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Performance Enhancements and easy Integration of Double Side Cooled Automotive SiC Power Modules enabled by a sophisticated Cooler System.

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Motivation

- Demand and supply of electric vehicles (EVs) increase at a CAGR of 17% from 2023 to 2027
- Traction Inverter today with strong contribution to system cost requiring:
  - Reduction of materials and efforts for integration
  - Enabling high volume production
  - Power density and System Efficiency increase
- This Presentation adresses aboves objectives by introducing integrated cooler system concept for Double Side Cooled (DSC) modules

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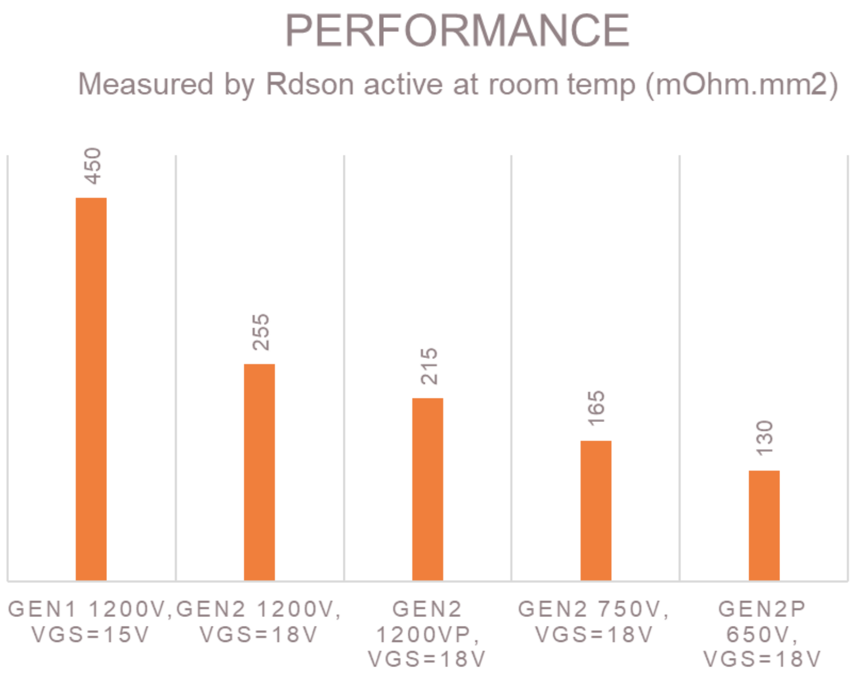
Semiconductor Technologies

Trench Technology

- Low channel resistance
- Shrink potential higher than in planar DMOS
- Oxide corners shielded by folded double trench
- Long experience in trench know-how

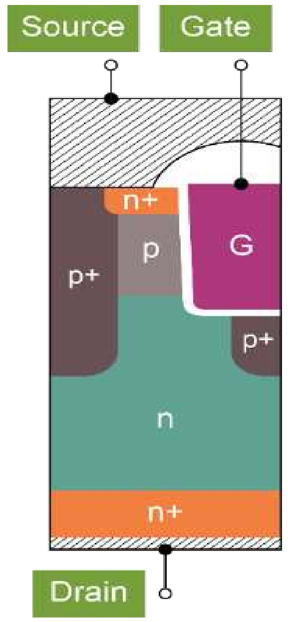
Automotive CooSiC™ Generation 2 1200 V "Performance" with RDSON*A with typically 215 mOhm*mm² at room temperature.

Automotive CooSiC™ Technology options



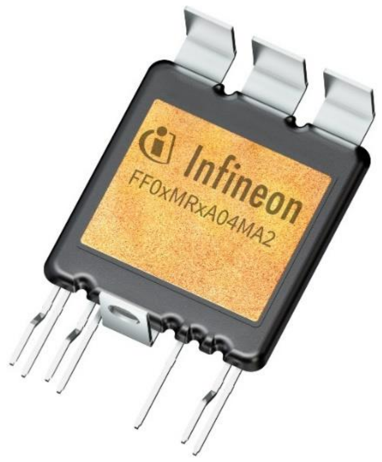
Source: Infineon internal accessment, Oct. 2020

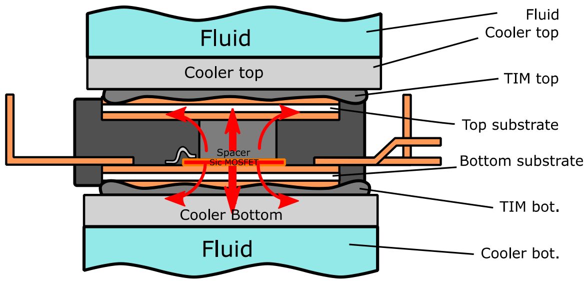
Infineon TRENCH

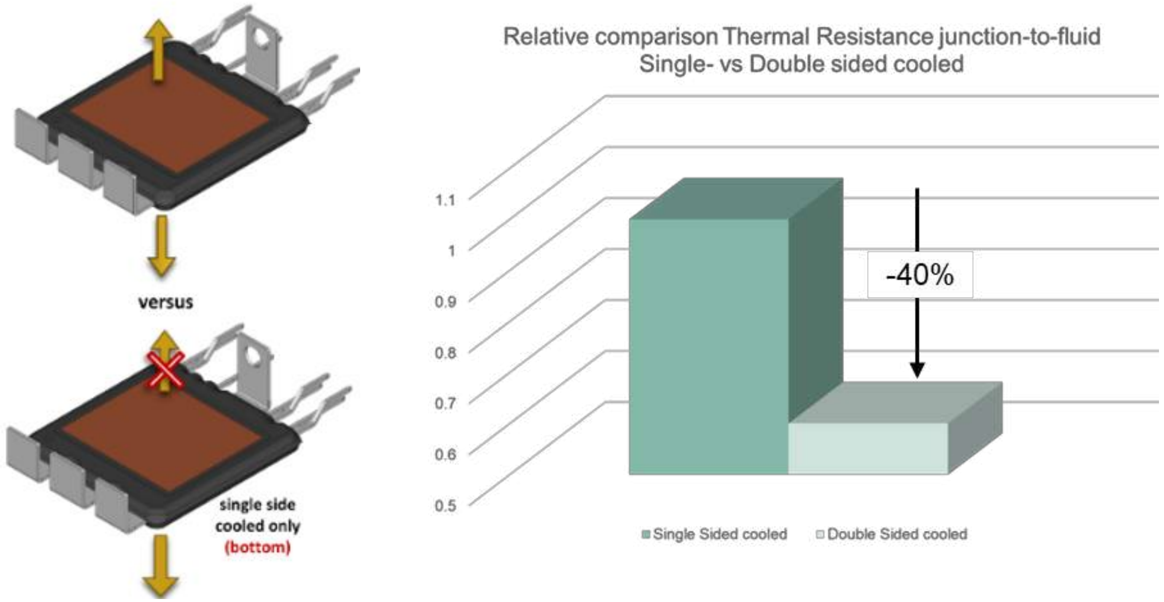


Power Module Package Technology

Double Sided Cooled Power Module	Thermal Stack of DSC	Advantage double side vs single side







FF01MR07A04MA2

- RDSON(typ, 25°C) = 1.9 mOhm
- Ls ~ 7 nH

- Thermal stack molded module with AIN AMB
- ~100 mm2 Chip area

- Thermal distribution Top / Bottom ca. 30/70%
- Additional top side cooling improves Thermal resistance by ~40% dependent cooling system

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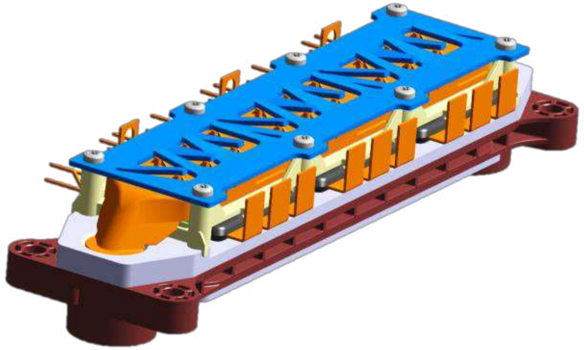
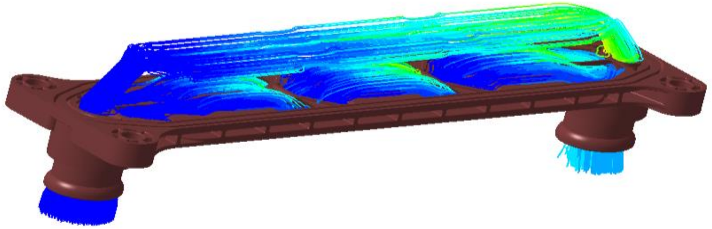
Hybrid Cooler System

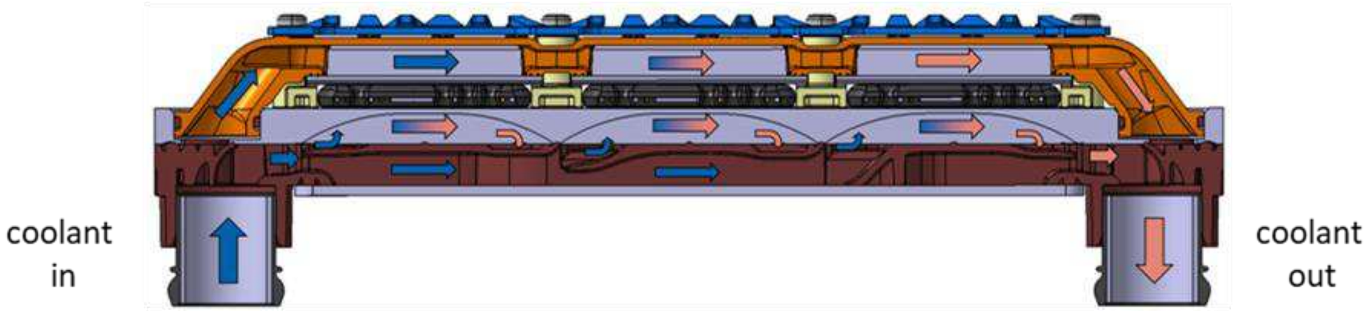
- 3* DSC Halfbridges positioned by support frame and clamped with ~800 N in-between top/bottom cooler.
- Hybrid Cooler with Plastic / Aluminium configuration
- Top-side: serial cooling
- Bottom-side: parallel cooling
- Top cooler flexible: adaptation to hight- and co-planarity tolerances as well as thermo-mechanical deformation

Cooler System Prototype





Cooler System Cross section

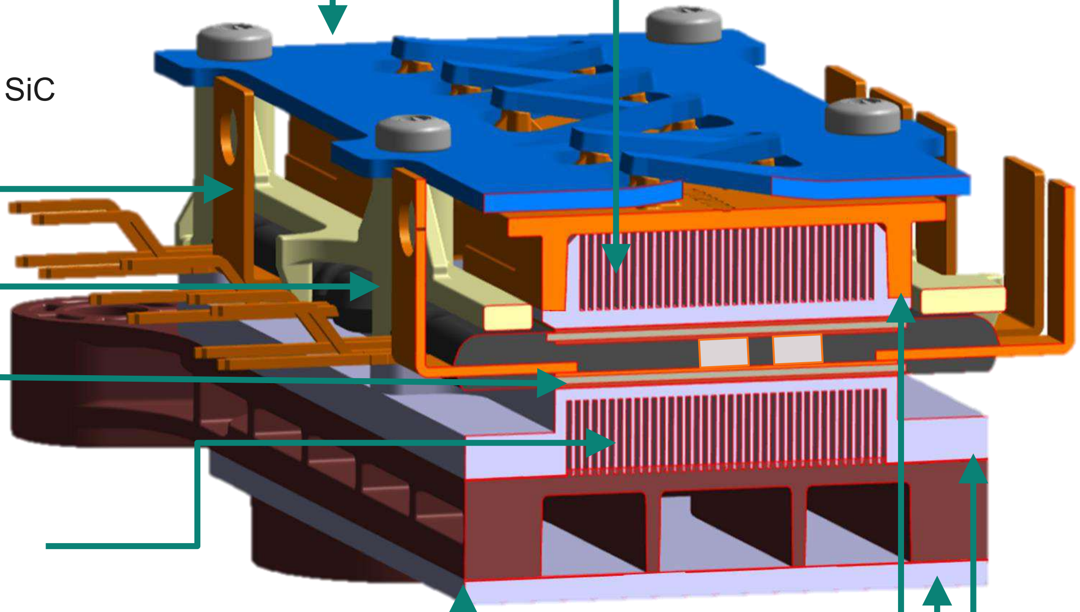


HybridPACK™ DSC with sophisticated cooler system concept

Spring for pressing the cooler onto the modules

Upper cooler with micro fins for extreme heat transfer

3* HybridPACK DSC SiC



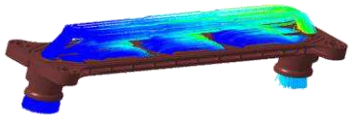
Interface solution without soldering or sintering

Lower cooler with micro fins for good heat transfer

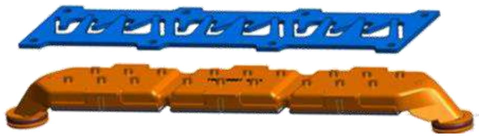
Cooling of the electrical Capacitor

Technology Innovation
new connection plastic – aluminum

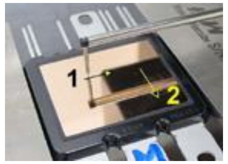
Homogenious temperature distribution due to parallel (bottom) and serial (top) cooling



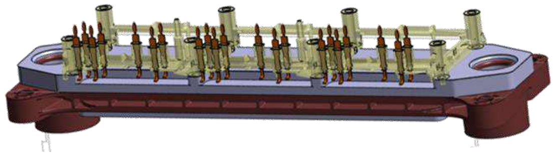
Flexible top cooler segment compensates mechanical tolerances and enables homogenious Rth-case-fluid



Grinded modul and cooler surfaces allows thin termal interface enable very low*, constant Rth-c-f

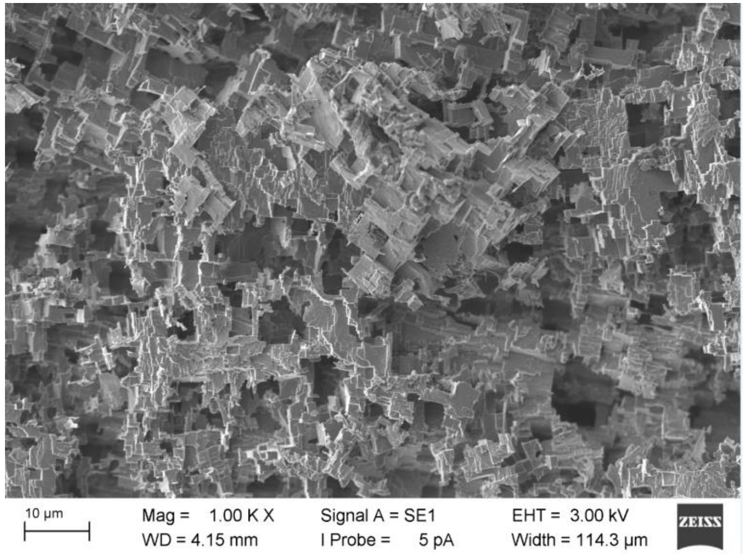


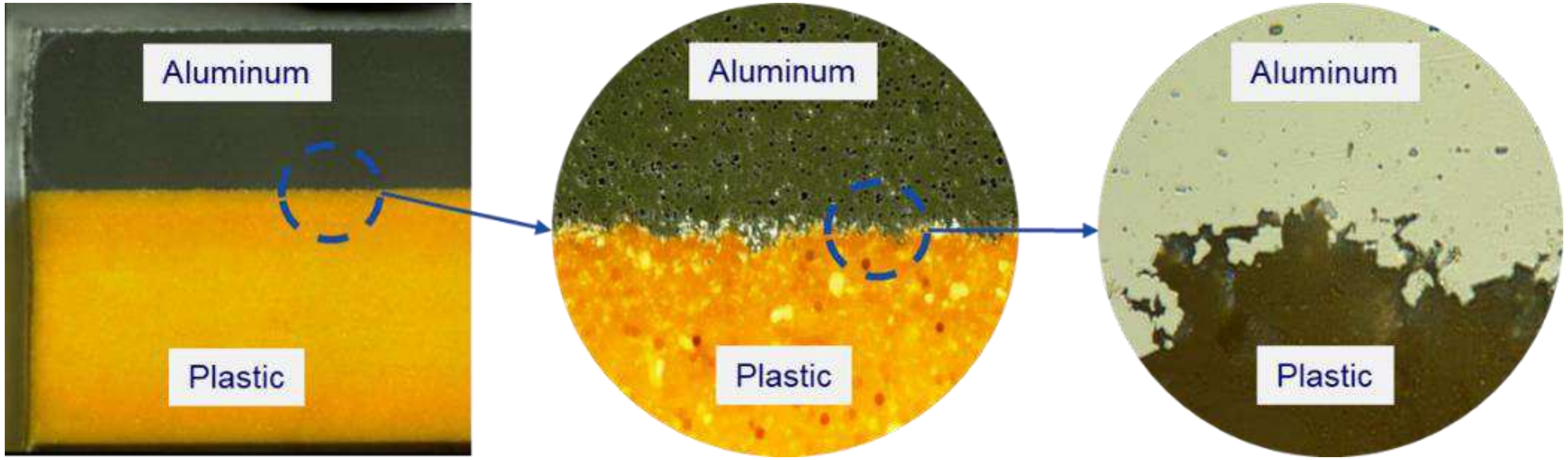
Flexible support frame element features supporting e.g. Positioning, signal pin adaptation, impr. Clearance, etc



Hybrid Cooler Technology – Cross section

Top view: Aluminum surface	Cross section of plastic/aluminum joined





- The aluminum surface is chemical structured to create micro contours, caves and undercuts on the surface
- During the joining process the molten plastic flows into these undercuts and fulfills all cavities
- There are no air pockets and voids in the connection
- The result is a high-strength mechanical and tight connection (Burst pressure test passed)

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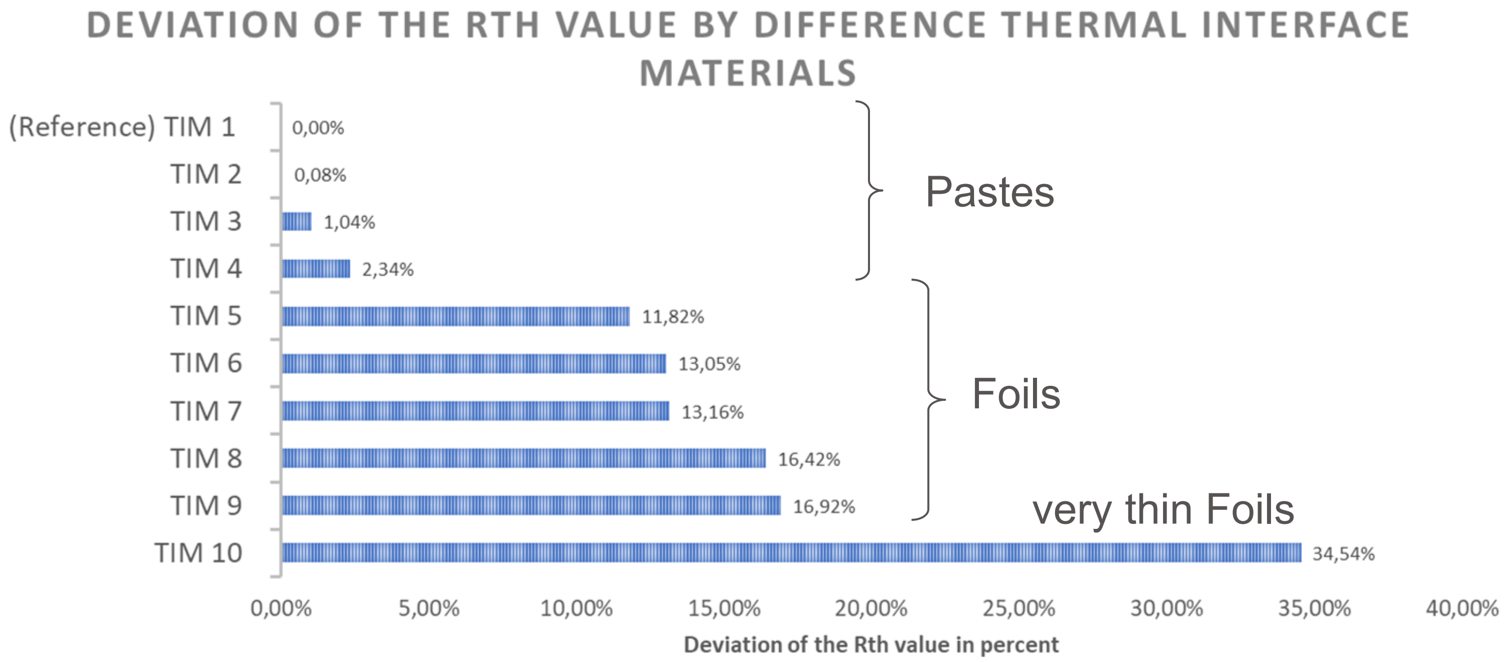
Selection of Thermal Interface Material (TIM)

- The assembly of the 3 hybrid packs and cooler were used for the measurements (DUT/ one switch heated)
- TIM: Pastes and foils including graphite foils and phase change foils were compared
- TIM foils with a thickness from 200 µm to 17 µm were tested
- TIM1 selected as reference system
- Learning: MOSFET shall be used instead of Bodydiode as heating method of junction



Thermal simulation and measurement results and analysis

Erwin Quarder Gruppe

Simulation

- TIM layer homogeneous thickness (0,05 mm); typical thermal conductivity of l=5 W/m*K
- Tjvmax of 175°C
- Fluid: W/G=50/50 at 10 l/min, 65°C, 1.5 bar
- Half Bridge powered: Rthjf(typ)=0,1514 K/W per switch
- dP(tot)~ 49,7 mbar

Measurement

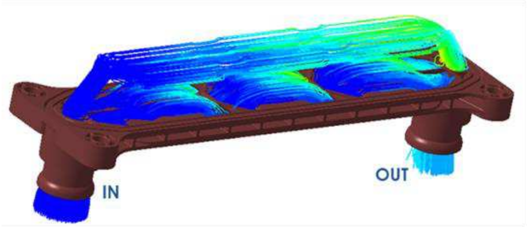
- According AQG 324/2019
- Fluid as above
- TIM layer: TIM1 of l=12,5 W/m*K
- Single switch powered: Pv=850 W
- All switches: Pv=730 W
- → Tvj,max to 175°C , dT~110 K
- Single switch powered: Rthjf ~ 0.12 K/W per switch
- Half Bridge powered: Rthjf ~ 0.14 K/W per switch

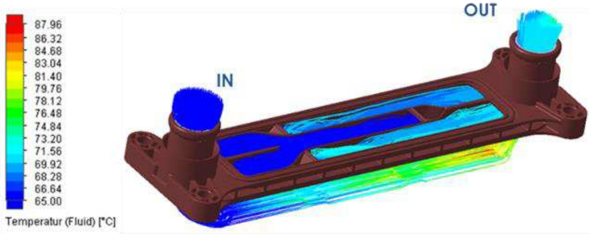
Comparison

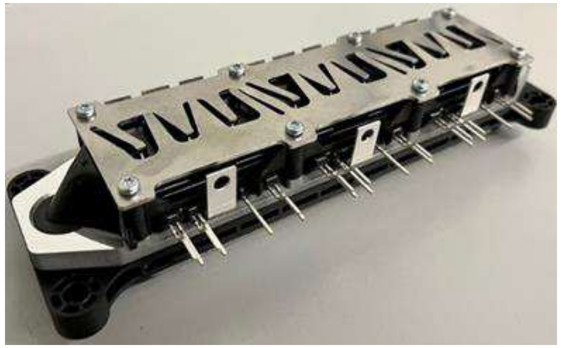
7.5% mismatch between simulation and measurement.
Reason: TIM layer and sample spread

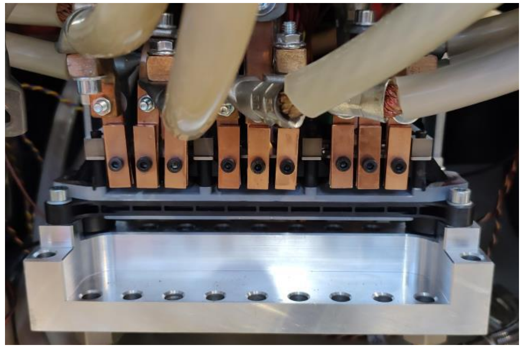
Learning

Thermal cross coupling between switches to be considered

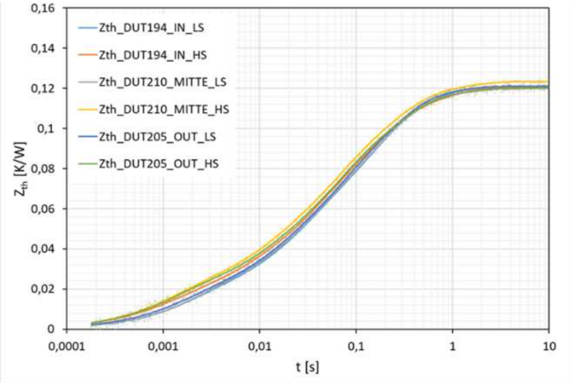




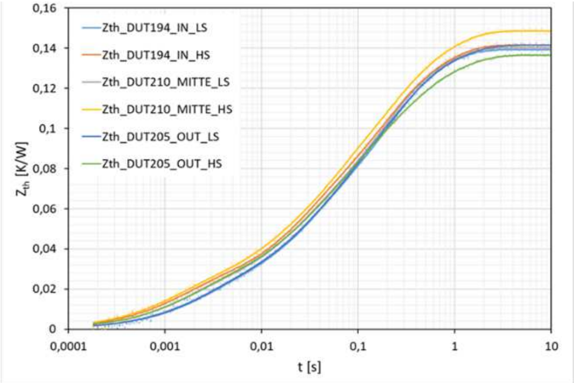




Zth: Single switch



Zth: Half Bridge



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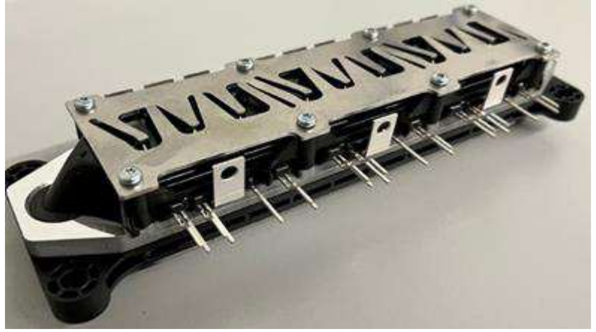
Summary and Outlook

- Rth,jf of 0.12 K/W was measured with ~100 mm² chip area in reference Double Sided Cooled HybridPACK™ DSC FF01MR07A04MA2
- → High power density can be achieved by innovative cooler system supported by AL-Plastic joining technology
- Sample Spread evaluation required
- Robustness validation of system setup leaned to AQG324 required, considering cooler aspects
- System's efficiency and cost were benchmarked [* this conference]



[* Dustin Meichner, Matias Leitner, Ben Rosam, Anthony Thomas, Christian Schweikert; (PCIM 2023); "Performance and feature benchmarking for novel SiC trench technology and cooling systems optimized for performance in traction inverter systems based on double side cooled power modules"]

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Thank you for the attention!

I'm pleased to answer your questions.
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Performance Enhancements and Easy Integration of Double Side Cooled Automotive SiC Power Modules - Enabled by a Sophisticated Cooler System

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Abstract

As the demand and supply of electric vehicles (EVs) increase at a CAGR of 17% from 2023 to 2027 [1], the focus on the performance- and price-dictating components also spikes. The traction inverter is one of those components. It contributes significantly to both the cost and performance of EVs. Hence, inverter optimization is needed for reaching the goal of affordable and sustainable EVs, that consume less energy, are manufactured with fewer components - thereby using less raw materials - and need less mechanical maintenance. We identified five trends for traction inverters. On the performance side (A) increased efficiency and (B) targeted performance are focused on, while (C) cost optimization, (D) volume production, and (E) vehicle integration are focused on the commercial side. This paper significantly contributes to the mentioned objectives, by presenting an integrated cooler concept for Double Side Cooled (DSC) modules, which is optimized for assembly (E), producible in high volumes (D), cost-optimized by choice of materials (C), and optimized for performance (A, B).

1 Motivation for cooler and feature set

Equal consideration for performance and cost targets is required when designing a power module for an automotive traction inverter. To achieve good cost performance, system level optimization - across single components - is vital. When solely considering cost per ampere, a basic half bridge power module (Chips on a substrate enclosed by mold) might be superior to a B6 configuration (Chips on a substrate bounded on a baseplate and frame). This component-level comparison does, however, not accurately reflect the contribution to system costs.

For a fair comparison, additional factors need consideration. Taking the example of the FF01MR07A04MA2 – a molded half bridge DSC module – this would result in considering a cooler and the interface between the DSC and the cooler. Beyond that, any comparison must reflect the subsystems performance dependency on the external setup, the systems durability over lifetime, and the assembly costs.

The cooler system assessed in this paper fulfills these restrictions and overcomes many of the mentioned gaps. The final features of the demonstrator under assessment are a result of the following considerations:

- Innovative thermal interface between module and cooler: Conventional indirect coolers are interfacing via a thermal grace [TIM] which buffers geometrical tolerances and thermo-mechanical deformations. This interface significantly dictates the tolerance, lifetime, and thermal resistance between power MOSFET and coolant fluid [R_{thjf}]. The interface chosen for this cooler system overcomes this bottleneck by using ground metal surfaces, flexible joints and a metal sheet spring. These measures compensate mechanical-tolerances and ensure the application of a constant force per unit area.
- Molded low-cost power modules typically come without a heat-spreading base plate. This cooler system integrates a heat spread, which is

tailored to the performance of the module. Furthermore, it improves the phase-to-phase homogeneity of the MOSFET junctions by utilizing parallel and serial cooling in one system.

- Ease of assembly: An integrated frame supports a one-step, fully automated assembly and integrates features like module positioning and fast signal pin connection via press-fits for various geometries.

2 Power Module and MOSFET Technology

Wide-bandgap semiconductors such as SiC increasingly power three-phase voltage source inverters or traction inverters in EVs as they lead to significant efficiency gains. [2], [3], [4] In order to fully realize the potential of this technology, it is essential to optimize both the chip technology and the packaging technology, as they are interdependent and can greatly influence each other in the design process.

For a deeper understanding of the relevant interdependencies, the Double Side Cooled [DSC] package with a Silicon Carbide Technology [SiC] Trench MOSFET Chip technology will be introduced here.

2.1 Silicon Carbide Technology

From the wide portfolio of Automotive CoolSiC™ technologies, the “Generation 2 Performance” (Gen2P 650V or 1200V), a Trench MOSFET technology, has been chosen for the above-described HybridPACK™ DSC package, to demonstrate the maximum current density. The technology is tailored to achieve a low RDSON*A with typically 130mOhm*mm² at room temperature for G2P 650V. This design utilizes the sweet spot between the lowest possible breakdown voltage and the intrinsic short circuit capability. This type of technology is well-suited for power module concepts with a very low stray inductance [Ls] as the requirements for Drain-Source-voltage overshoots are low. With a L_s of about 7nH (FF06MR0704MA2), the DSC presents a perfect match. The Trench cell concept shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** is designed for the highest cell-pitch density, an excellent RDSON*A and good switching performance. It possesses best controllability of switching, achieves minor switching losses and displays only a moderate temperature dependence.

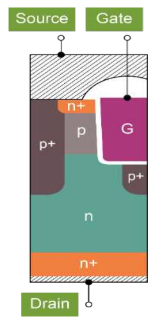


Fig. 1: Trench MOSFET

2.2 DSC Package – Thermal performance and implications on efficiency

The DSC module is engineered for optimal Root Mean Square Current [I_{rms}] output by reducing the chip area and maintaining an efficient package-to-chip ratio. The double-side cooling approach minimizes the thermal resistance between chip and fluid, with data showing reductions of up to 40% in thermal resistance [R_{thjf}] compared to the traditional approach of cooling from a single side. (See Figure 2)

2.3 DSC Topology – Thermal Stack

The package’s heat dissipation splits in a ratio of 30% to the top and 70% to the bottom, due to the

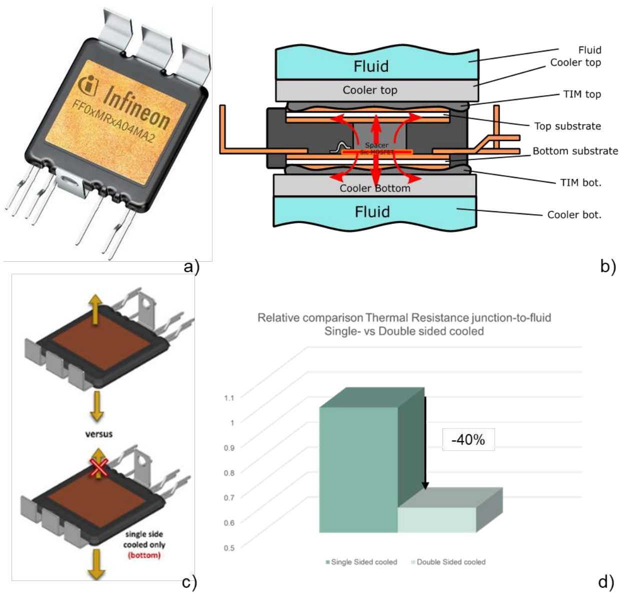


Fig. 2: a) Double Sided Cooled Module [DSC]; b) Thermal Stack of DSC; c) Single side- vs double side cooled molded power modules d) Thermal Resistance junction-to-fluid [R_{thjf}] comparison single side- vs double side cooled molded power module

thermal stack and positioning of the heat source (chip).

In Figure 2 the topology of a DSC can be seen. The performance and reliability are mainly driven by the substrate's material and the bonding technologies used for the respective interfaces. Characteristic for the DSC, is the electrically and thermally conducting spacer and the mold-compound, a polymer-based material. It is engineered to insulate electrical potentials, while withstanding the mechanical and thermal stress imposed by the application. The DSC is commonly indirectly cooled via at least one additional interface between either side of the package and the cooling liquid - mainly a water-glycolic mixture. The main trade-offs to consider in the design phase are each layer's thermal conductivity as well as electrical, thermo-mechanical and commercial considerations.

2.4 DSC Topology – System Considerations

The DSC is a half-bridge module. This creates additional flexibility for the inverter design, especially crucial for size- and weight-sensitive applications. As platform approaches are more frequented by OEMs - in an effort to reduce cost, complexity, and time-to-market – output scalability at a constant footprint becomes a key differentiator. The DSC package allows for voltage and current classes ranging from 650V to 1200V and from 1XXA to 4XXA, in the same footprint.

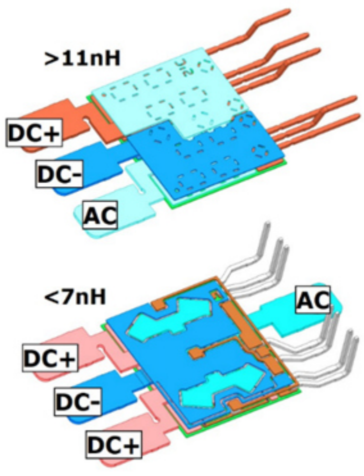


Fig. 3: DSC with low Ls - 3-tab, +/-/+ configuration for busbar connection to DC-link capacitor

Infineon optimized the DSC Gen2 for SiC. SiC MOSFETs are unipolar devices and can switch at high speeds, resulting in high dv/dt and di/dt. For facilitating the chip's capabilities, the package design must reduce overshoots from its commutation loops and reduce its' stray inductance. Based on experiments, Infineon adapted the Layout of the substrate and arranged the DC-Tabs (main contributor to stray inductance) in a +/-/+ configuration for the FF06MR1204MA2. This reduced the Ls by more than 50% compared to a 2-tab +/- module, such as FF400R07A01E3_S6, or other implementations of a 3-tab configuration (see **Fig. 3**)

3 DSC – Hybrid cooling system

For three-phase voltage source inverters, three modules are installed in the cooling system. The cooler is designed to dissipate heat as effectively as possible, while minimizing temperature difference amongst the modules. The base-material of both cooling surfaces is aluminum (See Figure 4 and Figure 5). The three aluminum blocks on the top are equipped with a nanostructure fin-topology, maximizing the effective cooling-surface. The aluminum parts are attached in a plastic frame (orange). Based on the mentioned heat dissipation ratio for DSCs, the system's top-part is cooled sequentially (from left to right). The bottom – where the modules dissipate 70% of the heat – is cooled in parallel. This means, each module is cooled by fresh water. The coolant is divided in a 20/80 ratio between top and bottom. The bottom cooler is geometrically designed to split the 80% into thirds, however with slight increases in the volume flow, from the first to the last module. This compensates for the constant heating of the coolant in the top cooler and achieves a homogeneous heat dissipation across all three modules at low-pressure losses. To permanently ensure good contact, the surfaces have a low level of roughness and flatness. Flexible joints and a metal spring force compensate for mechanical tolerances and thermo-mechanical phenomena. A thermal interface material (TIM) is applied to both sides of the module to ensure contact.

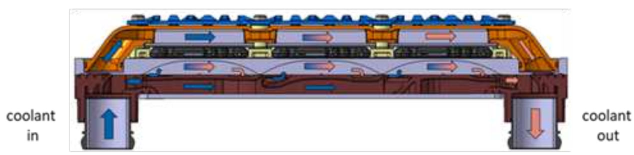


Fig. 4: Cooling path of the cooling system

The compact system with the sophisticated volume distribution is realized through the use of hybrid coolers, whereby only the heat-transferring surfaces are made of aluminum and the volume distribution is taken over by plastic components that are connected to the aluminum in a media-tight manner allowing for maximal design flexibility.

3.1 Hybrid Cooler Technology

The technological foundation of the presented cooler concept is a novel joining technology. It produces a durable connection between aluminum and plastic, allowing for hybrid power electronic coolers free of additives such as seals or adhesives. To realize a media-tight connection between aluminum and plastic, the aluminum's surface is structured (micro-nanoscale structure) using a chemical process called nanoscale sculpturing [5]. The structuring creates undercuts, ditches, and caves on the surface, resulting in a significant surface area increase due to the etching process. For the joining process, the aluminum is heated up to the polymer's melting temperature. Afterward, the plastic component is pressed on the heated aluminum surface. The polymer melts and penetrates the structured surface. The joining process takes place under non-specific environmental conditions without requiring a vacuum or an inert gas atmosphere. After the parts have cooled down, a mechanical and media-tight connection between the aluminum and plastic without voids is created, shown in Figure 5.

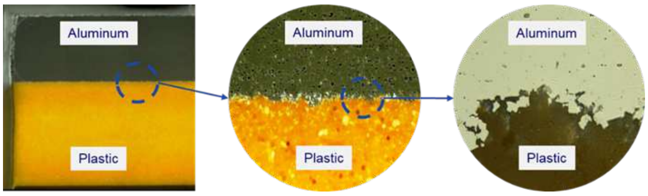
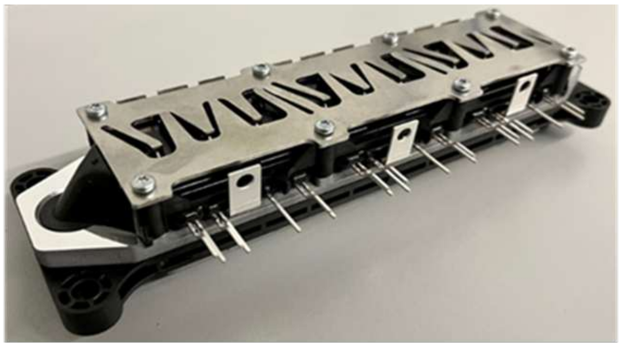


Fig. 5: Cross section of mechanical connection of aluminum and plastic

Multiple functional prototypes of the presented concept have been manufactured and adequately tested. The tests confirm the concept's feasibility and key simulated values (see Figure 6). As previously described, the prototype consists of two individual hybrid coolers. In the first assembly step, the TIM layer is applied to the contact surface of the pre-assembled bottom cooler. Afterward, the three modules are mounted in a frame determining the distance between bottom cooler and spring. Then, the TIM layer is applied to the top of the modules, on which afterwards, the pre-assembled top-cooler is placed. The tight connection between the two coolers is ensured by means of an O-ring connection. The TIM used can be a grease or a foil - like a graphite film with phase change material (PCM). By using TIM paste, the assembly order changes slightly. In the last step, the spring is placed on the assembly and fastened with eight screws.

The movement of the spring ensures constant force, which exerts a permanent contact from the upper cooler and the modules onto the lower cooler. The connection using TIM and spring force allows the module to move slightly in the X-Y direction (whereas X: length; Y: depth; Z: vertical), which reduces damage to the heat transfer over its lifetime. Module tolerances in Z-direction are compensated by movable joints in the plastic between each module in the upper cooler. The positioning of the modules in X-Y direction is taken over by the frame. The frame can be used for adding features, such as press-fit contacts for different applications. The systems water in- and outlets are located on the bottom of the system and use plug-in seals. Between the coolant in- and outlet is a second cooling surface which ca be used for capacitor cooling



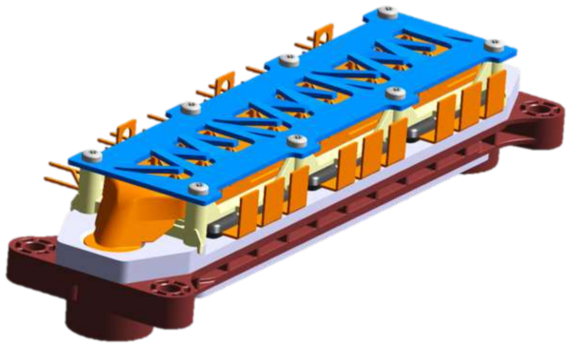


Fig 6: Prototype double sided cooling for three power modules in one system. Left side: physical prototype; Right side: feature enriched concept with Press-Fit adapter.

The three modules are built into one system for easy integration and handling. It is possible to enrich the system's features. Press-fit-Pins, for example, can be integrated into the frame.

4 Thermal assessment

4.1 Simulation results

For the performance simulation, the entire assembly, including a simplified model of the power modules and both coolers, was examined using Simcenter FLOEFD by Siemens. The temperature dependency of the materials thermal conductivity was considered; however, a median value was approximated for both aluminum and plastic materials. The TIM layer was assumed to be homogeneous and a layer of even thickness (0,05mm) with a typical thermal conductivity of 5 W/m*K. Since the surface conditions and connection to the TIM are not known, no contact resistances were assumed. No deformation of the modules or cooler due to thermo-mechanical influences was assumed due the described compensation mechanisms in place (i.e., 800N spring force). Each Chip on the active surface was applied with the maximal junction temperature T_{jvmax} of 175°C. The standard coolant volume flow of 10 l/min was assumed with a fluid temperature of 65°C. A coolant mixture of 50/50 water/glycol at a total pressure of 1.5bar was finally assumed. These assumptions correspond to general automotive requirements. In the first setup

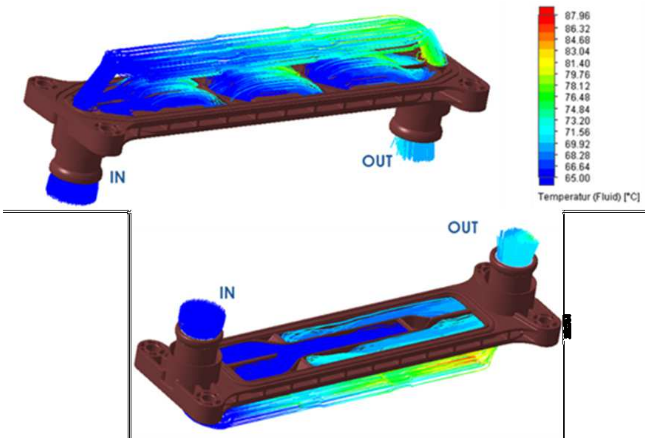


Fig. 5: Fluid temperature shown with streamlines

each active surface on the simplified Chip was applied with a different power loss to achieve homogeneously temperature and volume distribution.

The fluid temperature of the volume flow is shown in Figure 7. The graphic shows a constantly increasing temperature on the top and the more homogeneous temperature in the bottom cooler. The temperature difference at 150W per Chip is 3.2K between the first and last module measured on the hottest chip. To determine the system's performance, each switch was individually exposed to the maximal junction temperature T_{jvmax} of 175°C in the second simulation. The simulation shows - according to the AQG 324/2019 - an R_{thjf} of 0.1226 [K/W] per switch with a pressure loss of ~ 49,7 mbar for the assembly due to the high heat exchange surface, parallel cooling, and flow-optimized design from inlet to outlet. These values are used as references for the thermal measurement.

4.2 Thermal measurements

The thermal measurement and the determination of the thermal resistance has been executed according to "ECPE Guideline AQG 324", Chapter QC-02 "Determining thermal resistance", whereas in this case, the approach "Supplementary tests for DIN EN 60747-15:2012" has been considered: The device under test [DUT] here is the full system consisting of the DSC power modules, the interface and the fluid cooler. Hence, only the system R_{thjf} is of interest and assessed here. AQG 324 in chapter 9 "Lifetime testing", 9.2.2 "Test" allows optionally to utilize the Body Diode for heating the DUT instead of the MOSFET. This was not used here, as the Body Diode's forward voltage [V_f] characteristics, is typically spreading over a wide range. This is acceptable, as the Body Diode is not used in operating-/inverter mode (only during the very short dead time of <1…2µs). This Vf spread, in case of a static thermal resistance measurement or power cycling [PC] measurement, would lead to big sample-to-sample deviations, as every chip in a parallel connection would deviate strongly in its junction temperature and in that context the active area relevant for the R_{thjf} determination. The Body Diode is only utilized for calibration as means to measure the temperature during the Rthjf measurement process.

Power offer many degrees of freedom in their thermal design. This freedom is used to fulfil other design goals, such as stray inductance, current- and stray-inductance symmetry [6]. The case of the DSC module under assessment, the geometrical and thermal arrangement of the two switches in the half bridge configuration is slightly different and – due to the fact, that the thermal path junction-to-fluid is highly application dependent – it is useful to determine the Zthjf (Thermal Impedance) respectively the R_{thjf} per one switch, as well as the total R_{thjf} of one module. The two parameters are the extrema between worst- and best case under static consideration, as assessed in this paper for comparison. For dynamic conditions, as they are present in the application, the Z_{thjf_sw} of one switch and the $Z_{thsw1-sw2}$ (thermal impedance switch 1 to switch 2 in the half bridge) shall be determined and used for the thermal design.

4.3 Thermal measurements results

To validate the performance of the entire system, we conducted a Z_{thjf} measurement and extracted the relevant R_{thjf} value for comparison with our simulation. For the measurement, the assembly was mounted on a fixture and connected to the cooling system. The modules were then connected to impose the load and measure the currents. The measurement parameters were identical to those used in the simulation, with a coolant temperature of 65°C at a flow rate of 10l/min. The applied power is selected to bring the chip temperature $T_{vj,max}$ to 175°C in every switch, which corresponds to a temperature swing of ~110K.

In the first measurement, the switches are measured separately one after the other. A power of ~850W is applied to the respective switch for 20 seconds, followed by a cooling period of 20. The second measurement is done with each switch simultaneously, by applying ~730W at the same time for the same period as the first measurement. The temperature of the respective switch for both measurements are assessed over this period. The values are displayed in Figure 8

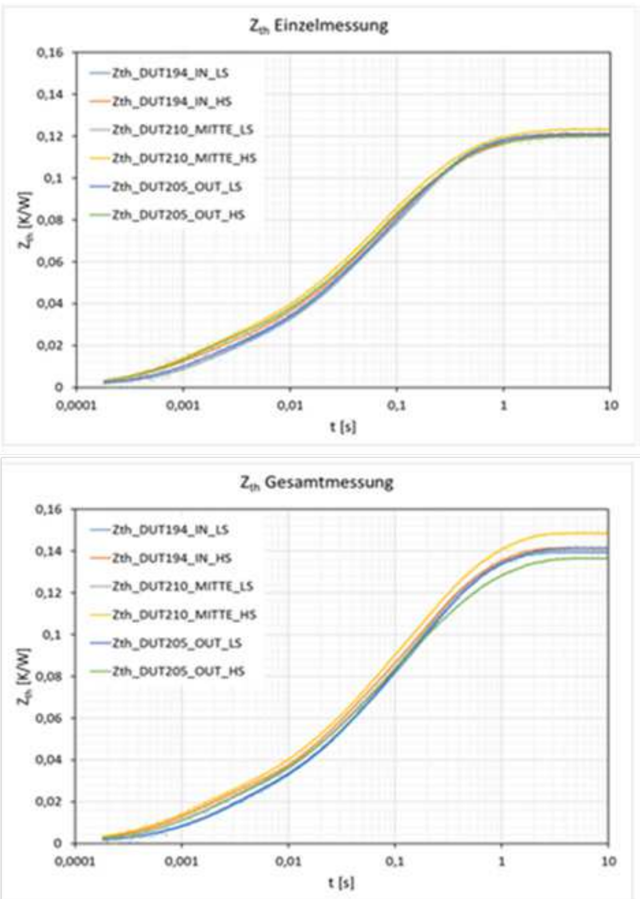


Fig. 6: Cooler system prototype build up with three DSC half-bridge power modules:
Power to each switch a) and all switches b) of a half bridge applied and measured.

The Z_{thjf}-Graph of both measurements shows the R_{thjf}-Value per switch. The first graph displays a R_{thjf}-Value of ~0.12K/W for each switch successively. The second graph shows the R_{thjf} for simultaneous measurement with a Value of ~0.14K/W. One switch is an exception due to coupling effects between.

To investigate the influence of the TIM layer, the identical prototypes were tested with different TIM properties at identical measurement conditions. The measurement clearly indicates the differences in performance due solely to TIM layer properties. The results of the study are presented in Fig. 9.

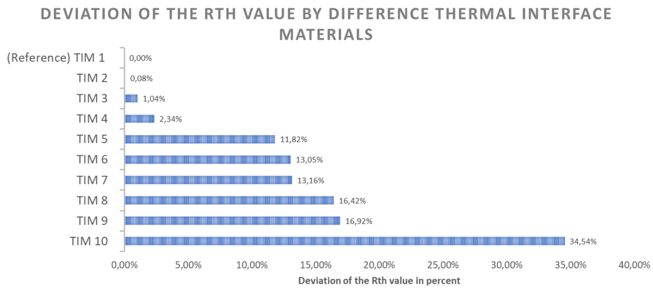


Fig. 7: Diagram of the deviation of the R_{th} values depending on the thermal interface material.

All values are normalized to TIM 1. The TIM layers include different pastes, graphite foils and phase change graphite foils. TIM layers with the same structure but different thicknesses are also included

4.4 Analysis thermal simulation vs measurement

The simulation results indicate a slight deviation from the actual measurements in terms of R_{thjf}. It's worth noting that the simulation was conducted under slightly different conditions than the actual measurements. In the worst-case scenario, where both switches in the half bridge were powered, the simulation yielded a R_{thjf} of 0.1226K/W, whereas the measured R_{thjf} was 0.14K/W, resulting in a 12.5% mismatch. However, in the case of a single powered switch, the measured R_{thjf} was 0.12K/W. These measurements were conducted on single prototypes, and the deviations can be attributed to typical sample variations. We recommend conducting further investigations, including measurements with a sufficient number of samples according to AQG324, to improve accuracy.

5 Robustness validation required

To ensure the robustness and long-term functionality of the cooling system, it is planned to conduct several tests on the prototypes. These tests will involve subjecting the assembly to various loads, such as mechanical, pressure, thermal, and chemical loads, in order to verify different failure mechanisms. All tests will be carried with the full system, consisting of cooler and DSC modules.

To ensure the functionality of the system, the leakage of each prototype before and after each test using differential pressure measurement will be tested. These tests will be based on AQG-324/2019 standards and will include Vibration & Mechanical Shock, Media- and High-/Low-Temperature Storage, and Temperature Shock tests. The cooler will also be tested using Pressure Cycling and Burst Pressure tests. Additionally, Z_{th}-measurements according to AQG 324/2019 must be conducted before and after individual tests to confirm that there are no performance changes.

To confirm the lifetime performance of the entire system, it is necessary to conduct a Power Cycling test based on AQG-324/2019 QL-01 with a constant volume flow and temperature-changing cooling. In this test, the module will be subject to alternating electrical loads to achieve a junction temperature of +175°C due to changes in the coolant temperature from +65°C to -15°C. This test will be carried out over 50,000 electrical cycles with a time of ton 3s and toff 6s, while the coolant temperature changes 2,000 times. During the power cycling test, all switches of the three modules will be loaded simultaneously. The R_{th}-value will be read out during the entire test to detect any possible changes in performance.

6 Summary and Outlook

The presented solution of Double Sided Cooled Automotive Silicon Carbide power modules combined with a customized cooler system achieves a remarkably low thermal resistance, resulting in high power density and performance. In the case of the FF01MR07A04MA2 - product under assessment - a single switch with a chip area of ~100mm² achieved an R_{thjf} of 0.12K/W, as measured. The system's efficiency and cost were benchmarked [8] against a conventional cooler system, as described in [7]. However, in order to ensure the product's robustness and compliance with typical Automotive requirements and AQG324 standards, further steps are necessary. These include validating the module-cooler interface under thermo-mechanical stress and determining the thermal resistance before and after stress, which is crucial for specifying the thermal performance of the system. These steps require a sufficient number of samples and tests which are beyond the scope of the present paper.

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