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Power Semiconductor Assembly to Boost Power-Density in Commercial Vehicle Drivetrain Designs

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Abstract

Commercial electric vehicles like trucks and buses combine the need for high-power drivetrains with restrictive space and cost requirements. Traditional approaches regarding power semiconductors are reaching physical limits. Within the internal construction, ceramic isolators limit the thermal transfer, in turn limiting the semiconductor's performance. As this class of vehicles features liquid cooling systems by design, direct liquid cooling can be used to massively enhance the power semiconductor's heat dissipation and improve performance on a similar scale. This work introduces the development of a new class of power devices, boosting power density to unprecedented levels.

1 State of the Art

Despite the physical size of a truck, space to integrate hardware is highly limited. The volume reserved for the drive-train inverter's power section is expected to remain well below 5 dm³ while offering a continuous output power of at least 600 kW. This represents a power density requirement in the range of 120 kW/dm³. Even at 99% efficiency, 6 kW of losses need to be expected and properly dissipated.
Liquid cooling is an inherent part of this class of vehicles, but the internal isolated construction of today's power semiconductors also puts a limit to thermal transfer.
While classical approaches mount power semiconductor modules to closed liquid cold-plates, better results were achieved by considering the power device as a closing lid to an open cold plate. Although this improves the thermal situation compared to a classical setup, it does not eliminate the internal thermal barrier. To increase turbulence and the contact area, pin-fin-style base plates [1] or similar structures on the module's base plate [2] have been used.

2 Direct Liquid Cooling

A new approach, developed from a feasibility study [3], relocates the isolation requirement from the internal construction to the cooling liquid and thus allows to directly mount the semiconductor to the liquid cold-plate. This eliminates several layers from the initial stack while especially removing the isolation layer massively improves thermal performance. A comparison is depicted in Fig. 1.

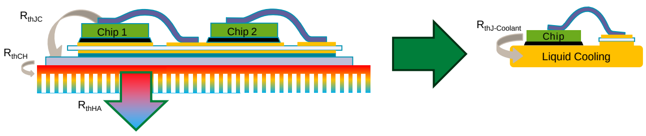

Fig. 1 Comparison between classical assembly and non-isolated setup

Prototypes based on this new structure have been built to evaluate thermal performance as well as the electrical behavior. Fig. 2 is a photo taken from one of these first devices.

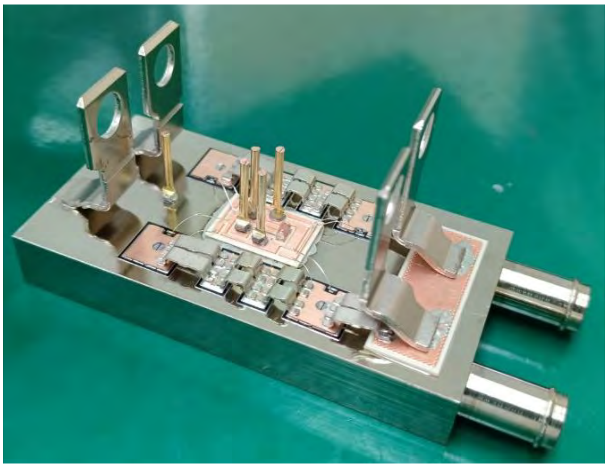

Fig. 2 Non-isolated power device

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The module features a single-switch configuration consisting of four paralelled IGBTs rated 1200 V and 150 A each and four freewheeling diodes with the same ratings. Both, IGBT and diode feature solderable front-side metallization and proprietary tab-and-clip interconnection technology.
The picture in Fig. 3 is a close-up view of the tab-and-clip interconnection technology that replaces bond-wires in this approach.

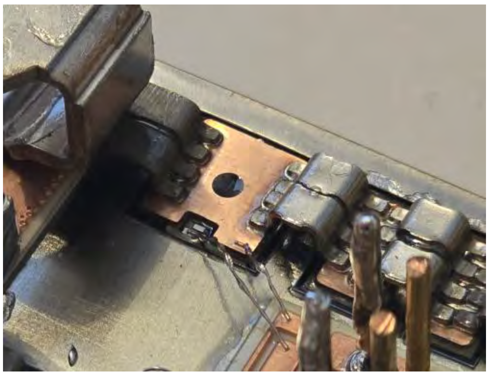

Fig. 3 Close-up view of the tab-and-clip connection

The clips offer a far larger cross-section to carry current at much lower losses and thus lower temperatures.
Both contributes to increasing the power-cycling capability and thus the lifetime in the field.
For thermal measurements, the device was blackened and observed by IR-Camera allowing to accurately capture local temperatures as well as observing thermal spread and temperature deviations between the paralleled chips.

The overall laboratory setup used for the measurements is pictured in Fig. 4.

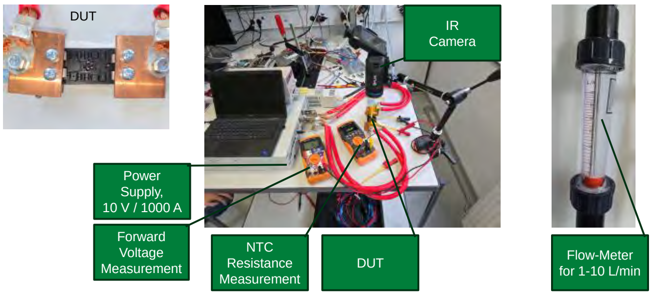

Fig. 4 Laboratory setup to conduct thermal measurements

2.1 Measured Thermal Data

The special focus for this measurement series was on the chip temperature development correlated to the liquid flow rate, first using water as coolant. Besides the IGBT and diode temperatures, the NTC-reading was of interest. Within the power device, there is a noteworthy distance between the NTC and the power semiconductors.

The IR-Images in Fig. 5 are example pictures, individually observing the IGBTs and diodes respectively.

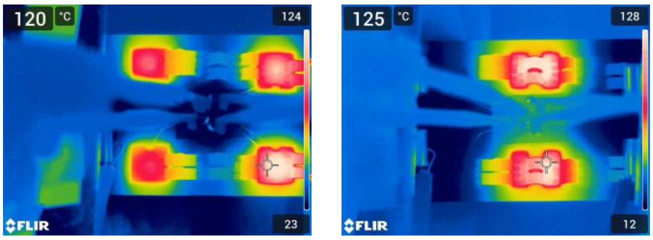

Fig. 5 IR-Images used for offline-analysis. IGBTs to the left, diodes to the right

The diagrams given in Fig. 6 sketch the maximum IGBT-temperature depending on current and coolant flowrate as well as the correlation between NTC-reading and IGBT-temperature.

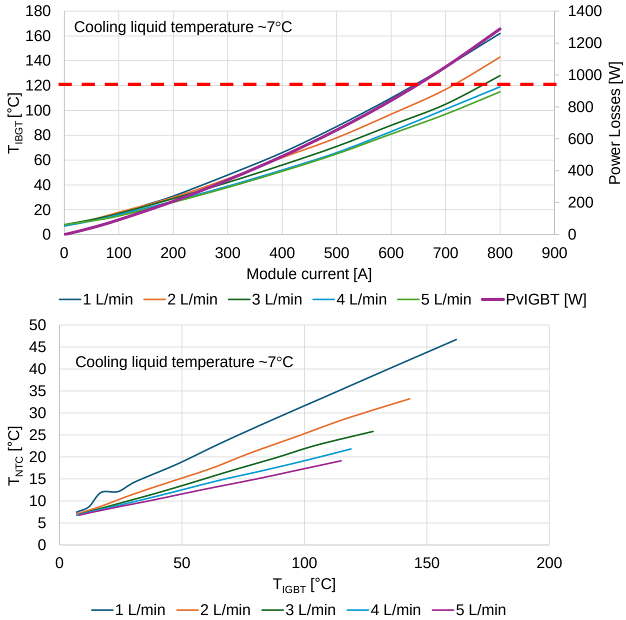

Fig. 6 Results for IGBT-Temperature and NTC-reading

Like the IGBTs, the diodes were measured in the same way with the results compiled in Fig. 7.

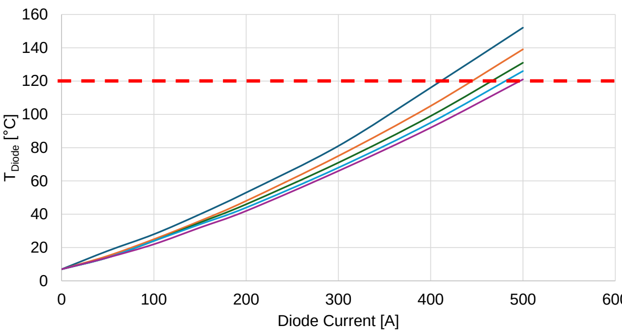

Fig. 7 Thermal development in the diodes depending on current and flowrate

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The dashed lines indicate the thermal limit which arise from the maximum inlet temperature limit. At 65°C, the maximum chip temperature of 180°C would be exceeded.
From these measurements, several conclusions can be drawn:
- The IGBTs current carrying capability exceeds the anticipated value of 600 A within the thermal limits for this given technology. This hints to a more than noteworthy increase in performance compared to other cooling approaches, reaching a thermal resistance junction to coolant of R_{thjc}<0.1 K/W.
- 800 A_{DC} can be drawn from the IGBT within the thermal limits and almost 1300 W of losses were dissipated by the cold plate.
- There is a nicely linear correlation between NTC-reading and die-temperature. This allows using the NTC for thermal monitoring tasks despite the aggressive cooling.
The diodes' thermal resistance is too high, correlating to their small size. Larger diode-area is needed to achieve a 1:1-ratio between IGBT- and diode-current which is desired in the targeted application.

3 Electrical Characterisation

As a next step the prototype modules need to be electrically characterized. Though real application scenarios are most wanted, at this stage of development inverter application is not an option.
The well-established double pulse measurements are performed to investigate the dynamic behavior on component level.

Internally, the setup comprising the single switch topology is constructed from four paralleled IGBTs and the same number of diodes, arranged in two lines as can be seen in Fig. 2

To keep the widest possible range of operation, no internal gate resistors are added.
As for all power components with parallel paths, a highly symmetric approach must be chosen. Besides building a symmetric setup, minimizing parasitic influences induced by the setup itself is mandatory.

For enhanced controllability, the module features an auxiliary collector to allow for precise DESAT-functionality of a gate driver and a Kelvin-emitter for clean gate-control.
To allow proper switching during the tests, a dedicated gate-driver board is designed, based on the single-channel, non-isolated gate-driver IX4352NE [6]. The driver setup includes DESAT-detection and an integrated charge pump to generate positive and negative gate voltages 15/-6 V from a unipolar supply.

With up to 9 A of gate-current, the driver offers sufficient output current to handle the four paralleled IGBTs.

Gate-resistors for turn on and turn-off were varied individually between 5 Ω and 15 Ω.

The board and the gate-driver-PCB are designed to achieve 3D-integration on the top of the module as depicted in Fig. 8.

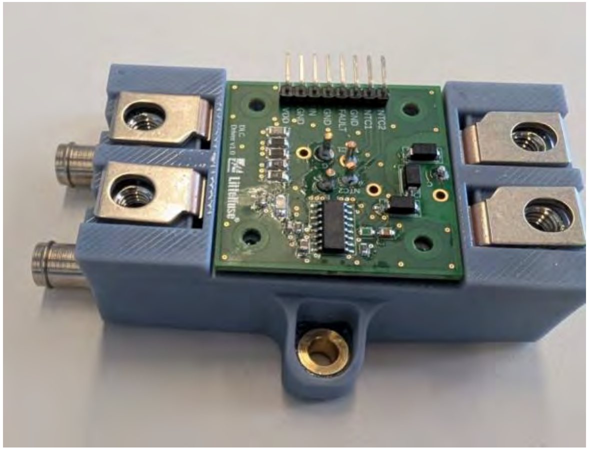

Fig. 8 Module with integrated driver PCB

For the double pulse measurements, a half-bridge configuration is chosen. A 100 µH inductor is used as a load as sketched in Fig. 9 .

The low-side switch in the setup is the device under test

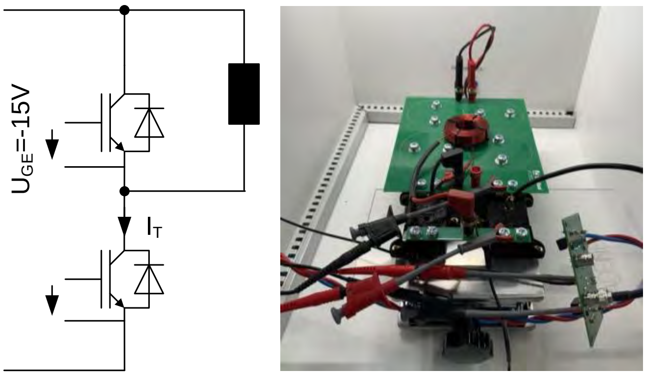

Fig. 9 Double-pulse test setup

While the voltages are measured with differential probes of 500 MHz bandwidth, the currents are measured with Rogowski coils.
The module was investigated using DC-voltages up to 800 V and currents up to 160 A.

Parameters of utmost importance are the switching losses and the semiconductors' transfer characteristics as these are needed to conduct the simulations and verify the thermal design.

Afar from this, the double-pulse test-setup also allows optimizing the gate resistor values.

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The forward characteristic of IGBT and Diode were recorded during the measurement with the results displayed in Fig. 10.

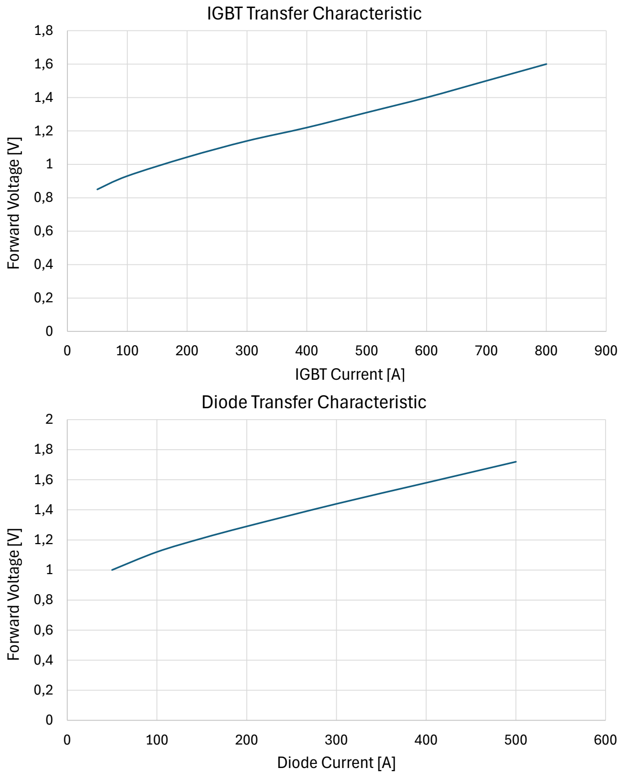

Fig. 10 Forward characteristic of IGBT and diode

The switching losses recorded for the device are summarized in Fig. 11.

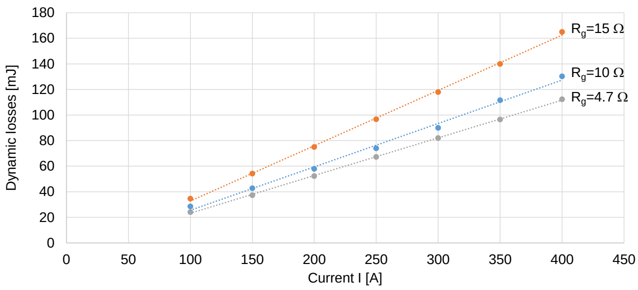

Fig. 11 Measured switching losses, $E_{on}+E_{off}$

Electrical and thermal values determined in these measurements were used as input to the simulation to evaluate the device's performance under operation in the targeted application [4,5].

4 The Truck Application

To evaluate the performance of a drive train equipped with the new devices, a simulation was generated based on a real-world load profile.

Fig. 12 represents the mission profile of the Mercedes-Benz GenH2 Truck, recorded on German highways travelling almost 700 km with 40 tons of gross weight.

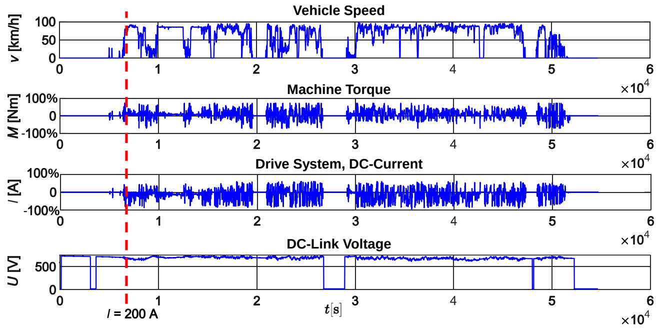

Fig. 12 Mission profile, recorded on German Highways

The vehicle's speed, torque of one permanent magnet synchronous machine (PMSM), DC current of the electric drive system in the high voltage (HV) power net, the rotational speed of one PMSM and the DC-link voltage were recorded.
These parameters are fed into the simulation model thus, the power module losses of the DUT can be simulated based on the real mission profile. The operation point examined shows a peak DC current of 200 A, which represents the most frequently occurring load condition in the mission profile. From a design perspective, this operation point is relevant for long-term thermal stress. A cooling system needs to be designed to cope with the applications' requirements to ensure operation remains within thermal limits and the design achieves the lifetime demanded by the application. Three different scenarios were examined by this simulation approach:

1) Classical, isolated power modules mounted to a liquid cold-plate
2) Direct cooling using oil as a coolant
3) Direct cooling using de-ionized water/glycol mixture as a coolant

The simulation is carried out with a switching frequency of 10 kHz and a coolant temperature of 25 °C.

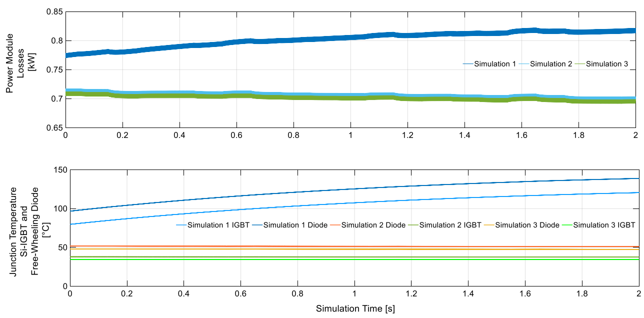

Fig. 13 Simulation results, losses and temperature development

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Losses and temperature development are calculated using a mean current value during the observed interval, the results achieved for operating point are summarized in Fig. 13 and Table 1.

	Losses [kW]	Junction Temperature [°C]	
	Half-Bridge	IGBT	Diode
Simulation 1	0.82	120.6	138.9
Simulation 2	0.73	49.1	55.2
Simulation 3	0.71	37.7	51.1

Table 1 Numerical simulation results

As seen in Table 1, the direct cooled power modules show a massive improvement regarding chip temperature and losses. The validation of the simulation results is in good accordance with the measurements given in Fig. 6.
The calculated losses of the direct cooled power module using water/glycol mixture reveal a loss reduction of 13.4 %.
The measured maximum chip temperature at 200 A is 35 °C as in seen Fig. 6.
The deviation in temperature swing is based on the difference between chip maximum temperature and the averaged value for the virtual junction temperature.
As expected, the temperature reduction achieved with oil as a coolant are slightly lower, still they prove to be much better than the state of the art.
The results demonstrate a clear increase in the safety margin relative to the chip limitations when direct water and oil cooling are applied, compared to the conventional cooling approach using a standard power module on a cold-plate.
For the IGBT, the direct cooling concept results in a temperature decrease of 71 K or a temperature swing reduction of 75 % in simulation 2 and 82.9 K or 86 % in simulation 3.
For the diode, the junction temperature is reduced by 82.2 K which reduces the temperature swing by 82 % in simulation 2 and 90.2 K or 77 % in simulation 3.
The loss analysis supports these findings: while the conventionally cooled module exhibits 0.88 kW of total losses, simulation 2 achieves 0.76 kW and simulation 3 only 0.75 kW, corresponding to a loss reduction of 13.6 % and 14.8 %, respectively. This translates into an overall reduction of losses by approximately 15 % compared to the conventional cooling approach.
Besides the appreciated gain in efficiency, the lower temperatures also lead to a massive increase in lifetime.
Recent work [7,8] focused on aging of silicone gel used for isolation. In that work, a temperature–lifetime relationship based on an Arrhenius-type 10-K rule is used, stating that an increase of the gel's temperature by 10 K approximately doubles the aging rate of the silicone gel. Applying the same model to the present study, the direct cooling concept reduces the junction temperature of the IGBT by 71.5 K in simulation 2 and 82.9 K in simulation 3. This corresponds to an estimated lifetime extension factor of about 88 and 153, respectively, with respect to silicone-gel-driven thermal aging. For the diode, the temperature reductions of 83.7 K in Simulation 2 and 87.8 K in simulation 3 translate into lifetime extensions by factors of approximately 298 and 519, respectively. These results indicate that the proposed cooling concept not only improves efficiency and reduces junction temperatures but is also expected to mitigate thermal aging of the silicone gel by roughly two orders of magnitude, thereby significantly enhancing the long-term reliability of the insulation system.
First power cycling tests with early prototypes have achieved more than twice the number of cycles currently achieved using bond wires [3].
Combined with the lower temperature swing, this too leads to a massive increase regarding one of the major failure mechanisms in power electronic devices.
Looking at the power cycling curve for classical solder-bond components depicted Fig. 14, it can be estimated, what sort of improvement is to be expected:

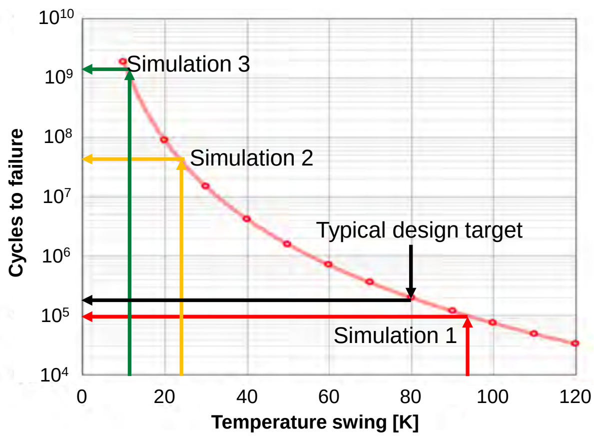

Fig. 14 Power cycling curve for solder-bond-type power modules

For a typical power electronic design, a maximum temperature swing of 80 K is considered, representing a junction temperature of <150 °C on a liquid cooling system with a maximum inlet temperature of 65 °C.
For the given example, this leads to an expected cycling capability of 200.000 cycles.
In contrast, within the classical setup based on isolated power devices in simulation 1, the temperature swing grows to 95 K for the diode chip, leading to a power cycling lifetime of only ~100.000 cycles which is insufficient for the application "Truck".

Doubling this number due to the change in interconnection technology is one step. The far larger impact results from reducing the chip's temperature swing from 80 K to 25 K in simulation 2 which increases the power cycling capability by a factor of 400, reaching 40 million cycles. Combined, this within the targeted application leads to an improvement by a factor of ~800.
With 80 million cycles possible, this renders power cycling a failure mechanism no longer of any concern.
Such a low temperature swing may look like heavy underutilization of the chips in place. Simulation revealed that the device can sustain a permanent current of 590 A_{rms}. Here, the semiconductors are operated at 98 % of the DC-current rating.
Additionally, some of the thermal margin could be used for optimizations like increasing the switching frequency without the need to invest into less economical wide band gap semiconductors.

5 Outlook and future work

The first set of prototypes is currently used to build fully functional inverters. These will be tested in the lab with a full emulation of the load profile to verify the results generated by simulation.
Assuming positive results, further on-road tests in real-world operation and tests on a road-to-rig roller type dynamometer are targeted.
The direct cooling approach and the clip-and-tab interconnection technology also serve as a platform for further developments, targeting different topologies as well as further semiconductor variants.
As the approach is not technically limited to silicon IGBTs, it may be transferred to Si- or SiC-MOSFETs, GaN-devices and even become an addition to classical bipolar devices like thyristors in the future.

Conclusion

From the work presented here, it becomes obvious how much power semiconductors can be improved, when application specific features are considered properly. Breaking with the dogma of building switches isolated by ceramics, instead shifting the isolation to the dielectric coolant and using it as isolating barrier between the electrically active cold-plates, massively improves the thermal transfer. As the application is equipped with this cooling system by design, the approach does not imply additional effort, but instead reduces complexity.
In turn, efficiency, lifetime and reliability increase. As a positive side-effect, this also reduces the amount of DCB-material used to build the components which impacts cost positively.

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