Liquid Cooling for High-Power Electronics

By **Javier Valenzuela**, President, **Thomas Jasinski**, Director of Thermal Systems, and **Zahed Sheikh**, Vice President of Business Development, Mikros Technologies, Claremont, N.H.

To remove heat generated in power semiconductor modules, a liquid-cooled cold plate offers a solution that reduces the barriers to heat flow while maintaining the mechanical integrity of the package.

Power conversion devices such as insulated gate bipolar transistors (IGBTs) convert a small portion of the power flowing through them into heat. These losses are small as a percentage of the power converted, but can result in huge heat loads. For example, a 98% efficient 100-kW converter will require 2 kW of cooling. As the devices and packages become smaller, these losses lead to extremely large heat fluxes at the die—300 W/cm^2 and beyond.

Cooling high-power electronic devices dissipating more than 300 W/cm^2 at the die is beyond the capability of most conventional air- or liquid-cooling solutions. To meet performance requirements, current systems must incorporate large heat spreaders and, in extreme situations, may resort to active refrigeration. This is obviously undesirable from both reliability and cost perspectives. In addition, as will be described in this article, the low thermal resistance required by some applications can only be achieved by intimately integrating the cold plate with the die, therefore removing the thermal resistances associated with the spreader and the interface material. This article describes the challenge in more detail and offers a single-phase liquid-cooled solution that meets both short- and long-term demands in the power electronics industry. In the short term, this cold plate meets the cooling requirements of today's power semiconductor modules. For the long term, as advanced technologies increase current densities and heat flux, it will be combined with other techniques to reduce the total thermal resistance of power modules.

The Thermal Challenge

In order to handle large heat fluxes, power electronics packages must meet the following requirements:

- Low thermal resistance—maximum junction temperatures below 150°C while dissipating several hundred W/cm^2.
- Low electrical losses—low resistance, inductance and capacitance.
- Good electrical isolation—standoff voltages as high as 15,000 V.
- Low thermal stress—coefficient of thermal expansion (CTE) of electronic component in the low ppm/°C.

To discuss these requirements in detail, consider a common packaging approach for high-power IGBT switches illustrated in Fig. 1.

The IGBT and diode die are soldered to a direct bonded copper (DBC) substrate with one of its copper layers patterned to form the electrical connection to the die. The other copper layer of the DBC is soldered to a copper or AlSiC (aluminum silicon carbide) heat spreader, distributing the heat over an area approximately 5 to 8 times larger than that of the die. The heat spreader is mechanically attached to the external cold plate, usually with a thermal interface material to improve thermal communication. In

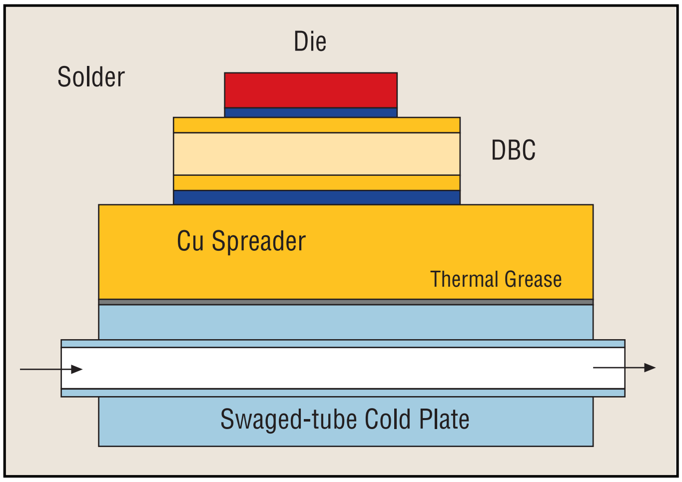


Fig. 1. *Schematic of a power module with thermal management hardware.*

Component		Thermal Resistivity (C/(W/cm²))	Percent of Total
Die attachment structure	R''_I	0.15	22%
Spreader, cold plate & TIM	R''_C	0.50	72%
Fluid - water, 0.3 (L/cm²)/min	R''_F	0.05	7%
Total package resistivity	R''_{ja}	**0.70**	**100%**

Table 1. *Typical resistivities of IGBT power modules.*

low-power applications, the external cold plate may be a bonded-fin, air-cooled cold plate. In higher-power applications, an aluminum or copper swaged-tube cold plate is normally used.

The junction-to-ambient temperature difference of the package (ΔT_{ja}) can be divided into three components:

$$\Delta T_{ja} = \Delta T_I + \Delta T_C + \Delta T_F \qquad (1)$$

where:

ΔT_I = Internal temperature rise associated with conduction through the die attachment structure, including the DBC.

ΔT_C = The cold plate core temperature rise associated with the core and the conduction losses through the heat spreader and interface material.

ΔT_F = Temperature rise of the coolant.

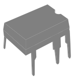
To allow comparison of packages with die of different dimensions and power levels, Equation 1 can be normalized by the maximum die heat flux and rearranged as Equation 2:

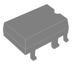
$$R'' = \frac{\Delta T_{ja}}{q''_{max}} = R''_I + R''_C + R''_F \qquad (2)$$

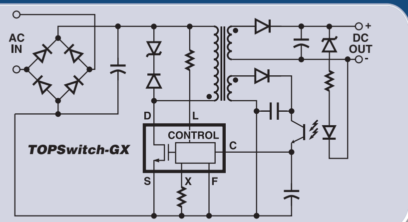
We refer to as the package *resistivity* (to differentiate from the commonly used "resistance," which is defined as the ratio of the approach temperature difference to the total power dissipated by the package).

Table 1 summarizes typical values of thermal resistivities in present power module packaging technology. The total resistivity is about 0.7°C/(W/cm²). For a typical junction-to-ambient temperature difference of about 70°C, the die heat flux is limited to about 100 W/cm². This cooling performance is achieved with a swaged-tube cold plate that is rather large—spreader area ratio of 8—compared to the power module itself.

It is clear from the values of resistivity shown in Table 1 that the greatest room for improvement is in the cold plate/spreader component. Once that resistivity is reduced by an order of magnitude, it also would be desirable to reduce the flow resistivity (defined as $1/\dot{m}c_p$ where $\dot{m}$ is the







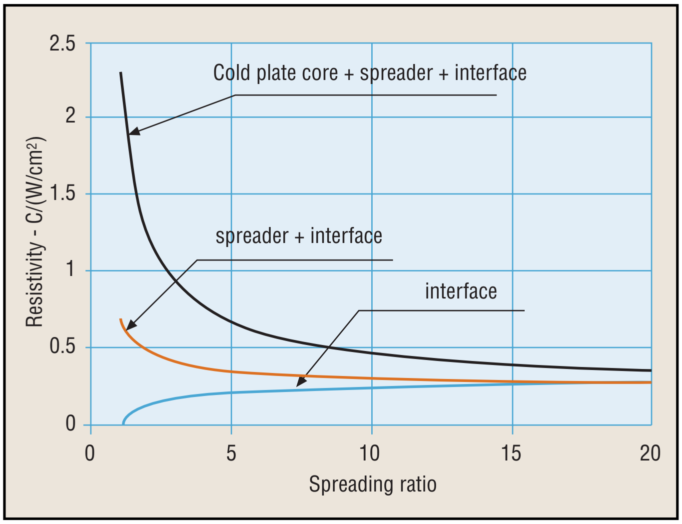


Fig. 2. *Cold plate resistivity as a function of spreading ratio.*

mass flow rate per unit area and C_p is the coolant specific heat) and the die attachment structure resistivity. The flow resistivity can be decreased by increasing the flow rate. The die attachment structure resistivity also can be reduced by a factor of three by eliminating the bottlenecks to the flow of heat resulting from the current die attachment structures. The goal is to make all three resistivities comparable (each having a resistivity of around 0.05°C/(W/cm^2)), with a target for the total package resistivity of 0.15°C/(W/cm^2). That level of improvement would allow dissipation of more than 300 W/cm^2 with an approach temperature difference of less than 50°C.

Facing the Challenge

To achieve a significant reduction in cold plate resistivity (cold plate + spreader), we should look at the contributions from each component in order to find the highest leverage point for our engineering efforts.

The thermal resistivity associated with the cold plate and the spreader can be separated into three components: the cold plate core resistivity, the spreader/cold plate interface resistivity and the spreader resistivity.

- *Cold Plate Core Resistivity.* In most of the cold plate vendor literature, a single value is given for the sum of the cold plate core resistivity and the flow resistivity. This is appropriate for most commercial cold plates because, at the recommended flow rates, the flow resistivity is a small fraction of the total cold plate resistivity. However, in order to compare alternative cold plate technologies, it is best to subtract the flow resistivity from the total cold plate resistivity. Therefore, cold plate core resistivity refers to the cold plate resistivity in excess of the flow resistivity.
- *Core Resistivity = Cold Plate Resistivity – Flow Resistivity.* The core resistivity is a function of the cold plate configuration (number of passes, tube diameter, tube spacing, total area, etc.), cold plate and fluid thermal conductivities, and flow rate. As the flow rate is increased, the core resistivity decreases rapidly at first (because of the increase in the fluid heat transfer coefficient with increasing velocity), and then approaches a constant value (associated with the conduction resistance through the cold plate and tube walls). Conventional swaged-tube cold plates have a core resistivity around 1.6°C/(W/cm^2). To meet our goal, we must reduce the core resistivity by an order of magnitude or more.
- *Interface Resistivity.* Power modules usually are bolted to the cold plate, and care is taken to minimize the gap between the heat spreader and the cold plate. In many cases, the bottom surface of the heat spreader is slightly convex to ensure that the clamping pressure extends over the entire surface of the heat spreader. Thermal grease is placed between the spreader and the cold plate to further

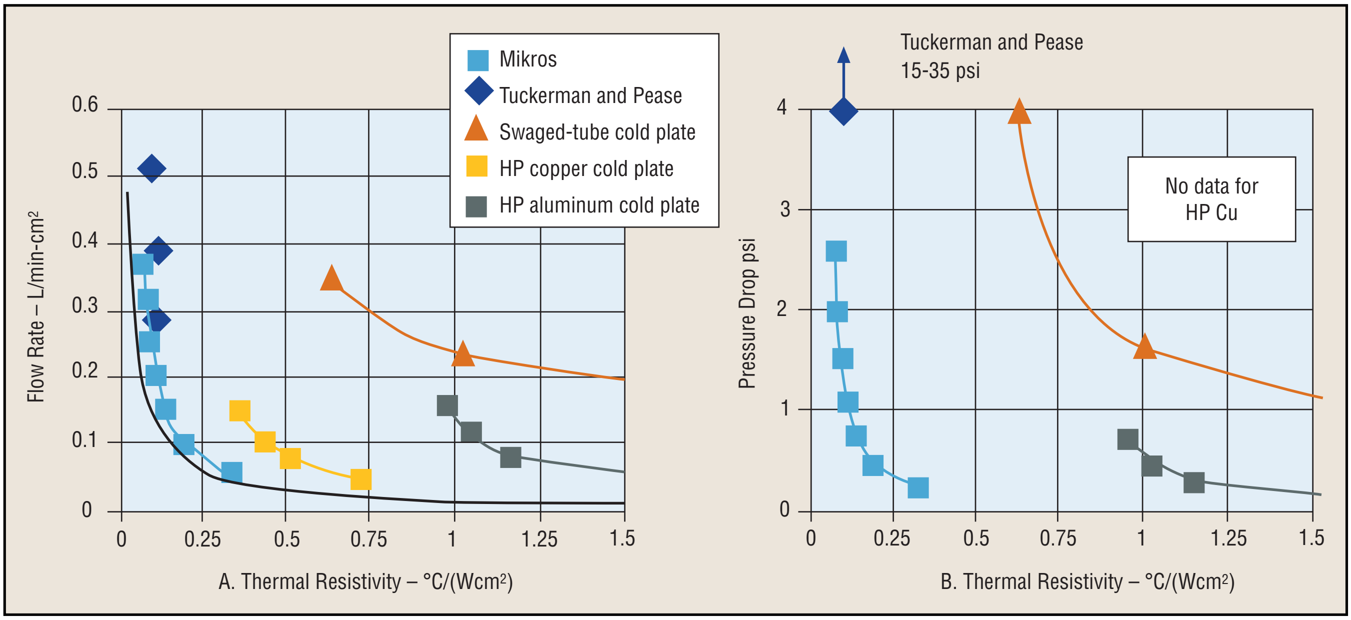


Fig. 3. *Performance curves for NCP cold plates illustrate flow rate versus thermal resistivity (A) and pressure drop vs. thermal resistivity (B).*

Component	Thickness (microns)	Thermal Conductivity (W/ºC-m)	Thermal Resistivity (ºC/(W/cm^2))	
			One-sided cooling	Two-sided cooling
Silicon die	200	150	0.013	0.003
Solder joint	150	35	0.043	0.021
Cu contact	300	380	0.008	0.004
Al Ni ceramic	600	180	0.033	0.017
Die attachment structure total			0.097	0.045
NCP core resistivity			0.040	0.020
Flow thermal resistivity (water, 0.3 L/min-cm^2)			0.049	0.049
Total package resistivity			**0.190**	**0.110**
Total thermal effectiveness			**0.260**	**0.430**

Table 2. *Comparison between one and two-sided cooling.*

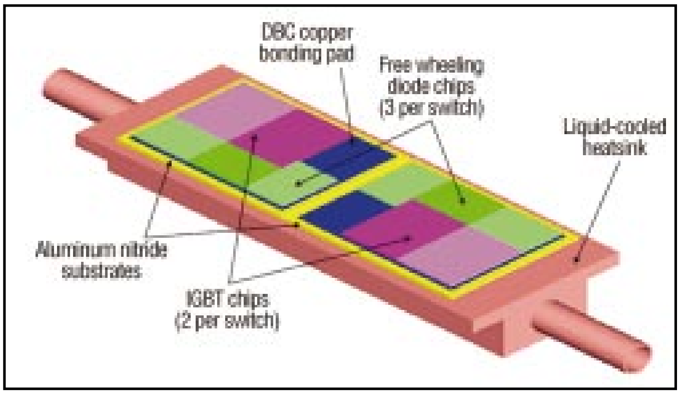


Fig. 4. *Complete assembly for a power module.*

reduce the contact resistance. A typical value of the interface resistivity is 0.7 °C/(W/cm^2) [1].

- *Spreader Resistivity.* For high heat flux power devices, a heat spreader is placed between the power module and the cold plate in order to reduce the heat flux at the cold plate surface. In this manner, the temperature rise associated with the cold plate resistivity and the interface resistivity is reduced by the spreading ratio.

However, the spreader itself introduces an additional thermal resistance, called "spreading resistance." The value of this additional thermal resistance is a function of the spreader thermal conductivity, the size of the die and the spreading ratio.

Fig. 2 shows cold plate/interface/spreader resistivity as a function of spreading ratio for a 2-cm × 2-cm die attached through a copper heat spreader to a swaged-tube cold plate. At a spreading ratio of 8, the total resistivity associated with the spreader, interface and cold plate core is about 0.5°C/(W/cm^2). Note that this resistivity is based on the heat flux at the surface of the die.

The external cold plate and the associated heat spreader and grease interface represent about 72% of the present package thermal resistivity. This resistivity can only be reduced in a significant way by eliminating the grease interface and attaching the cold plate directly to the heat spreader. Otherwise, even order of magnitude reductions in cold plate matrix resistivity would result in at most a 25% reduction in total package resistivity.

In order to reach our resistivity goal of 0.05°C/(W/cm^2) for the cold plate core/heat spreader combination, it is apparent from Fig. 1 that the heat spreader must be eliminated as well. A spreading ratio of 1.2 would already introduce a spreading resistivity of 0.05°C/(W/cm^2), our target for the combined cold plate/spreader resistivity.

With the interface and spreader resistivities eliminated, one major challenge remains. It is now necessary to use a cold plate that has a core resistivity of less than 0.05°C/(W/cm^2) and can be directly bonded to the DBC.

A New Solution

A novel micro-channel cold plate designed and fabricated by Mikros Technologies achieves the required performance levels with very low thermal resistivity and modest pressure drop. This cold plate uses normal flow configuration as opposed to parallel flow found in other cold plates and micro-channel heatsinks. Incorporating this patented flow configuration into a novel cold plate design has resulted in a solution that can remove in excess of 1000 W/cm^2 with a low pressure drop and very low core resistivity.

Fig. 3(a) and (b) shows the thermal resistivity and pressure drop of the Normal Flow Cold Plate (NCP) compared to other high performance cold plates. The solid line in Fig. 3(a) represents the flow resistivity, which provides the theoretical lower bound for the resistivity of any cold plate.

In addition to low resistivity and pressures drop, the NCP cold plate demonstrates high values of effectiveness, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. A high effectiveness cold plate uses a high fraction of the cooling capacity of the coolant. Most commercial swaged-tube cold plates have effectiveness of lower than 40%. The NCP cold plates can reach values of 80% to 90% in effectiveness.

Integrating NCP into an IGBT Module

The high effectiveness of the NCP allows the thermal designer to remove significant amounts of heat not possible with conventional methods. This performance stems from the very low thermal resistivity of the cold plate that allows one to eliminate the heat spreader and the thermal interface material.

Fig. 4 shows the schematic of the cold plate housing to which the electronics devices are bonded using DBC. While the housing is designed to accommodate the placement of all devices, the NCP cold plates themselves are placed directly below the IGBT die and occupy a small portion of the housing.

While the improvements described above will reduce the thermal resistivity of present power modules by a factor of about 2.5, it will not be long until performance is again limited by our ability to cool the devices. It is anticipated that advanced power devices—possibly based on SiC or GaAs technology—will operate at current densities resulting in heat generation of 500 W/cm^2 to 1000 W/cm^2 and perhaps even higher. To take advantage of the reduced system size and weight this technology makes possible, it is necessary to decrease the total package thermal resistance by another factor of two or more.

The next step in reducing the total package resistivity should focus on improving the die attachment structure. This can be done by reducing the resistivity associated with the solder joint at either side of the DBC substrate. Further reduction of the die attachment structure resistivity could be achieved by cooling the die from both sides. Table 2 shows the results that can be anticipated by the above improvements. The total thermal resistivity of the package would now be reduced to below 0.15°C/(W/cm^2).

The ability to remove large amounts of heat that is generated in current and emerging power electronic devices depends on a careful examination of all thermal resistances from the junction to ambient. It is shown that the target thermal performance for high heat flux applications can only be achieved by eliminating the thermal interface and spreading resistivities. This can be done only if the cold plate has a very low thermal resistivity and is directly bonded to the die attachment structure.

The NCP provides the low resistivity required in high heat flux applications and, at the same time, reduces the size and the weight of the integrated module. In addition, the high effectiveness achieved by using the NCP cold plate means that coolant flow rate can be reduced.

The primary thermal design challenge is to reduce any barrier to the heat flow without reducing the mechanical integrity of the package. The steps outlined in this article go a long way toward removing a significant part of the total resistance. Further improvements in the total package resistivity will require a new die attachment structure that can eliminate bottlenecks such as the solder joint on both sides of the DBC substrate. **PETech**

References

1. *Khatir, Z. and Lefebvre, S.* Seventeenth IEEE SEMI-THERM, *2001, pp 27-34.*