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Isolation Integration into Cold Plate and Thermal Densification of Liquid-Cooled Power Modules

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ABSTRACT

Active cooling integration into substrates can be utilized to significantly improve power density per unit volume, reduce weight, and improve overall heat dissipation for power semiconductors. The principal limitation for semiconductor device reliability has been identified as device operating temperature for decades. Electronic systems that are required to operate in extreme environmental conditions require direct and highly efficient thermal management materials and solutions. This investigation compares traditional power semiconductor packaging and thermal management incorporating multiple thermal resistances to a novel substrate with integrated active cooling, utilizing proven and established materials introducing active cooling directly under the die.

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1. INTRODUCTION

Electrification of propulsion drives across various transportation industries (rail, air, ship, ground mobile vehicles) enables significant improvements, including reduced noise, thermal signature, particulate and other emissions, and a decreased reliance on carbon-based energy sources. Additionally, these advancements lead to notable reductions in the size and weight of cooling systems and inverters. These benefits are not exclusive to propulsion drives but apply to other electronic systems as well. Gallium Nitride (GaN) and Silicon Carbide (SiC) semiconductor materials are known for their high efficiency. However, GaN RF device dies typically have a smaller footprint than the silicon dies they replace, often resulting in increased heat flux (power density per unit area). To maximize performance and operate in high ambient temperatures, active cooling (which requires electrical energy for pumps or motors for liquid or forced-air cooling) is used. Liquid cooling technologies, paired with appropriate control systems, enhance device lifetime and system reliability under maximum operating load conditions by maintaining device operating temperatures within a tightly controlled range, compared to forced air cooling without refrigeration systems for chilled air. Pumped liquid cooling has been employed for over five decades in various electronic systems, including enterprise servers, electrical drives, machine tools, electric traction (rail and freight propulsion), long-distance energy transmission and conversion, shipboard power conversion and thruster drives, mining vehicles (rail and truck), and large pumps for the chemical and energy industries. These systems typically use either thyristors and similar compression-pack semiconductors or isolated gate bipolar transistor (IGBT) modules capable of dissipating kilowatt-level waste heat.

Proper thermal design is crucial for managing and controlling system and device temperatures to:

(a) improve device lifetime and reliability,

(b) withstand heavy power cycling conditions, and

(c) handle rapid changes in the rate of thermal expansion of mating packaging materials. Controlling the coefficient of thermal expansion across the multiple packaging materials in a power module or inverter is vital for reliable operation with strict temperature control.

A traditional commercial IGBT power semiconductor module, as shown in Figure 1, uses standardized module footprints designed and manufactured by semiconductor suppliers. These modules include a copper or AlSiC baseplate, which provides structural support for a Direct Bond Copper (DBC or DCB) electrical isolation structure soldered to the baseplate. Die is joined to the DBC multilayer (copper-ceramic-copper) structure with traditional reflowed solders or silver sintering films or pastes. Wire or ribbon bonding on the die provides electrical interconnection. This assembled module is then bolted with mechanical fasteners in specific sequences and torque values to a liquid cold plate or another form of heat removal component. This standardized packaging concept provides the necessary electrical and mechanical structure and connections. Up to nine thermal interfaces are typically required, each adding significant thermal resistance to the heat removal path through this assembly, with accompanying thermal mismatches between materials [1].

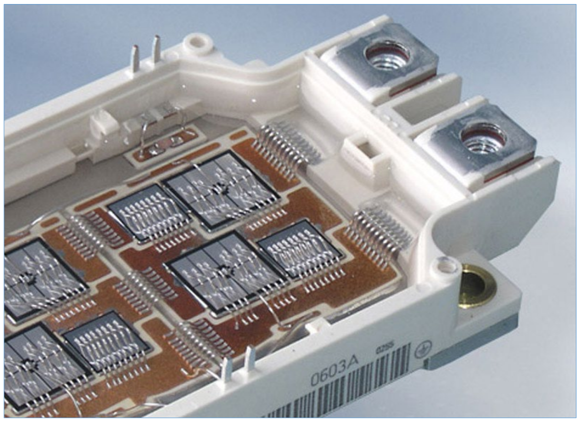


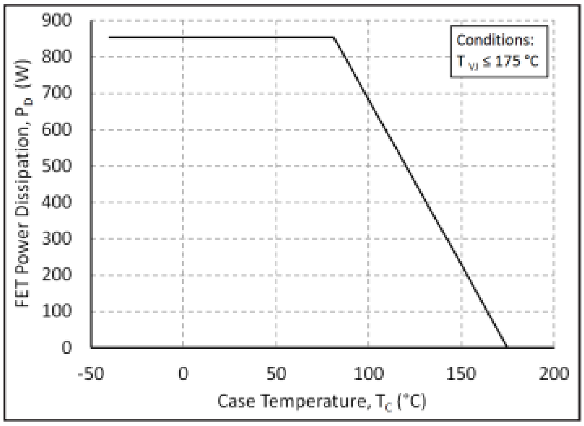
Figure 1: Martin Knecht, Roman Tschirbs & Roland Ott 05/26/2011 Infineon Technologies AG

High-performance electronic systems utilize pumped liquid cooling with heat sources attached to liquid cold plates of various sizes, materials, and configurations. At each assembly level, thermal management and stress minimization are critical to overall reliability. Multiple boundary conditions affect efficient heat dissipation from the module. Module manufacturers make commercially motivated choices to address broad applications, but in some niche applications, removing all waste heat from the module can be challenging. The conditions controlling die temperature include:

- Module baseplate and liquid cold plate surface flatness and roughness

- Module material characteristics and internal component design
- Liquid cold plate material and coefficient of thermal expansion (CTE) values and inherent internal stresses
- Liquid cold plate internal coolant manifolding, internal turbulators (if present), and flow channel configuration
- Single- or two-phase flow selection
- Coolant flow rate
- Type, viscosity, and performance characteristics of the coolant
- Operating temperature of the coolant
- Pressure drop of cooling system components (cold plates, heat exchangers, filters, quick disconnect fittings, meters, etc.)

Module performance is primarily defined by the case temperature, as illustrated in Graph 1.



Graph 1: Datasheet (page 7), Cree Wolfspeed CAB450M12XM3.

In the example case, module performance is limited when the case temperature reaches approximately 75°C due to the junction temperature (TJ) of the device reaching 175°C. Maintaining the case temperature below 75°C for full performance is challenging without active temperature management. Heat exchange with an outside temperature of ~35°C will only provide a coolant temperature of ~45°C.

The integrated liquid cold plate structure demonstrated in production applications and described below challenges the traditional interface. Better performance can be achieved through a higher level of integration, reducing the number of packaging materials and steps. As seen in [1], eliminating the thermal interface material (TIM) and additional resistances (module base metal and two interfaces) by integrating water into the substrate significantly improves the overall junction-to-coolant thermal resistance of the assembly. This substantial reduction in total thermal resistances through the material stack offers several advantages:

- Improved semiconductor device lifetime with reduced operating temperature
- Higher peak performance capability
- Improved device tolerance for higher temperature environments
- Reduced overall assembly size
- Reduced weight
- Potential total cost reduction (combining the liquid cold plate and module)

2. Direct mount on DBC cold plate

The proposed solution incorporates a Direct Bond Copper (DBC) structure within the liquid cold plate. Direct Bond Copper is a controlled atmosphere furnace process technology that joins copper with ceramics such as alumina (Al_2O_3) or aluminum nitride (AlN) at very high temperatures (>1000°C). This technology is widely used in high-volume manufacturing of DBC electrical isolation substrates for IGBT power semiconductor modules produced globally.

The same high-temperature oven process is used to join copper layers together (without solder or sintering materials) to form isothermal monolithic structures. Patterned and etched copper sheets are joined in this manner to build internal coolant channels and manifolds. This method of creating all-copper liquid cold plates has been successfully demonstrated in volume manufacturing for twenty years.

Two DBC substrates, including AlN (similar to those used in power modules), are used to construct the liquid cold plates. To manage stress effectively, the design is symmetric to avoid deformation caused by CTE mismatch between AlN and copper. A DBC cold plate has a greater thickness and thermal mass than a standard DBC substrate due to the internal coolant channels. With careful design and appropriate adjustments, this construction can utilize the same manufacturing and packaging technologies as traditional DBC substrates.

Custom patterning and the addition of copper or ceramic layers are possible to meet specific thermal performance requirements. The integrated cold plates are manufactured using the same proven DBC substrate manufacturing technology used in power modules (e.g., MOSFET, IGBT, diode laser). Notably, the DBC liquid cold plate does not utilize solders, sintering films, or other joining materials to build the basic structure, providing a monolithic and relatively isothermal component.

Given the process technology and design concept described, the ceramic (one or more layers, as required) integrated into the DBC structure provides the necessary electrical isolation. Using traditional DBC manufacturing processes, the assemblies now incorporate the electrical isolation provided by the DBC, integrated into the liquid cold plate. An all-copper liquid cold plate can be manufactured with one or more exposed surface layers of ceramic (Al_2O_3 or AlN, as necessary) for electrical isolation.

The semiconductor die is placed and joined using a silver sintering film or paste (or traditional reflowed solder) directly to the exposed copper surface of the DBC ceramic integral to the liquid cold plate. Other standard components can be added through a reflow step with suitable solder. Wire or ribbon bonding of electrical interconnects is then completed to achieve a fully integrated power semiconductor module with the lowest conducting thermal interfaces removed. This assembly eliminates the need for a separate DBC structure, baseplate, or internal solder attachment between individual built-up components. The use of polymeric thermal interface material (TIM2, external to the module) between the module baseplate and the liquid cold plate is eliminated. The eliminated components and interfaces are:

- Solder attachment of the DBC isolation structure to the module baseplate.
- Baseplate to cold plate TIM2 with three thermal resistances (bulk resistance and resistance at two surfaces).

Coolant can be supplied to the integrated liquid cold plate module using standard O-ring sealing technology or screw-in fittings as required. The arrangement of such manifolds may be comparable to the geometry of a custom cold plate. Additionally, new and innovative arrangements are now possible, allowing for unit stacking because the cooling is already included in the substrate. These stacked arrangements can provide further size reductions.

Overall thermal resistance (θ or R_{th}) is significantly reduced in the described integrated assembly due to:

- Shorter thermal path from heat source to coolant.
- Use of all metallic materials (e.g., silver sintering film, copper), eliminating all polymeric TIM2 materials which have substantially higher bulk thermal conductivities.
- Elimination of thermal interfaces and accompanying thermal resistances.

The cross-section of our novel power semiconductor module assembly (Figure 2) shows the material layers. Bulk thermal conductivity values for each material layer are listed in Table 1.

Material Layer	Material	Bulk Thermal Conductivity (W/mK)
SiC Semiconductor	SiC	375
Joining Material	AuSn Solder	50
	Ag sinter film	200
Ceramic Isolation	Al_2O_3	35
	AlN	170-200
Liquid Cold Plate	Cu	360

Table 1: Bulk thermal conductivity, material layers, fully integrated power module/liquid cold plate.

Note that the design of the liquid cooling internal flow channels and manifolding will dictate the number of copper layers used to construct the cooling structure. The effectiveness of lower layers in the cooling structure depends on the thermal connection to the topmost layer. Given that uniform joining is accomplished in the high-temperature furnace process, the result is an integral copper structure, essentially isothermal throughout, which is highly advantageous from a thermal design perspective.

Many different cooling structures can be created with this manufacturing process to meet varying requirements. Coolant channel design can be modified to accommodate fluids with differing viscosities and potentially higher flow rates as necessary. The internal coolant channel design can be adapted to different requirements for viscosity, flow rate, and hydraulic resistance within the existing design rules.

In applications where the available conditioned fluid is limited, locating the structures directly under the heat source can create more efficient systems requiring reduced pumping power. Within larger assemblies, structures can be designed with selected parallel flow designs (each heat source designed to meet a specific T_0) or serial fluid flow.

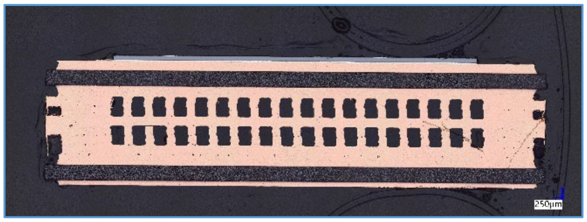


Figure 2: Direct die mounting on the integrated DBC structure on the all-copper liquid cold plate (coolant channels visible in this cross-section).

Resolution of internal coolant structures with this process can be as small as 0.3 mm. This allows for a large A_{sf} value (surface area, solid-to-fluid). The addition of appropriate filters, if desired, can be implemented to allow such structures to operate without clogging, if the presence of potential fluid contaminants is a concern.

3. Lifetime

Module operational lifetime is an important topic and can only be addressed with all design specifics for a given application considered. The use of different fluids, temperature cycles, and semiconductors will impact the results of a qualification process.

In the case of a common coolant, such as water, operating experience and performance data can be provided (Graph 2).

Liquid cold plates manufactured with the described DBC process technology have experienced degradation of the internal cooling structure. Channel erosion appears from examination to be more closely related to specific internal geometries than to a fundamental technology issue.

3.1. DBC liquid cold plate lifetime testing with water.

In a closed water circuit, we demonstrated 35,000 hours of operating cold plate lifetime in a diode laser system. In this test, no additives such as antifreeze or biological agents were present; the initial coolant supplied was deionized water, but operation was under uncontrolled conditions. As a result, this test was based on tap water with no control agents.

Samples were evaluated after removal from the operating system, with cross-sectioning to ensure that no indirect methods (such as pressure drop measurement) caused any measurement drifts over time. The electrical isolation of the powered layer and grounded inner layers avoids electro-corrosion. The material loss measured on the samples (compared to the nominal value) indicated only a loss of ~50 µm over the tested 35,000 hours. This is not enough to impact the performance of the liquid cold plate. Graph 2 shows the channel size and how it developed over the operational period of 35,000 hours. A widening of the channel can be observed: the nominal value was 480 µm, and the highest flow condition measured 535 µm after the stated 35,000 operational hours.

3.2 Module lifetime

The lifetime of a custom-designed module will have to be tested in a qualification procedure that might be specific. Due to comparable mounting technologies used to attach the semiconductors, comparable failure mechanisms are to be expected. If the improved cooling performance results in a lower average operation temperature, it is likely that this technology will positively affect module lifetime since the root cause for most failures is the CTE mismatch of different materials used.

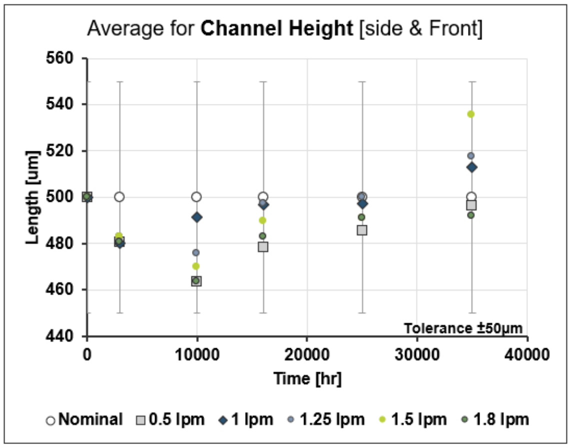
4. Thermal simulation for optimized packaging

A comparison between the cooling behavior of:

a) A 10x10mm die on a DBC substrate attached via TIM to a simple cold plate.

b) A 10x10mm die on a DBC substrate attached via a thermal interface material to a sophisticated, multi-channel cold plate.

c) A 10x10mm die directly mounted onto a DBC cooler is demonstrated here with the help of simulation tools.



Graph 2: Lifetime test of Trumpf Photonics DBC liquid cold plates with different coolant flow rates.

4.1. Model definition

Figure 3(a) shows a single hole in the cold plate as the cooling system for the water to pass through. This represents the technology used in many low-cost, readily available liquid cold plates. Figure 3(b) shows a structure with 1mm cooling channel width nestled tightly, allowing for improved performance due to the significantly greater area (A_{SF}). Also, the proximity to the heat source is improved. Figure 3(c) shows Trumpf DBC integrated direct bond liquid cold plates with 300µm coolant channels.

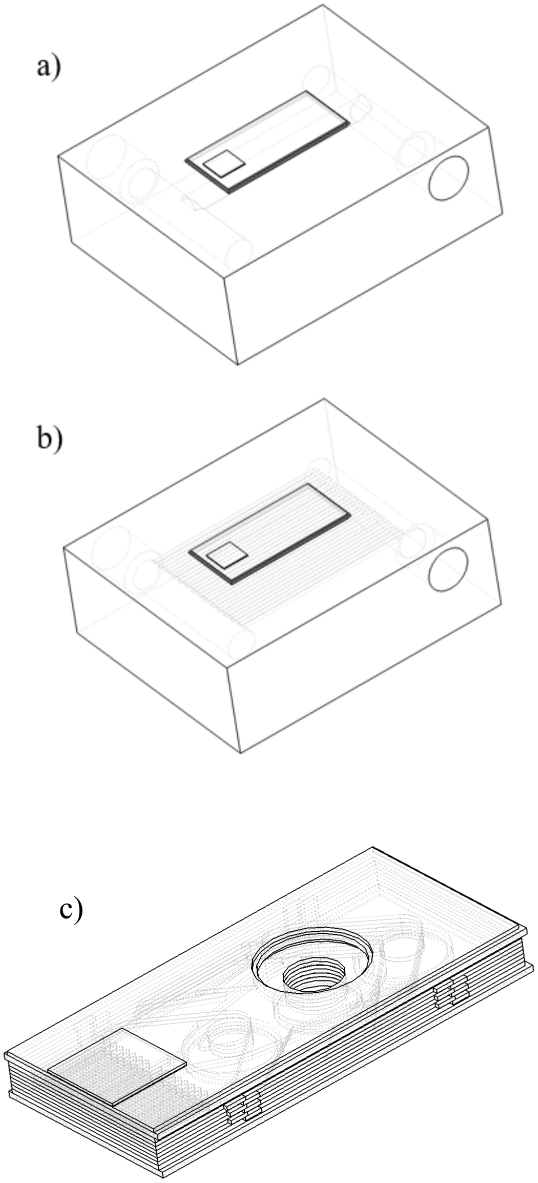


Figure 3: Illustration of models used in thermal simulation**s.**

4.2. Simulation

The thermal interface material used for these simulations to connect the DBC to the coolers in Figures 3(a) and (b) has a thickness of 100µm and bulk thermal conductivity of 1 W/mK, as modeled. Silver sintering film was used as the joining material between the die and DBC for all three cases with a bulk thermal conductivity of 200 W/mK. Water was used as the coolant with an inlet temperature of 70°C.

Cold plates in configurations (a) and (b) and cooling layers in configuration (c) are made of copper with a bulk thermal conductivity of 401 W/mK and heat capacity at constant pressure of 384 J/kgK.

The heat source is a 5.45×5.45 SiC die with 100W of dissipated heat. AlN is used as the middle layers of DBC (170 W/mK bulk thermal conductivity) in these simulations.

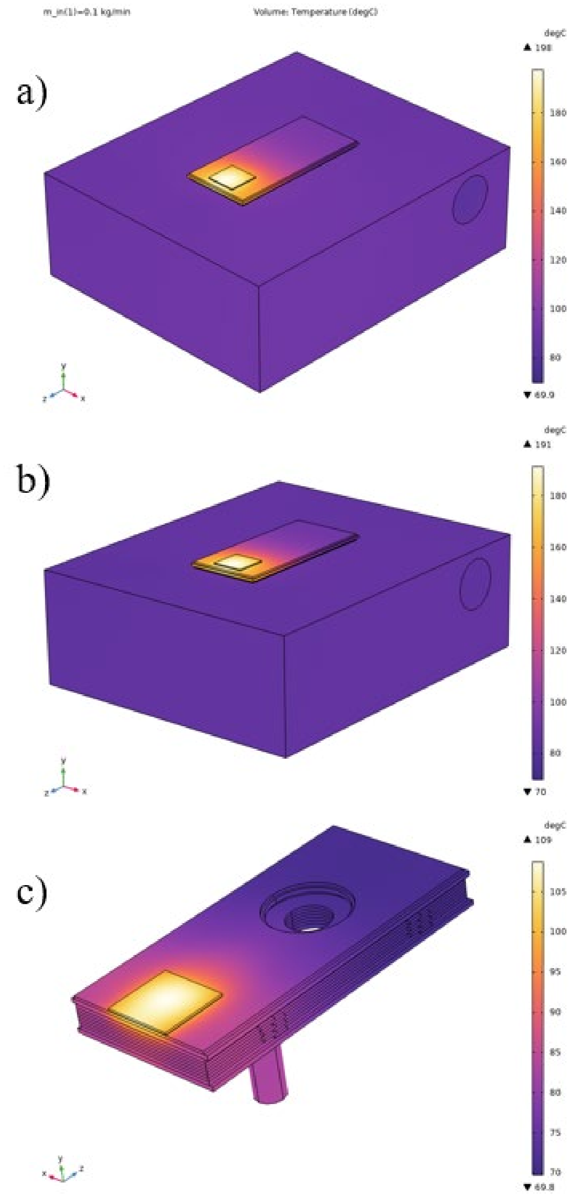
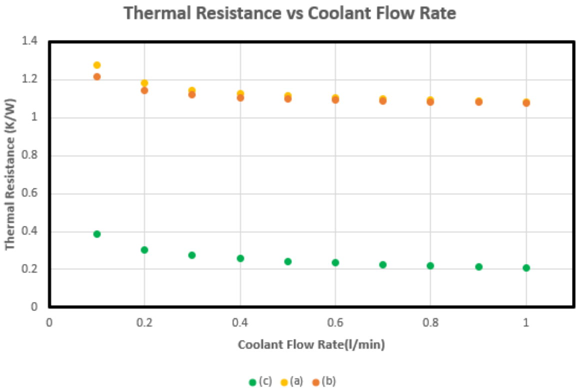


Figure 4: Temperature distribution comparison in a) single pipe liquid cold plate, b) highly structured cold plate and c) Ilasco cooler.

Using computational fluid dynamics and thermal simulations in COMSOL, different flow rates of coolant (water) from 0.1 l/min to 1 l/min, with increments of 0.1 l/min, were simulated. The dissipated heat load (P_{loss}) in all cases was 100W. Figure 4 shows the temperature distribution on all configurations for a water flow rate of 0.1 l/min. A stark performance difference can be seen between configurations a) and b) versus c), all at the same P_{loss}.

Graph 3 demonstrates the difference between the three configurations in thermal resistance versus water flow rate. This clearly demonstrates how much of a thermal barrier is created by thermal interface materials. Due to the usage of heat spreaders, these negative effects can be mitigated to a modest degree. However, heat spreaders add cost and require more space, which increases costs again. What also becomes quite visible in Figure 4 (a) and (b) is the housing temperature. As can be seen in Graph 1, the housing temperature limits the dissipated power Ploss that the module can handle.



Graph 3: Thermal resistance vs. coolant flow rate

The values in Table 2, measured on DBC liquid cold plates comparable to Figure 4, can be used to estimate possible cooling performances.

Die Size [mm]	Cooling Method	Flow per Liquid Cold Plate [l/min]	Thermal Resistance, Rth [K/W]
5x5	single	0.4	0.42
5x5	single	2	0.33
5x5	double	0.5	0.15
5x5	double	2	0.06
10x10	single	1	0.15

Table 2. R_{th}, coolant flow speed and thermal resistance.

The values were generated using these equations:

$$\frac{\Delta T}{Ploss} = R_{th} \tag{1}$$

$$T_J - T0 = \Delta T \tag{2}$$

T_J represents the junction temperature of the die, while T_0 signifies the temperature of the incoming coolant fluid.

The die size influences the overall cooling performance, as evident when comparing line 2 with line 5 in Table 2. For a larger die, the R_{th} value is lower since the same Ploss is distributed over a larger surface.

In the "cooling method" column in Table 2, two call-outs are identified as "single" and "double". "Single" refers to a packaging technology as shown in Figure 3 (c). "Double" is a value achievable when two DBC liquid cold plates sandwich the die from the top and bottom. While this can be done, it represents a significantly more involved technology that will not be detailed further in this paper.

5. Traction inverter design

To compare the improvements possible with the suggested technology, the next step is to propose a new design and compare it to a more traditional approach.

5.1. Component selection and layout

Figure 6 illustrates a standard layout chosen for a traction inverter. DC from the HV battery is switched into frequency-controlled three-phase AC to power an ASM or a PMSM electric motor. Two IGBTs and one free-running diode are used per channel (U, V, W) and per polarization (+, -). Different layouts are possible but can all be designed to fit on a DBC cold plate. The current limitation of the chosen components is 200A, which can also be adapted to customer requirements with an appropriate layout. At 400 Volts of battery voltage, this results in 100kW motor power. For 600 Volts of battery voltage, 200kW can be assumed.

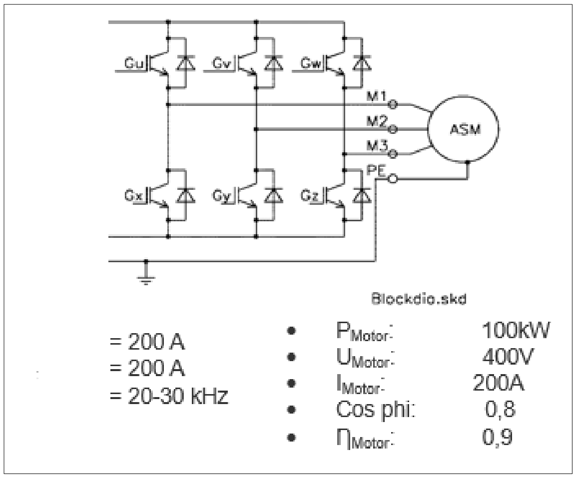


Figure 5: Electrical layout used for comparison.

Since the described integrated DBC liquid cold plates have a front and a back and need to use a second AlN layer for symmetry reasons rooted in the manufacturing process, this second side can be used and populated with additional components. In this case, the second battery potential is ideal since it shows in mechanical layout almost identical to the front. It is another advantage that the phases (U, V, W) or (L1, L2, L3) can be easily collected off the device and allow equally simple stacking of multiple modules.

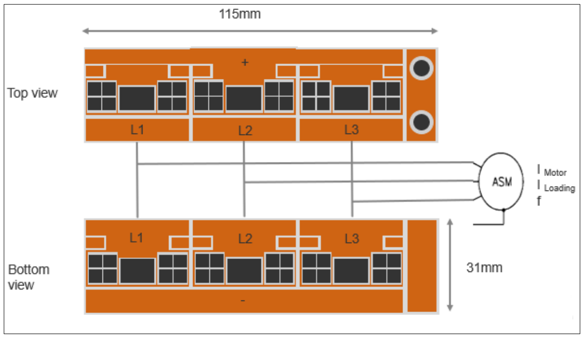


Figure 6: Double-sided cooling concept layout.

5.2. DBC cooler design

The inner structure of the cooler can be designed to allow the liquid to enter from a common port. To allow a stacked arrangement such as displayed in Figure 5, a through hole can be manufactured to allow for a parallel fluid connection. From this common port, the liquid is guided directly underneath the heat source (IGBT die). With the appropriate cooling structure in place, this can look like what is shown in Figure 2. After heat exchange is accomplished, the fluid is collected and guided out the common exit port.

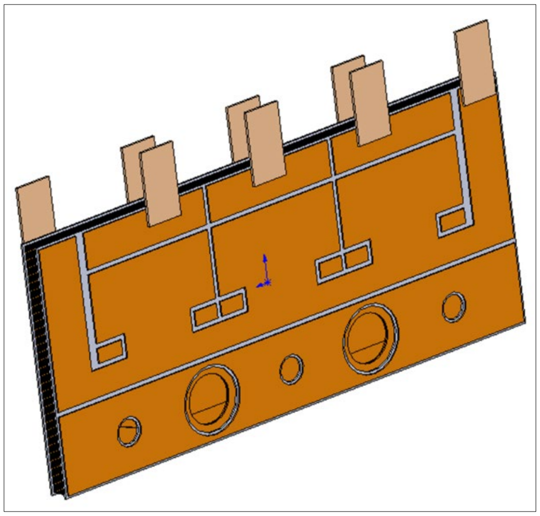


Figure 7: Double-sided and populated liquid cooling concept layout. Front and back appear as the same and both may be populated.

5.3. Module assembly

In a first step, the tabs or lead frame will have to be attached. This can fundamentally happen in different ways:

- Inserted in the original bonding process.
- Added by laser welding.
- Brazing.
- Attached by AuSn solder.
- Attached by SAC solder.

The list above is from highest to lowest rank in terms of thermal stability. Metallization can occur before or after this step. The power components can be attached via a reflowed solder process or Ag-sintering film. Thermal conductivities and component internal stress will vary, impacting performance and lifetime. The pressures used during sinter attachments and the required heat cycle to complete either soldering or sintering are not a problem for the DBC structure. The temperatures the device is exposed to during the manufacturing process greatly exceed those necessary to attach the semiconductors. The mechanical stress in the form of pressure from both planar sides is also manageable for the DBC structure without deformation or destruction. Due to the higher thermal mass, process parameters and temperature ramps in processes must be adjusted compared to traditional substrate. Wire-bonding or clip attachment are options to connect the die top (gate and source) with the respective pads. For gate signals and temperature sensors, a PCB can be added as a cost-efficient way to deal with low-power signals. The described unit called a module is now functional. Common fillers can be used to protect the unit from dust and particles. This can happen at this step or even later in the assembly process. As mentioned earlier, modules can be stacked to allow power scaling. In this study, stacking of two modules is used to demonstrate the technology and to create a comparable traction inverter to a more standard approach.

6. Conclusion

The proposed integrated DBC liquid cold plate design demonstrates a reduced junction temperature at the same operation point. Simultaneously, the assembly volume is significantly reduced per watt dissipated. In an approach with 6 high-power modules bolted to a very compact custom heat sink, a volume calculation yields approximately 214 mm^3/W, compared to approximately 25.7 mm^3/W for the proposed integrated DBC liquid cold plate. This represents a very significant and valuable reduction (~10x) in footprint and unit volume for a high-performance SiC IGBT module design.

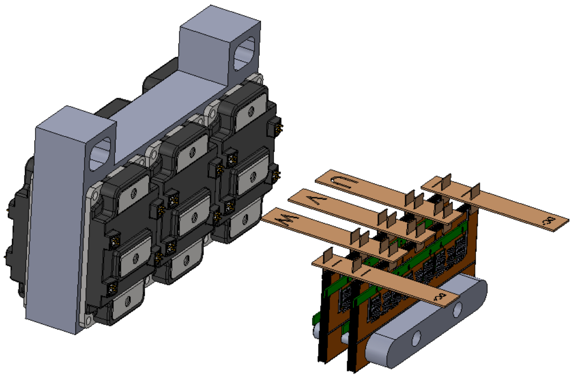
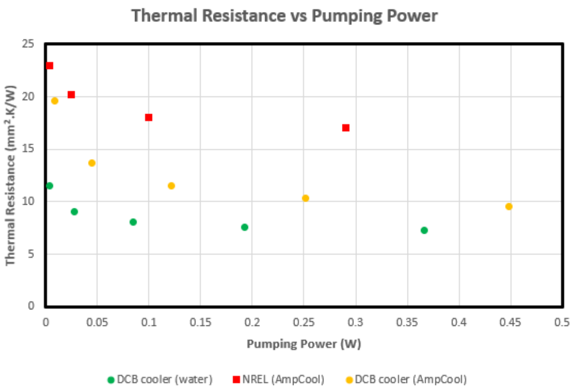


Figure 8: Physical size comparison traditional approach [3] versus the described fully integrated DBC cold plate design.

It should be noted that the fully integrated DBC all-copper liquid cold plates described herein have been in volume production for extremely high-performance diode laser bar assemblies for more than fifteen years. This established production performance record indicates the success and long-term reliability achieved with this approach for a narrow application area and suggests that this process technology is well-defined for use in other applications.



Graph 4: Thermal resistance versus pumping power for DBC all-copper liquid cold plates.

Another way to compare cooling performance is thermal resistance versus pumping power, as shown in Graph 4. Note that in this graph, the thermal resistance is normalized per area unit (mm²) of the heat source. This comparative performance of integrated module thermal resistance versus pumping power is of significant importance for mobile electronic and electrical systems performance, such as electrical drives designed for airborne applications, where thermal efficiency versus physical volume, weight, and system pumping power are critical to overall performance.

7. REFERENCES

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[2] Delphi Pedrosa et al. "Unified Power Converter Based on a Dual-Stator Permanent Magnet Synchronous Machine for Motor Drive and Battery Charging of Electric Vehicles, page 2, 2021.

[3] Geomety for Power Module used in this model was taken from the Wolfspeed website (XM3 Half-Bridge SiC Power Module Family | Wolfspeed). The custom cold plate is inspired by a Lucid inverter: (Inverter | Tech Talks | Lucid Motors (youtube.com)