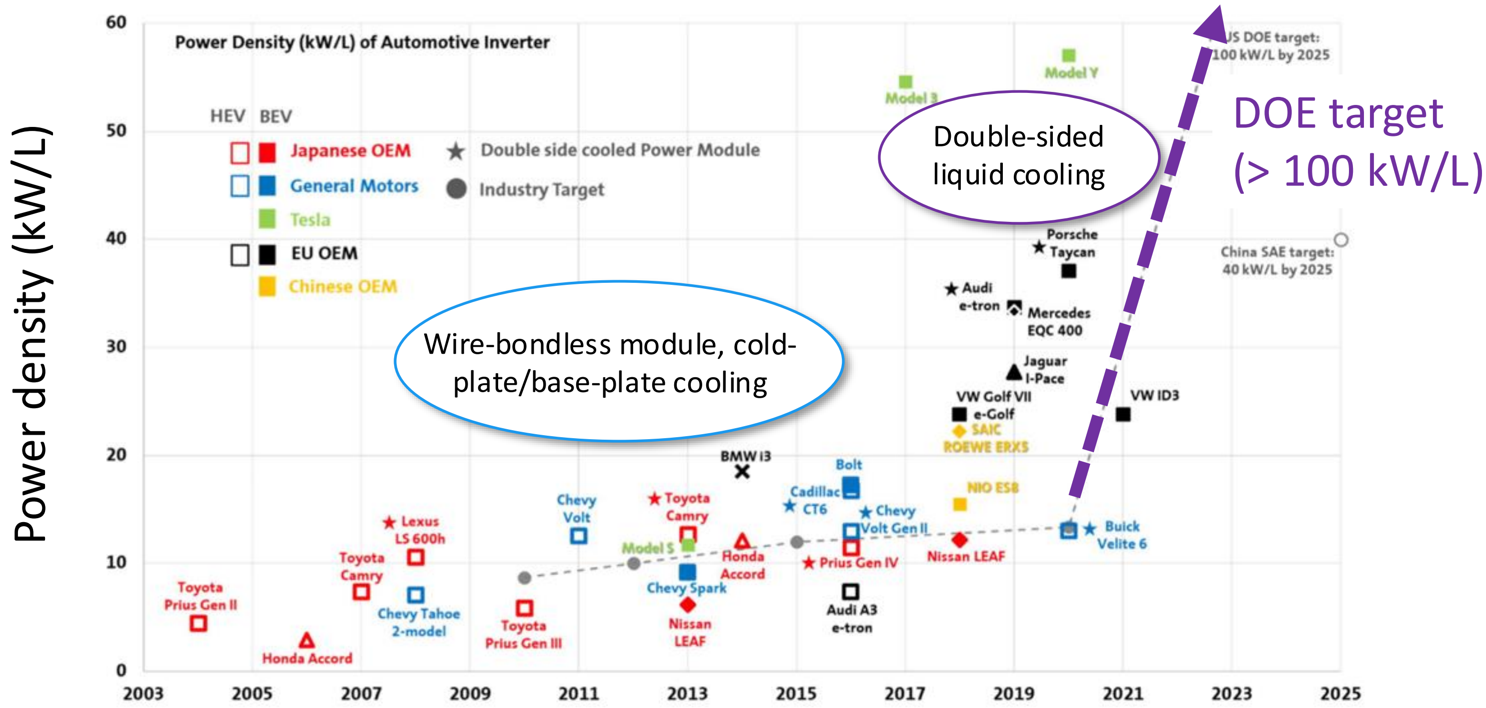
6-in-1 power module for a compact motor drive design



- Power modules are critical in **DC - AC conversion** in motor driver and traction inverter.
- The compact package design increases power density and efficiency.

https://www.bosch-mobility.com/en/solutions/electric-motors/electric-drive-module/
M. Liu et al., "Comprehensive Review and State of Development of Double-Sided Cooled Package Technology for Automotive Power Modules," IEEE Open J. Power Electron., 2022.

Forecast of the power density of the modules



M. Liu et al., IEEE Open J. Power Electron., 2022

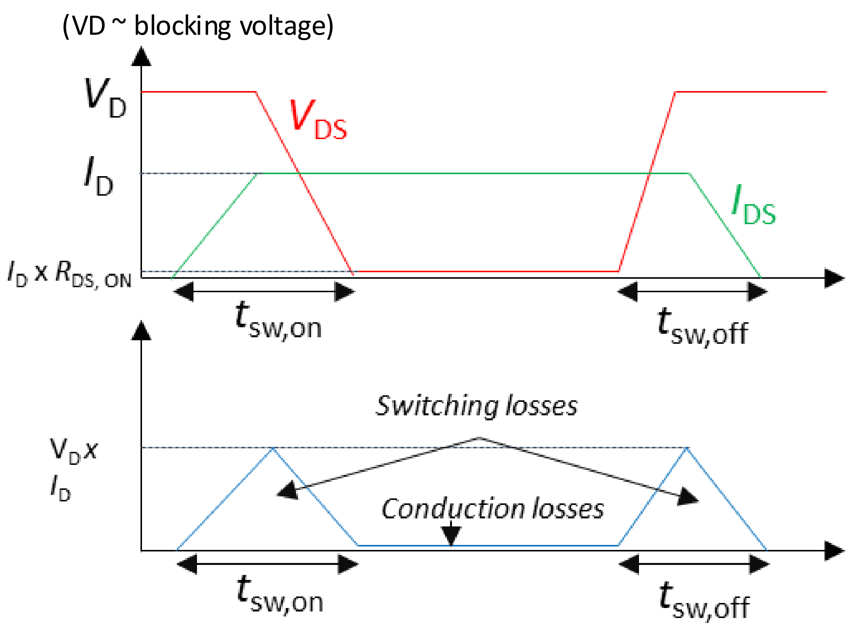
The growth of EV industry is the driving force for the power module development:

- The overall goal is to lower the energy consumption/loss by increasing the power density.
- The compact design for downsizing the package.
- Double-side design for lower inductance and better thermal management.

M. Liu et al., "Comprehensive Review and State of Development of Double-Sided Cooled Package Technology for Automotive Power Modules," *IEEE Open J. Power Electron.*, 2022.

Losses in power semiconductors

- The power losses in the power semiconductors include:
  - ○ **Switching losses** occur when the device switches from ON-state to OFF and vice-versa
  - ○ **Conduction losses** occur during ON-state of the device.



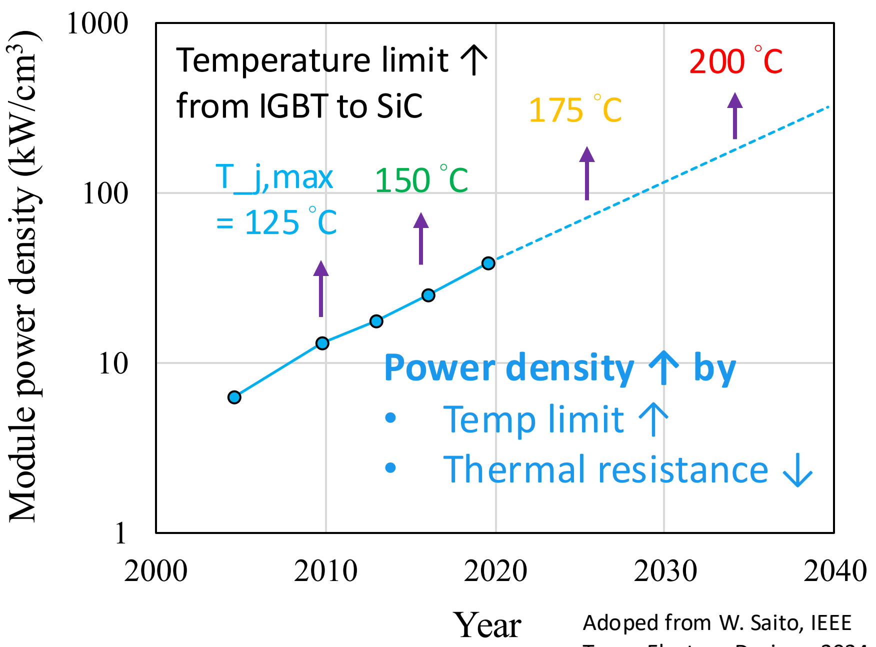
A simplified representation of MOSFET losses

- A good thermal design ensures a selection of heat sink which allows following:
  - ○ It dissipates the device losses into the ambient;
  - ○ It keeps the **junction temperature of the device within the limits** under all operating conditions.

Motivation of improved thermal management

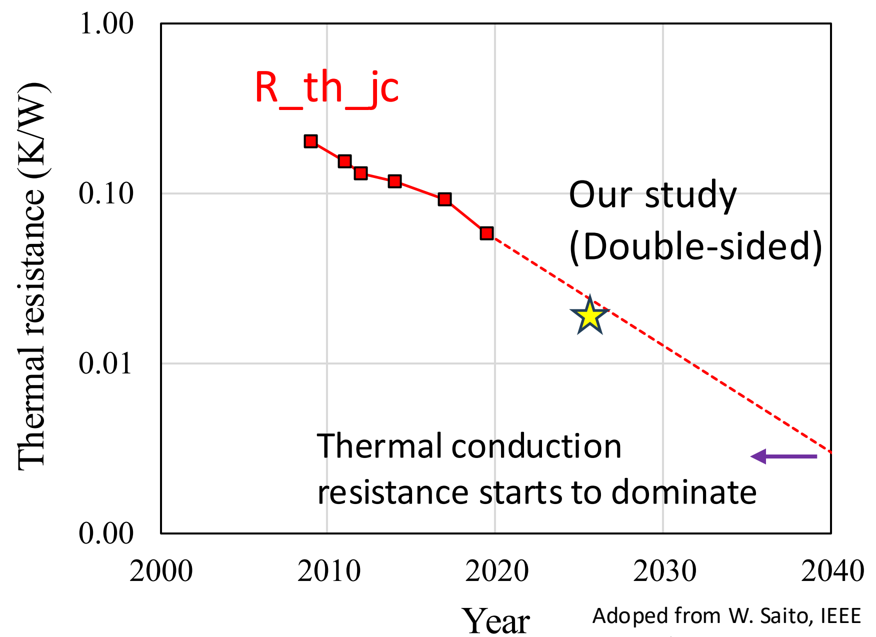
- The **performance (power density)** is limited by the thermal management of the module

Power density limit of a module



Adoped from W. Saito, IEEE Trans. Electron Devices, 2024.

Projection of thermal resistance



Adoped from W. Saito, IEEE Trans. Electron Devices, 2024.

Factors that limit the power density increase:

- Device temperature limit (Thermal budget dT = T_j,max – T_in).
- Thermal resistance (dT = R * PWR).
- Higher device temperature limit and lower thermal resistance contribute to higher power density.

W. Saito, "A Future Outlook of Power Devices from the Viewpoint of Power Electronics Trends," *IEEE Trans. Electron Devices*, 2024.

S. Jones-Jackson, et al, "Overview of Current Thermal Management of Automotive Power Electronics for Traction Purposes and Future Directions," *IEEE Trans. Transp. Electrif.*, 2022

Thermal-related failure of the power module

- Thermal management is critical to the **reliability** of the power module.

The common failure modes and mechanism of the power module

Component	**Failure**	**Location**	**Reason**
Power devices (chips) ***- Most relevant to today's talk***	Cracking	Bond wires heel/ Die/Ceramic layer	**Thermal stress**/brittle material
	Metallization reconstruction	Die connecting pad/ Bond wire	Stress during **thermal cycling**
	Delamination	Bond layers/ Solder layers	Accumulated strain during **thermal cycling**
Busbar	Corrosion	Copper layer	Surface **oxidation at high temperature**
	Loosened joints	Joint	Thermal strains
Capacitance of the module	De-rating of the capacitance	The entire module package	**Change of material properties** such as dielectric constant at high temperature.

Table is adopted from:
S. Jones-Jackson, et al, "Overview of Current Thermal Management of Automotive Power Electronics for Traction Purposes and Future Directions," IEEE Trans. Transp. Electrif., 2022

Power module - Single sided cooling

Nissan Leaf BEV Inverter

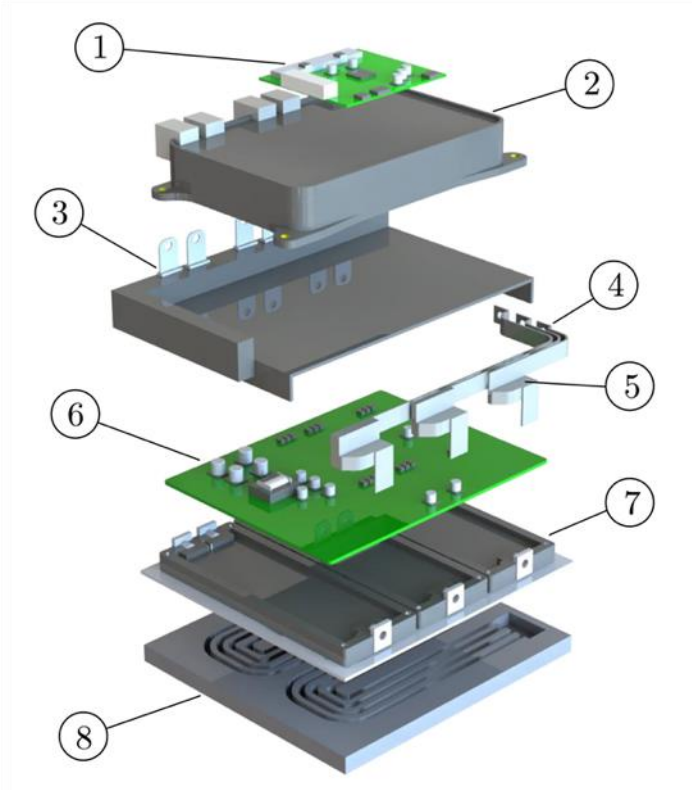
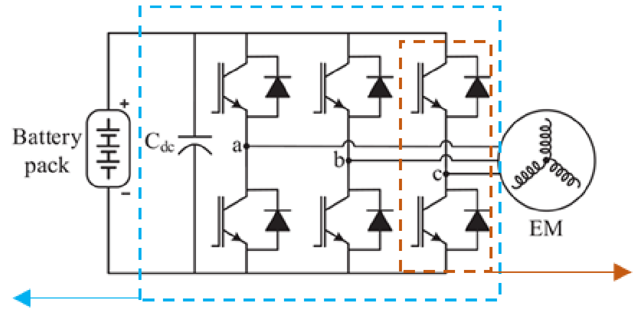


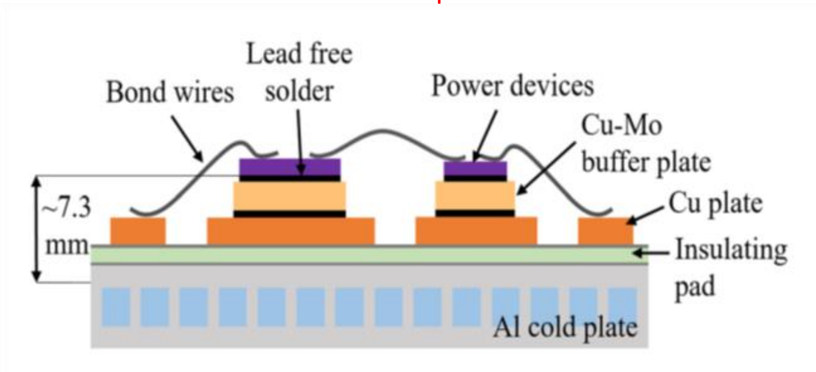
Fig. 4. Nissan LEAF inverter components [53]: 1) Control board. 2) DC-link capacitor. 3) DC-link busbar. 4) Phase busbars. 5) Current sensor. 6) Gate driver board. 7) IGBT power modules. 8) Serpentine heat sink.

Source: Reimers et al., Automotive Traction Inverters: Current Status And Future Trends, IEEE Transactions On Vehicular Technology, Vol. 68, No. 4, April 2019



Half-bridge Power Module

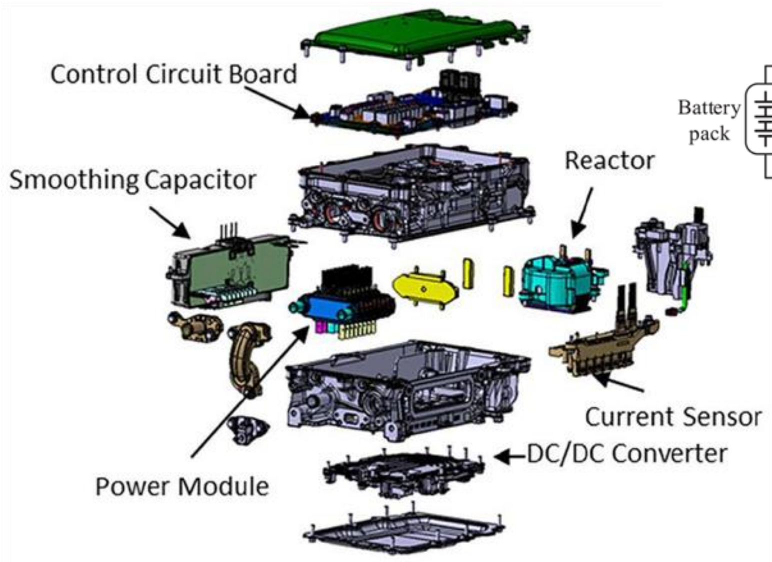
Thermal Stack-up

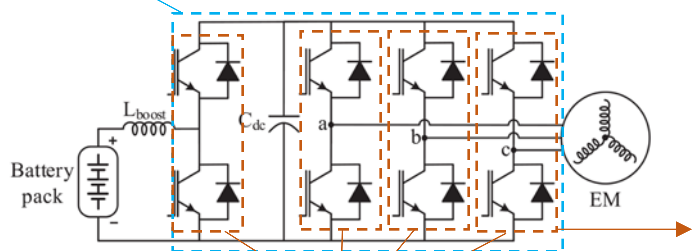


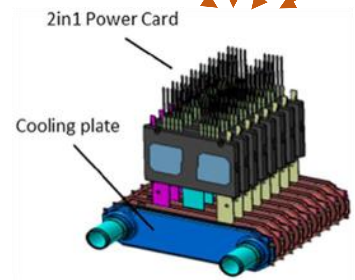
Source: Broughton et al., "Review of Thermal Packaging Technologies for Automotive Power Electronics for Traction Purposes", ASME J. Electron. Packag, 140(4), 040801 (11 pages), 2018

Power module - Double sided cooling

Toyota Inverter for Hybrid Vehicles



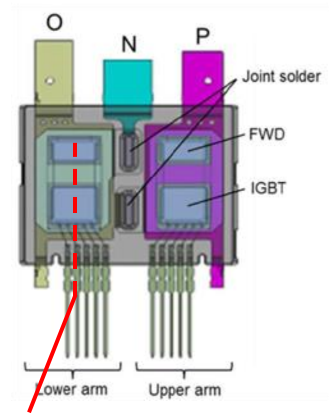




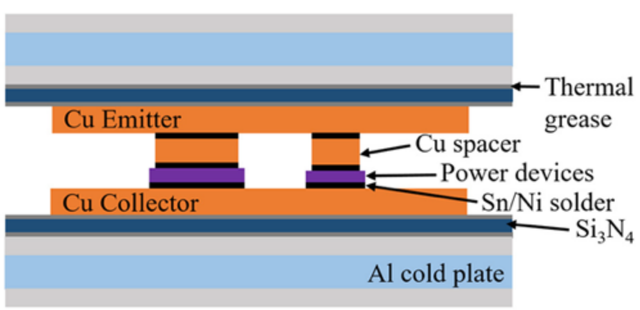
Power Module

Ikeyama et al., “Development of Power Control Unit for Compact-Class Vehicle,” SAE Technical Paper 2020-01-0456, 2020

Power Card



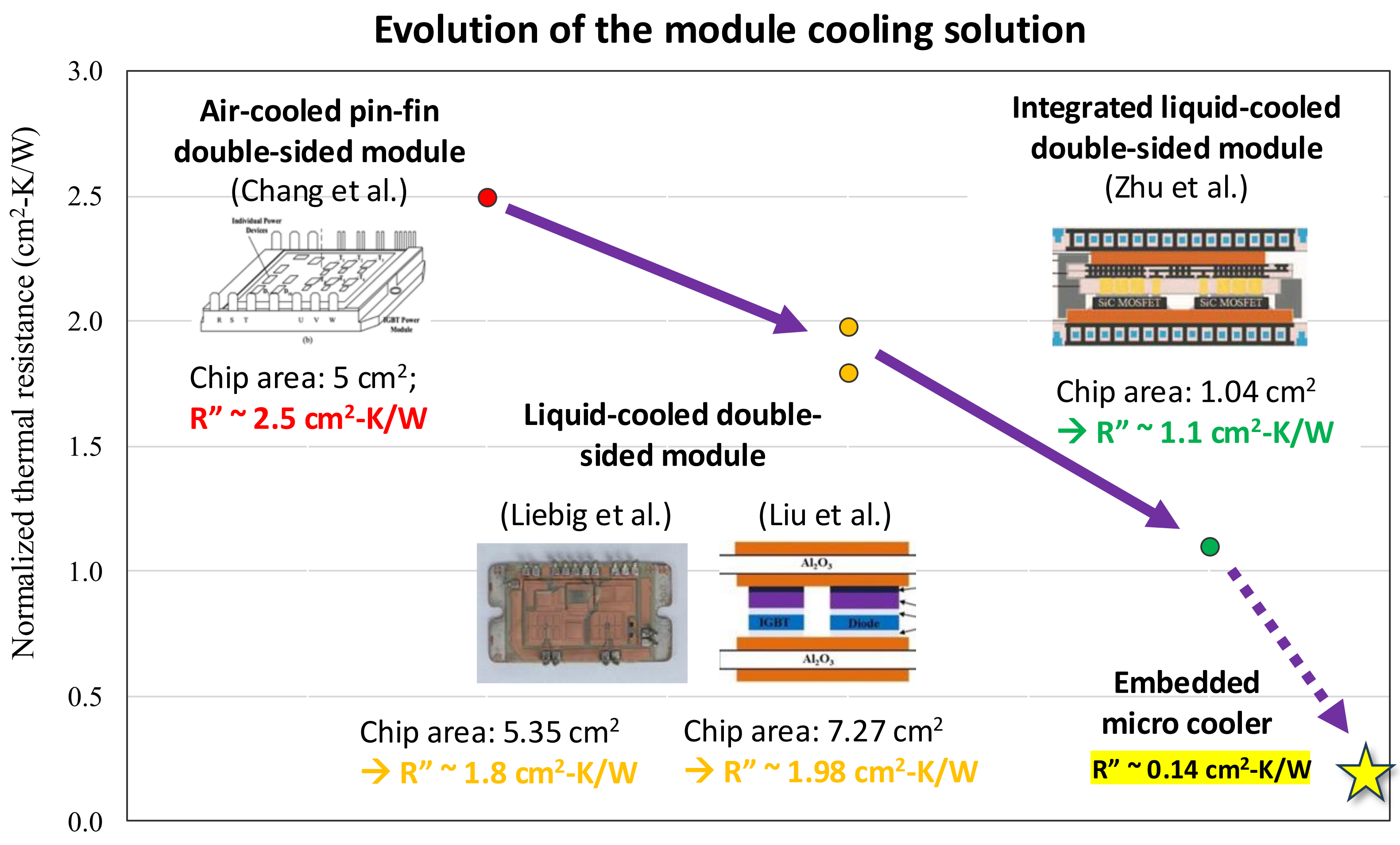
Thermal Stack-up



- Double-side design for lower inductance and better thermal management.

Source: Broughton et al., “Review of Thermal Packaging Technologies for Automotive Power Electronics for Traction Purposes”, ASME J. Electron. Packag, 140(4), 040801 (11 pages), 2018

Comparison of the double-sided cooling solutions



- **Thermal impedance** (specific thermal resistance in unit cm^2-K/W) is shown.

J. Chang and C. Liao, "Novel dual-side thermal interfacing of IPM for elevated-temperature applications," *Conf. Rec. - IAS Annu. Meet. IEEE Ind. Appl. Soc.*,, 2006
S. Liebig, et al., "Evaluation of enhanced power modules with planar interconnection technology for aerospace application," *PCIM Eur. Conf. Proc.*, 2014.
W. Liu, et al., "Design and characterizations of a planar multichip half-bridge power module by pressureless sintering of nanosilver paste," *IEEE J. Emerg. Sel. Top. Power Electron.*, 2019
N. Zhu, et al., "Design and evaluation of press-pack SiC MOSFET," 2016

The double-sided power module with an embedded micro cooler

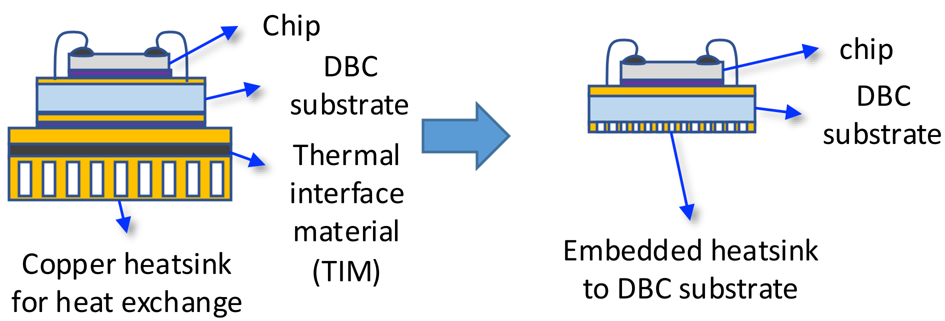
The improved cooling by the embedded micro cooler

Size of the cooling solution per chip

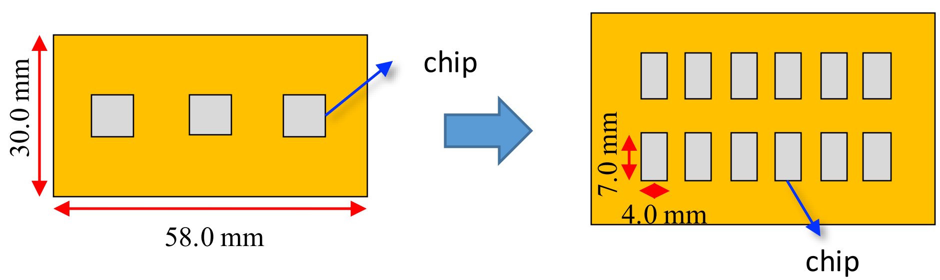
Cold-plate

Embedded micro cooler

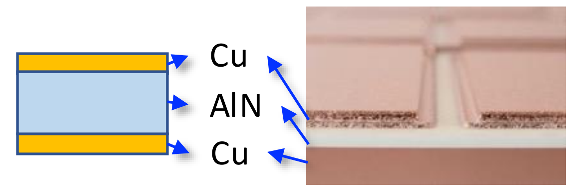
Cross section



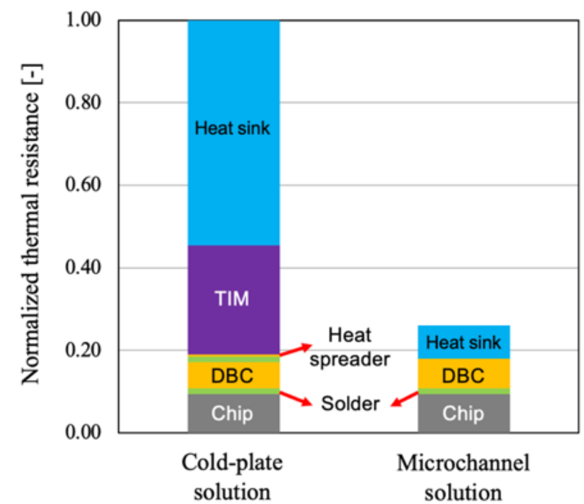
Top view



DBC = Direct Bonded Copper



Comparison of thermal resistance



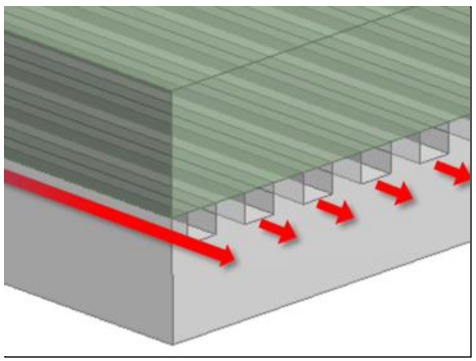
- Decreased thermal resistance because of the elimination of the interface.
- The improved cooling performance enables power module designs with higher power density.

https://www.rogerscorp.com/advanced-electronics-solutions/curamik-ceramic-substrates/curamik-endurance

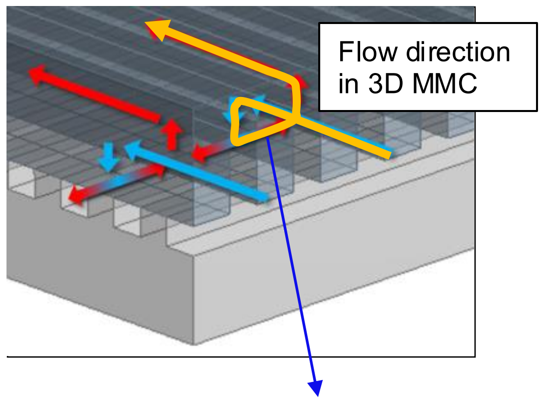
The DBC substrate with an embedded micro cooler (3D MMC)

The DBC substrate with embedded micro cooler

Single-layer
2D microchannel cooler



Two-layer structure
3D microchannel cooler



Shortened coolant traveling distance in the microchannels

Direction of the inlet flow (cold)

Direction of the outlet flow (heated)

Different layers of the power module and 3D MMC

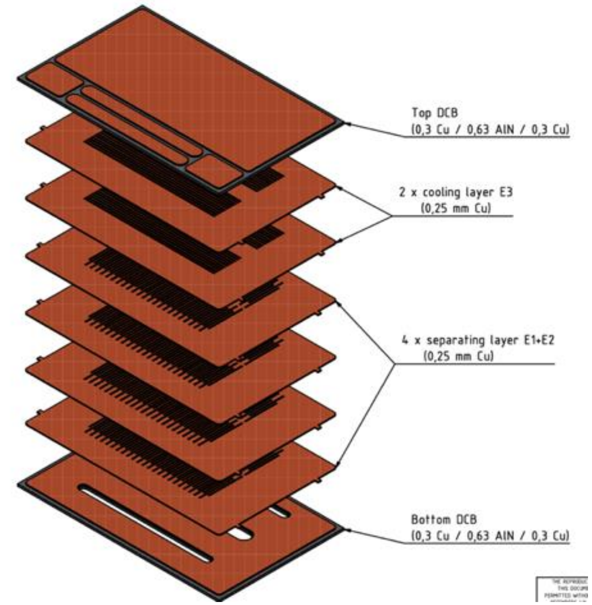
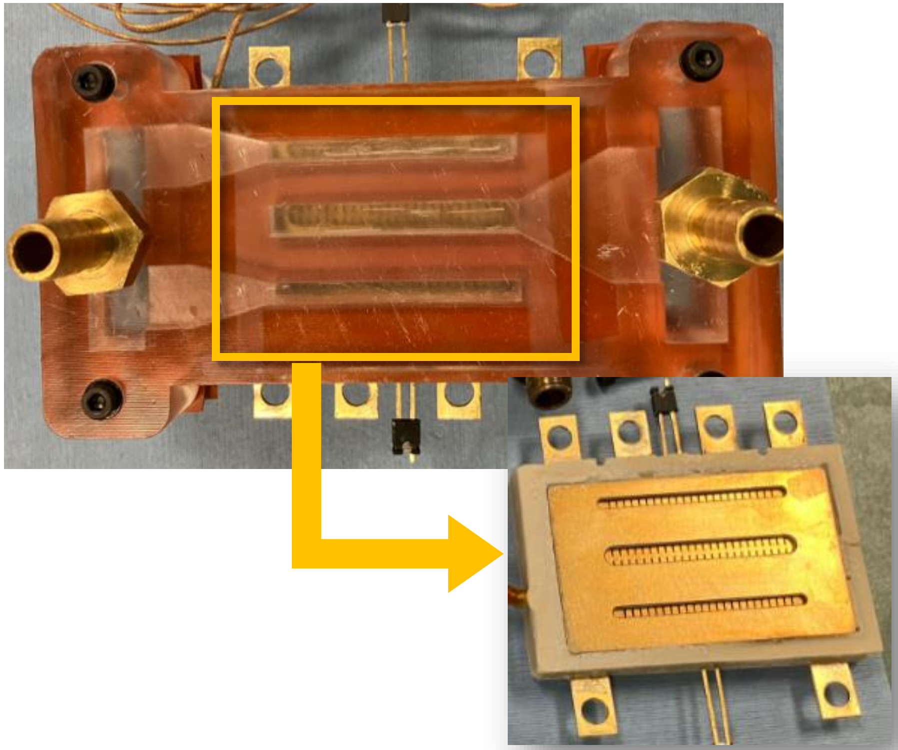


Image credit: Rogers corp

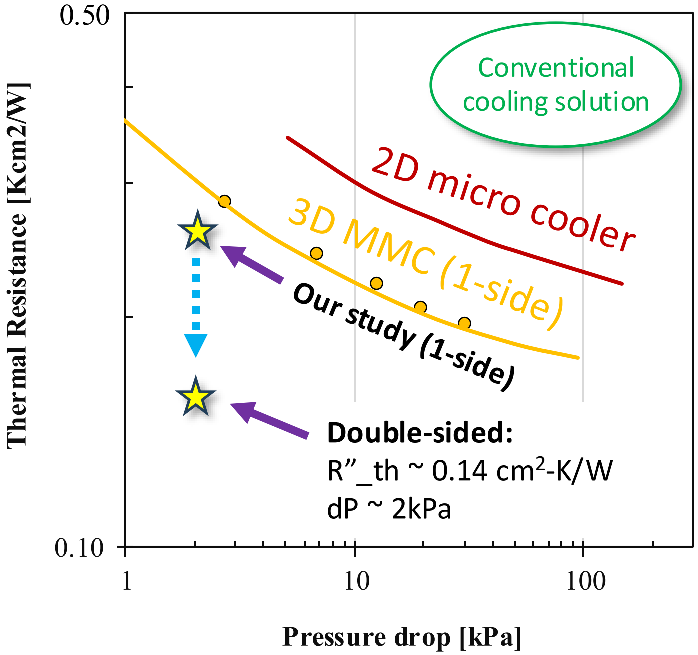
- A layered structure of Cu is used to build the substrate with an embedded 3D MMC.
- The 3D MMC channel network comprises laser-patterned copper sheets.
- The embedded cooler design is compatible to the half-bridge and 6-in-1 module.

Performance characterization of the embedded micro cooler

The double-sided module with embedded cooling

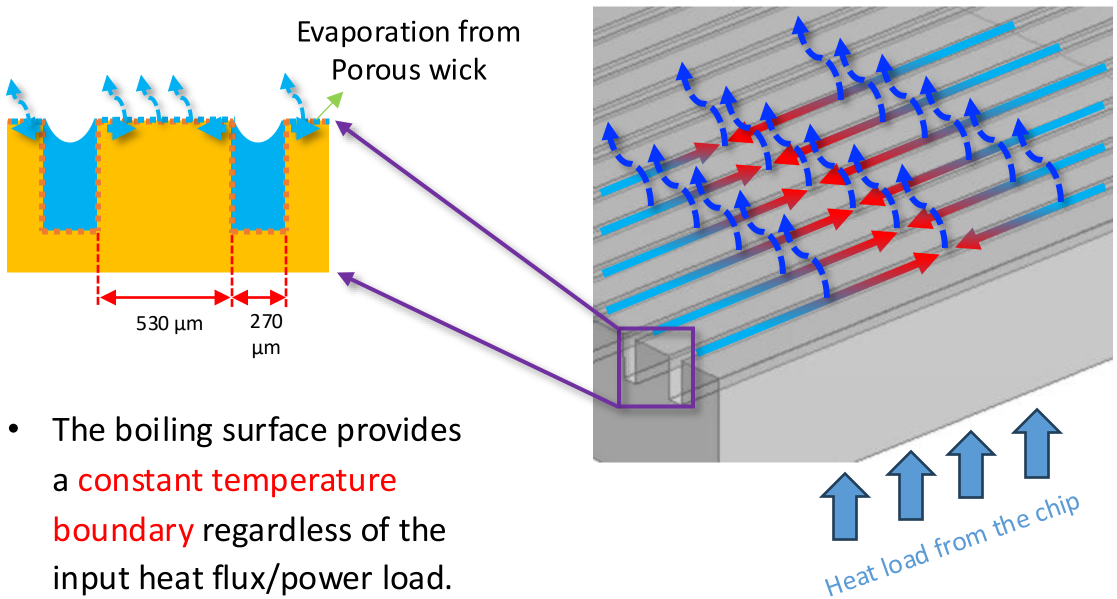


Thermal resistance vs. pressure drop



- The flow rate Q = 0.5 LPM (0.25 LPM on each side) is supplied to the module.
- The characterization includes a body-diode test with different current ratings supplied to the module.
- The thermal resistance R_th ~ 0.5 K/W (R"_th = 0.14 cm^2-K/W) and dP ~2 kPa is achieved.

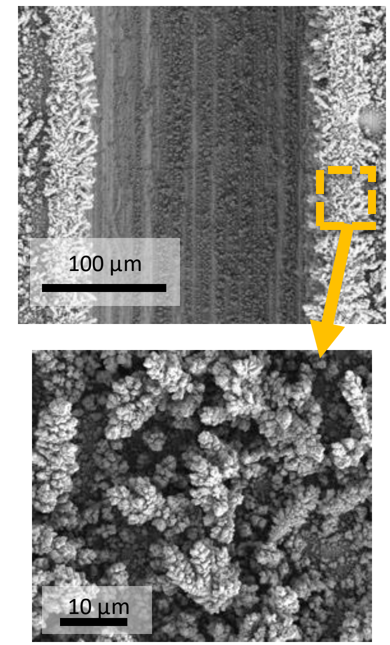
Next step: Two-phase (boiling/evaporation) cooling



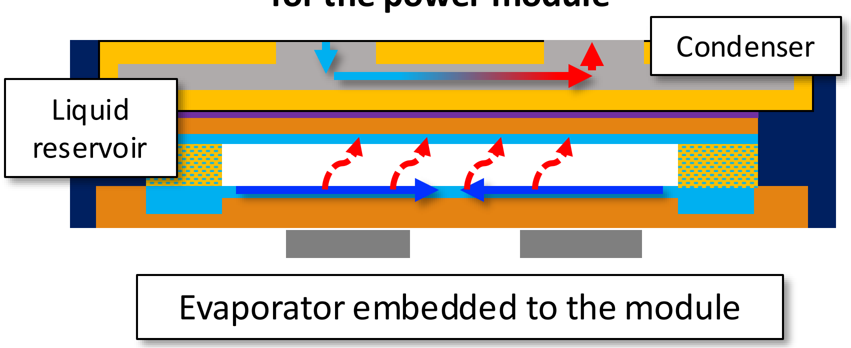
- The boiling surface provides a constant temperature boundary regardless of the input heat flux/power load.

Microchannel with porous wicks

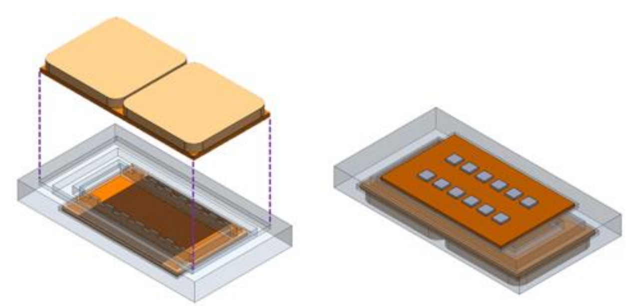
The dendritic Cu porous wicks



The 2-phase cooling package for the power module



The drop-in replacement of the cold plate

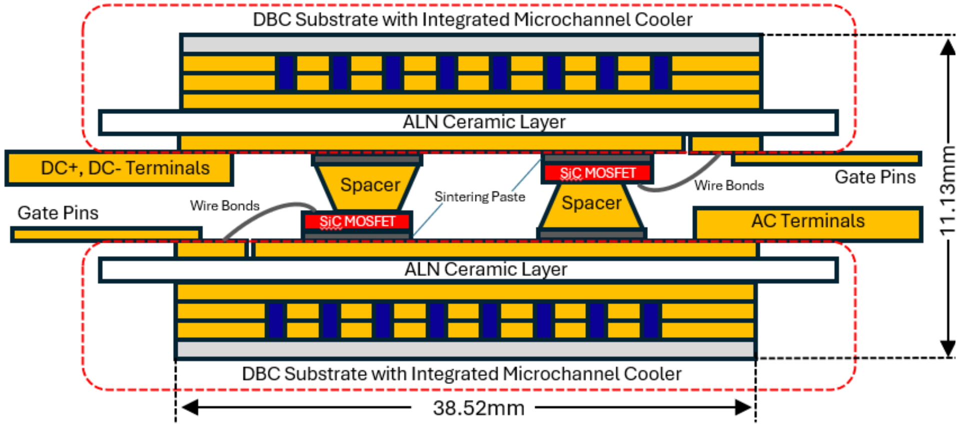


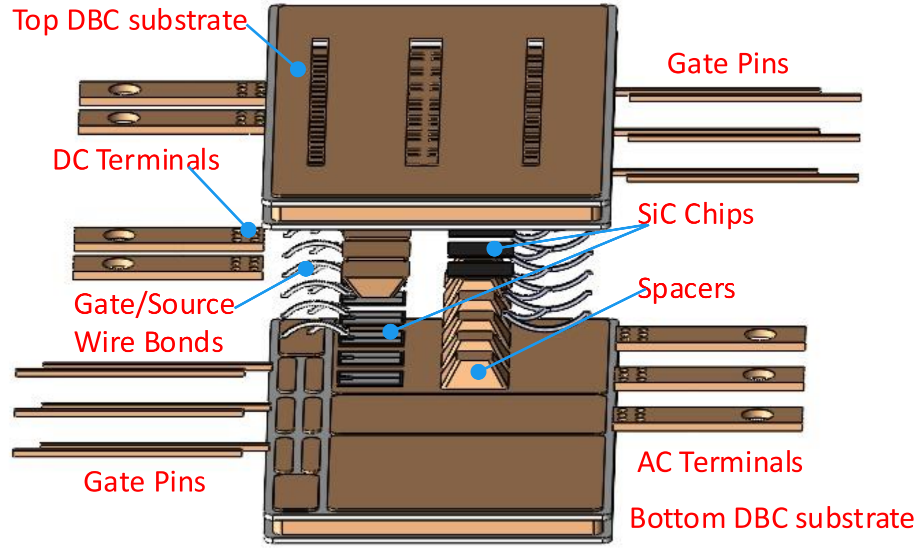
- The design resembles the **vapor chamber**, allowing direct replacement of the current cooling solution.

Details of the double-sided power module design

The Double-sided Module With an Embedded Cooler

Power module cross-section view





Power module exploded view

- 2 topologies: **Half-bridge(6 chips in parallel) and 6-in-1(2 chips in parallel)**
- Double-side structure for **two thermal path**

- 1.2kV blocking voltage for **800V bus voltage** application;
- Laminated busbar design reduces power loop parasitic inductance, and **spacer connection** for ultra-low source inductance.
- Compact and **higher power density** fit in a variety of applications

Challenge of Power Module Fabrication & Assembly

1. Fixture Design

- Complexity of double-sided structure and multiple components
- Misalignment and pocket offsets to put in the small chips and spacers

2. Components Attachment of Power Module

- Overflow of the sintering or soldering pastes causes electrical insulation issues
- Mechanical overstrength during soldering causes gate defects

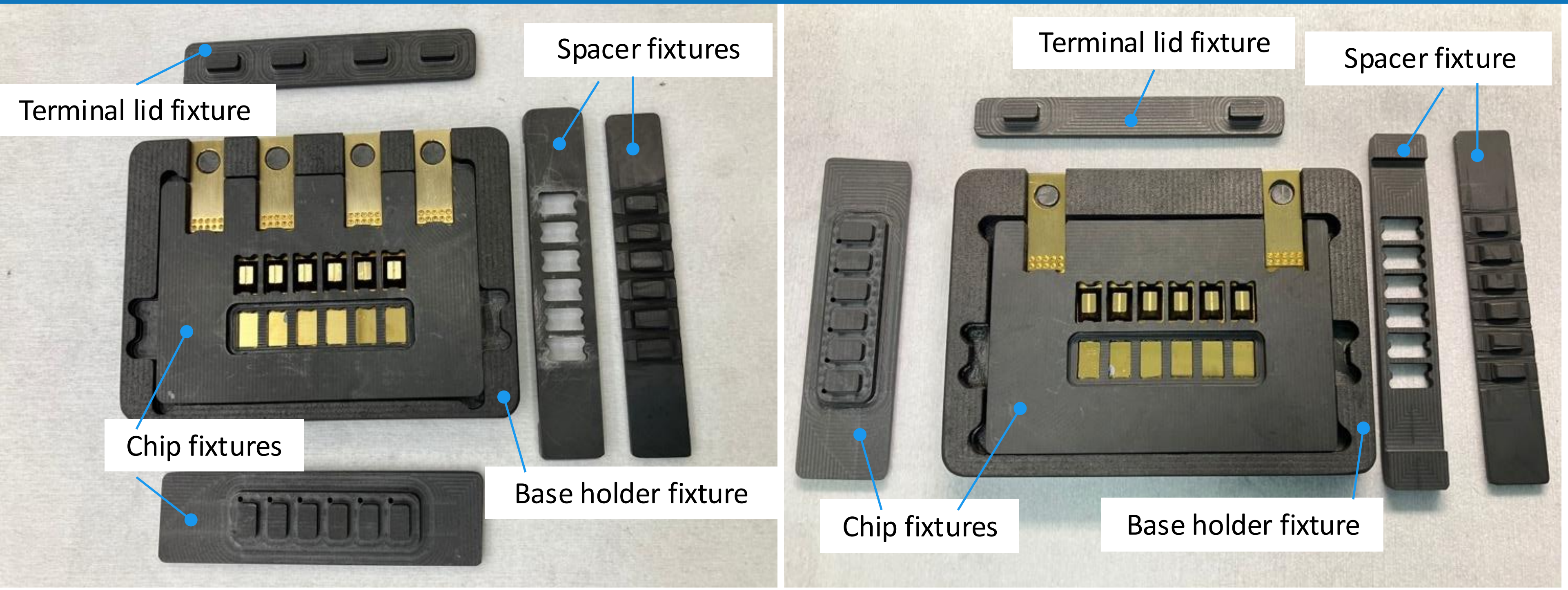
3. Encapsulation and Compound Mold

- Insufficient degassing causes insulation and local overheating issues
- No planar direction for degassing, should try different angles for a complete degassing

4. Electrical and Thermal Test

- Voltage overstress during high voltage and high current switching
- Higher pressure drop during a high fluid rate causes fluid leakage in thermal test

Fixture Design

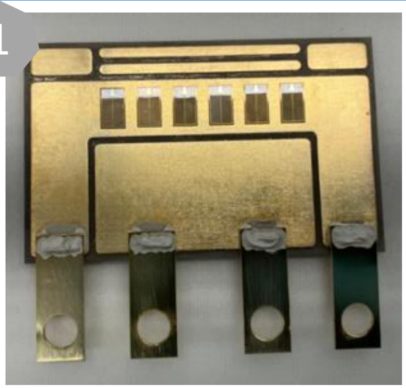


- **Chip fixtures:** locate each die and add extra weights
- **Base holder fixture**: hold DBC substrate
- **Spacers fixtures:** Locate each spacer on the source pads of dies
- **Power terminals lid**: add extra weights on power terminals

Tolerance: within ±20um **Chip and spacer pockets offset: 35um** Terminal offset: 100um

5-Step Fabrication Process of Power Module

1



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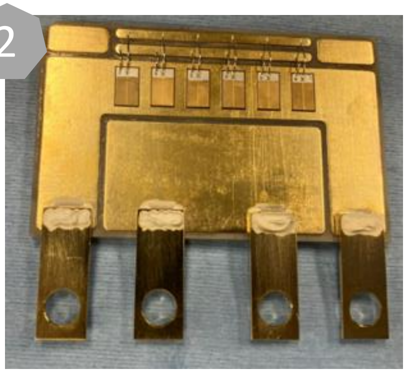

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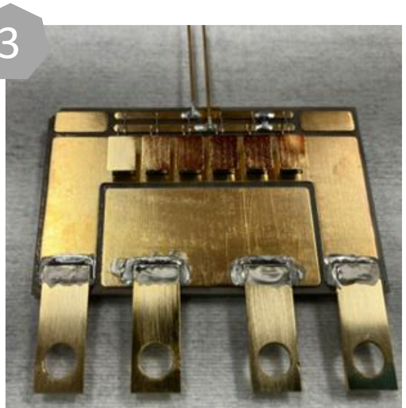
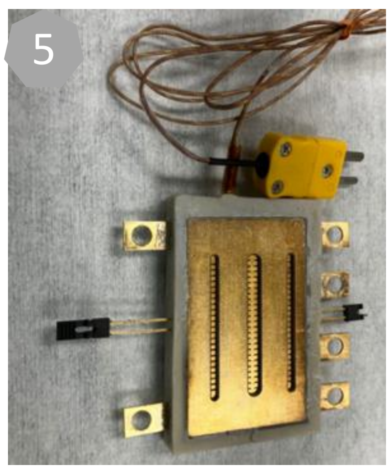
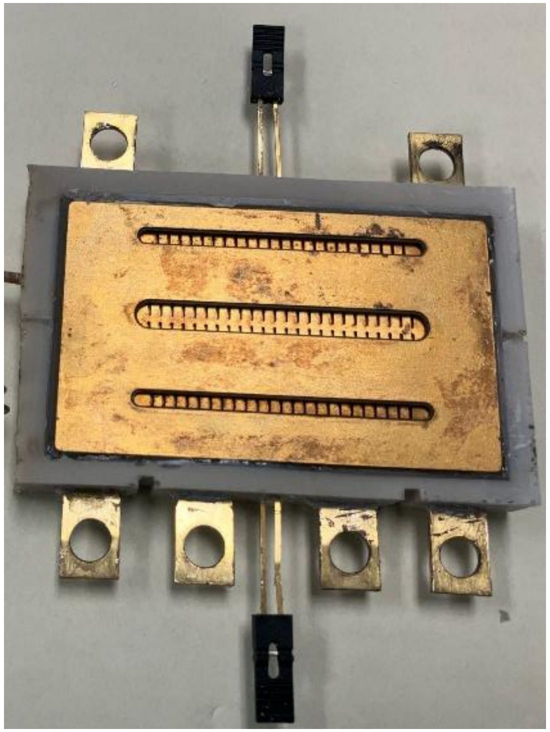


4

5



1. Die Attachment
2. 12 mil Wire Bonding
3. Spacers Soldering
4. Top/Bot Part Soldering
5. Encapsulation



Fabricated Half-bridge Power Module

- 1200 V 900 A (6 chips in parallel)
- Dimension: 68.16 mm × 44.52 mm × 11.13mm

Encapsulation and Compound Mold

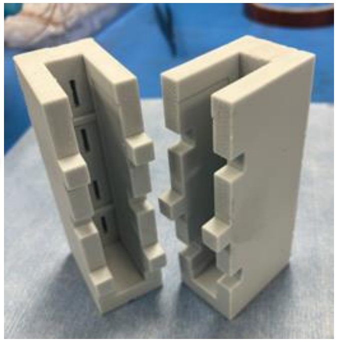
Compound Mold Fabrication Process

Step 1: Negative Part 3D printing

Step 2: Mix Mold Material

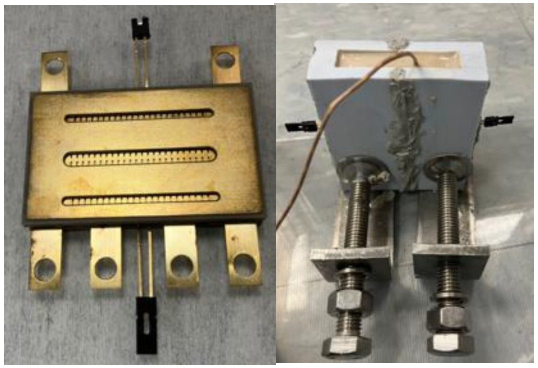
Step 3: Degassing @760mmHg In EXACT

Step 4: Apply Material to Negative 3D part



Step 5:Get the Mold After Curing for 24h

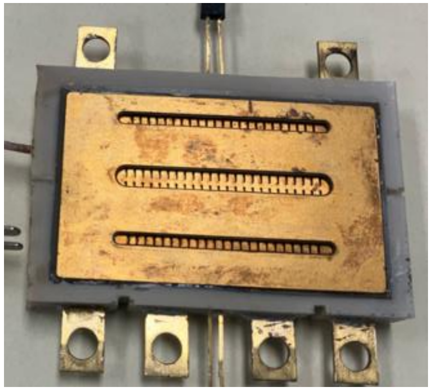
Encapsulation Process



Step 6: Seal Module with Mold Using Silicon Sealant like RTV167-85ML

Step 7: Prepare Epoxy Resin for Degassing at 760mmHg

Step 8: Curing in a vacuum oven

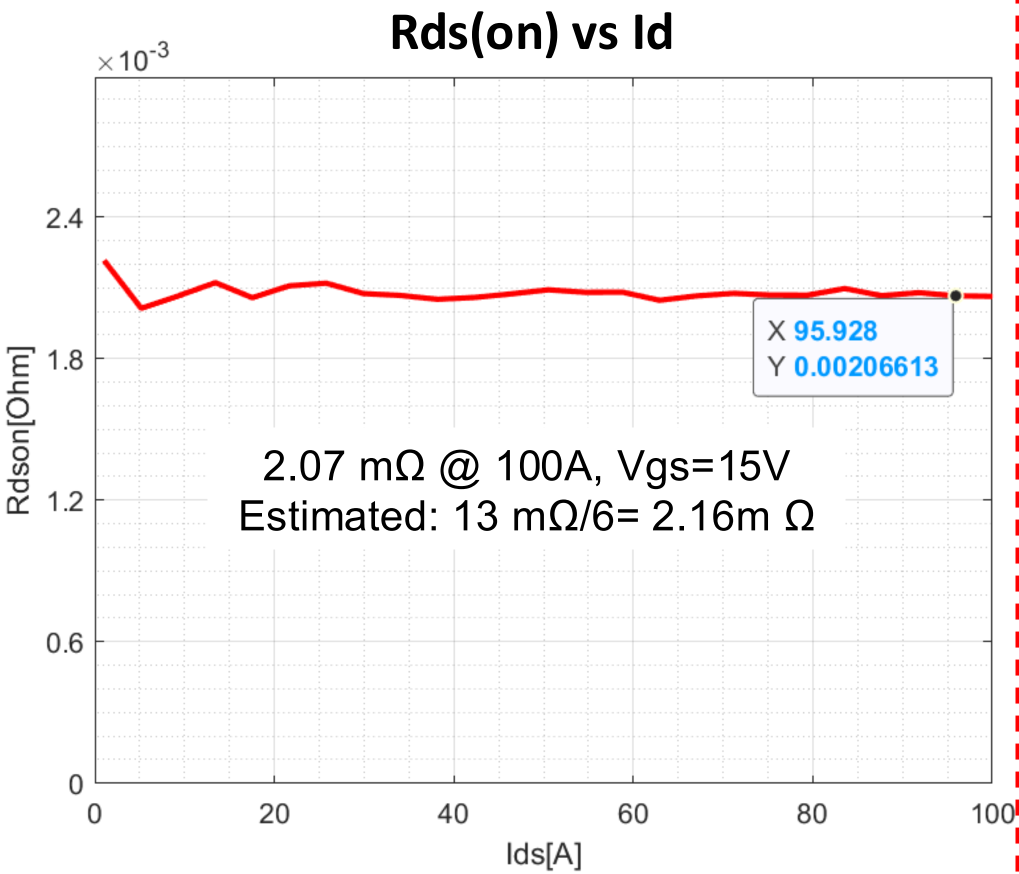


Step 9: Take module off from the compound after curing

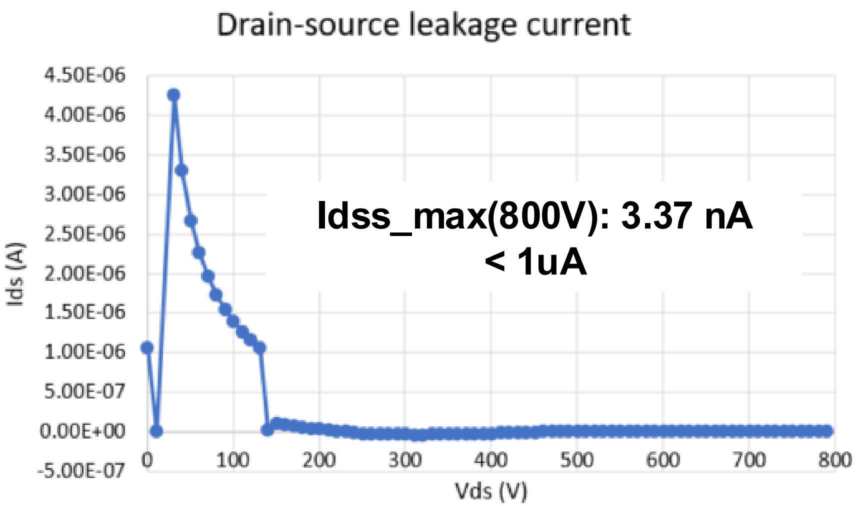
- Epoxy Resin: **reliable protection for sensitive components** inside Modules
- **Degassing**: Complete degassing, different angle

Power Module Electrical Test

Rds(on) Test: essential to evaluate the static performance of the fabricated module

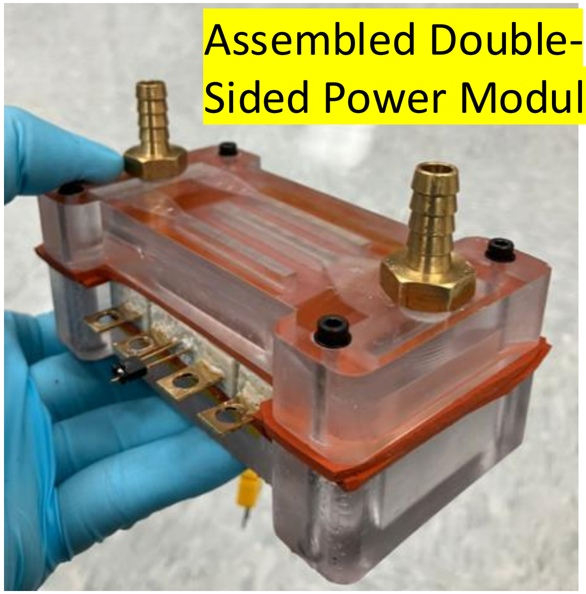


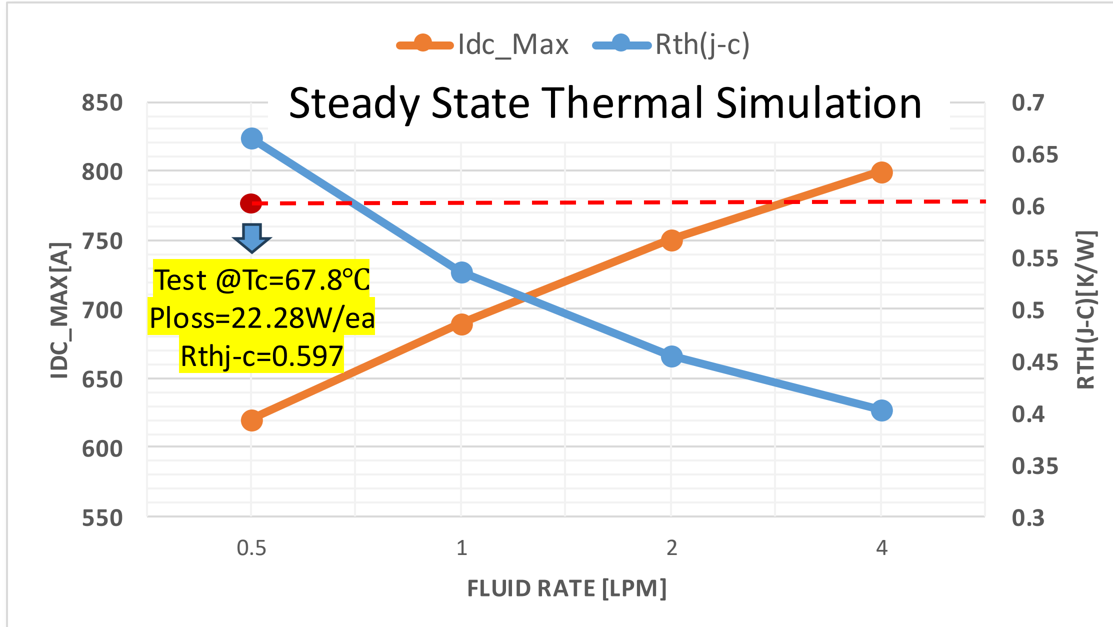
Leakage Current Test: it's critical to check if SiC gate oxidization layer have some defects during fabrication



Thermal Performance Characterization

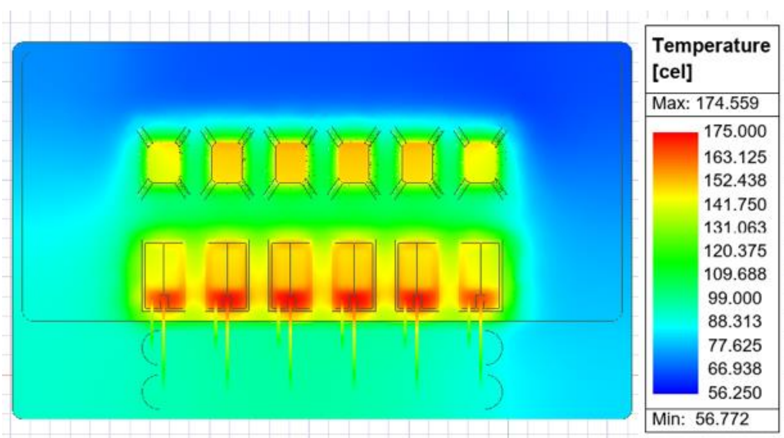
Assembled Double-Sided Power Module



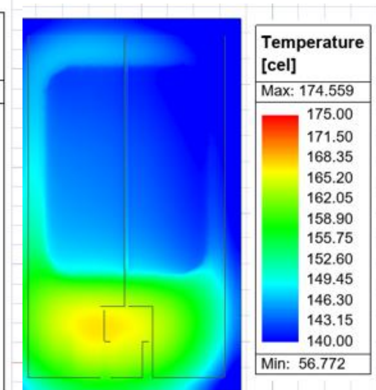


- Rth(j-c) is decreasing significantly from **0.5LPM to 4LPM.**
- **Rth(j-c) ↓ , Idc_Max ↑**
- **High Current density** is Ensured: no significant thermal couple between each Die(2mm distance), manifold layer distribute independent coolant branch

Full Double-sided Module Thermal Simulation



Thermal Within a Die



Conclusion

- The power density of the modules aligns with the cooling performance.
- The embedded heatsink demonstrated a superior cooling performance compared to the conventional cold-plate solutions.
- Wire bondless double-sided cooling SiC power module has been designed, fabricated, and tested.
- The 2-phase cooler would be a promising solution moving forward.

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