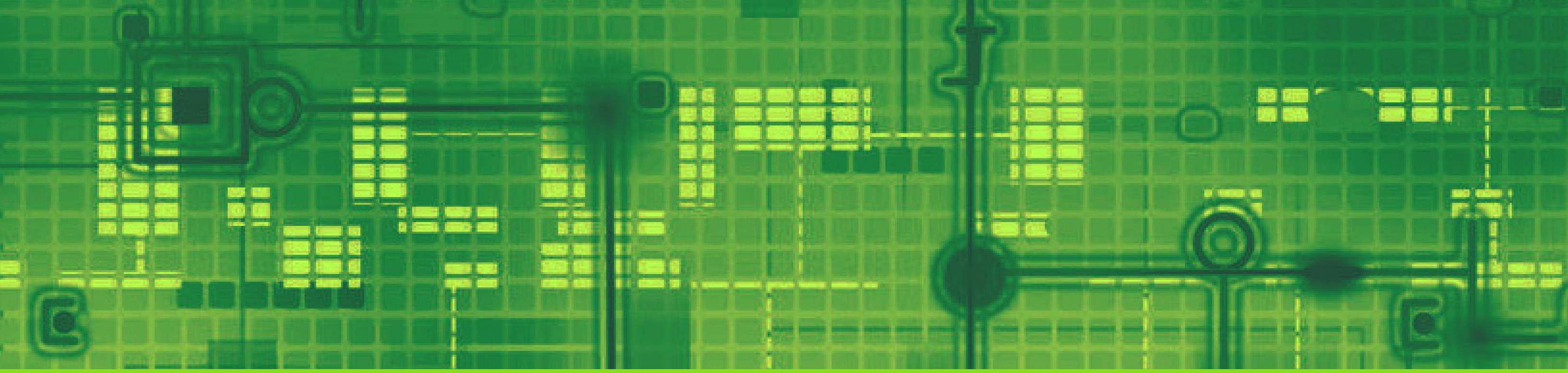


Microchannel Heat Sink Application

in IGBT Modules

Advancements in semiconductor technology have pushed engineers to look for more innovative and effective methods to cool semiconductor devices with increasing power density. There have been continuing efforts to shrink the Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) and Insulated Gate Bipolar Transistor (IGBT) gate size. However, this has made it impossible, for a standard electronics package that is pure air-cooled, to handle the heat load dissipated by some high-power devices, such as high end CPUs, power transistors, DSP chips, etc. Innovative packaging methods and high performance liquid-cooled microchannel heat sinks have thus become the research focus to solve the thermal problem of high-power devices.

IGBT is a three-terminal power semiconductor device primarily forming an electronic switch and, in newer devices, is noted for combining high efficiency and fast switching. It switches electric power in many modern appliances, vehicles and devices: Variable-Frequency Drives (VFDs), electric cars, trains, variable speed refrigerators, air-conditioners and even stereo systems with switching amplifiers. IGBTs of newer designs have a smaller footprint and higher power handling density than their predecessors, which brings more challenges to cool these kinds of devices. Although the thermal problems have been offset by advances in IGBT chip design, the cooling capabilities of present modules limit the device performance.

Traditionally the IGBT modules were cooled by forced air-cooled heat sinks. Air-cooled heat sinks are still good thermal management solutions for lower-power and less temperature- restricting IGBT modules. However, the high-power IGBT modules are exclusively cooled by liquid-cooled heat sinks (cold plates). Liquid-cooled heat sinks for IGBT modules can have a variety of designs depending on their power density, cooling fluid type, fluid flow rate, heat sink operating temperature and pressure drop, etc. The low cost solution is an aluminum cold plate with embedded copper tubing; a moderate solution can be a copper cold plate with gun-drilled liquid cooling paths; the most expensive and complex solution is a copper cold plate with machined or etched microchannels. Liquid-cooled microchannel heat sinks have an extremely low thermal resistance when compared with traditional liquid-cooled, tubed heat sinks. A well-designed liquid-cooled microchannel heat sink can dissipate over 100 W/cm^2 heat flux at the device level. This paper discusses several methods of using liquid-cooled microchannel heat sinks on high-power IGBT modules.

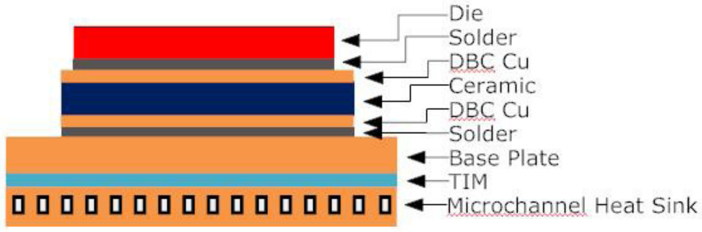


Figure 1. IGBT Module with External Microchannel Heat Sink

Figure 1 shows the typical IGBT module structure with an external heat sink attached to its base plate. The major layers in the thermal path of a conventional IGBT module are the die attach solder, a metal-clad ceramic substrate (copper directly bonded on alumina or aluminum nitride), substrate attach solder, metal or composite baseplate, thermal interface material (TIM) and the external liquid-cooled heat sink.

The thermal resistance of the IGBT module from die to ambient can be calculated based on the following equation,

$$R_{ja}=R_{die}+2R_{solder}+2R_{DBC}+R_{substrate}+R_{base}+R_{TIM}+R_{microchannel}$$

The summary of thermal properties of the typical layers are listed in Table 1,

	Material	Thermal Conductivity (W/m·°C)	Thickness (mm)	Unit Thermal Resistance (°C·cm²/W)
Die	Silicon	149	0.5	0.017
Solder	Sn96.5Ag3.5	55	0.1	0.018
DBC	Copper	401	0.3	0.008
Ceramic	Aluminum Nitride (ALN)	270	0.8	0.008
DBC	Copper	401	0.3	0.008
Solder	Sn96.5Ag3.5	55	0.1	0.018
Base Plate	Copper	401	1	0.025
TIM	Grease	2	0.05	0.25
Microchannel Heat Sink	Copper	401		0.10-0.5 (at 2 GPM flow)

Table 1. Thermal Properties of Typical Layers

All layers contribute to the overall thermal resistance. Even the thermal resistance of solder layers and DBC copper layers have a significant effect on total thermal resistance. Although the TIM and microchannel heat sinks have a large unit thermal resistance, their thermal resistance is at a similar level as other layers, because they have a large surface area. Figure 2 shows the typical machined copper microchannel heat sink. The thermal resistance of the microchannel heat sink varies by design and is directly related to fluid flow rate.

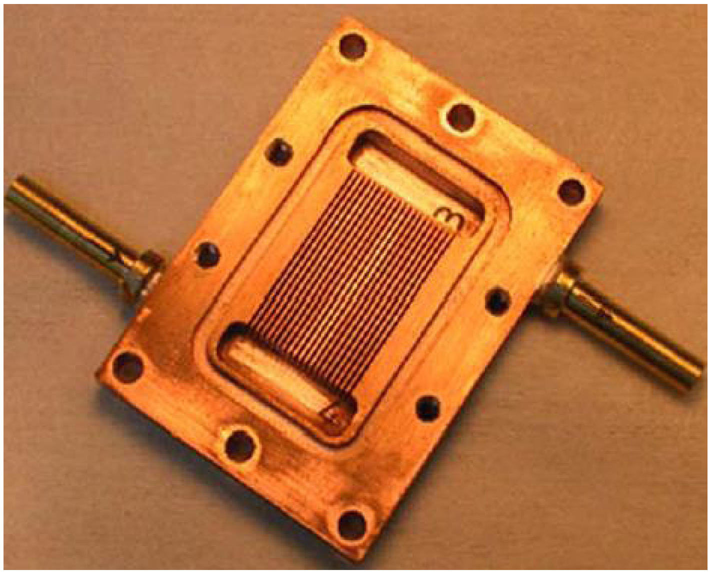


Figure 2. Typical Copper Microchannel Heat Sink [1]

To increase the IGBT module power density, the microchannel heat sink can be integrated into the base plate (see Figure 3). By doing this, the thermal interface material and base plate are eliminated.

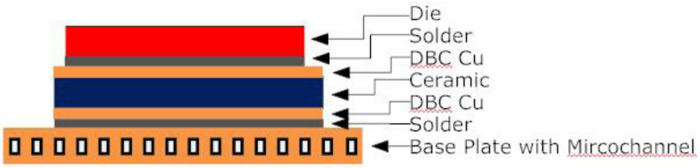


Figure 3. IGBT Module with Integrated Base Plate Microchannel Heat Sink

The thermal resistance of the IGBT module becomes,

$$R_{ja}= R_{die}+2R_{solder}+2R_{DBC}+R_{substrate}+R_{base}$$

Because most base plates are made of copper or copper alloy, mechanical machining and chemical etching can be used to fabricate the microchannel.

Its thermal performance (R_{base}) is expected to be similar to an external copper microchannel heat sink ($R_{microchannel}$). However, the overall IGBT model thermal resistance will be smaller because of the elimination of TIM and the extra layer. It is expected that the overall thermal resistance will be reduced by 20%.

To further reduce the IGBT module overall thermal resistance, the microchannel can be integrated into the ceramic of substrate layer (see Figure 4).

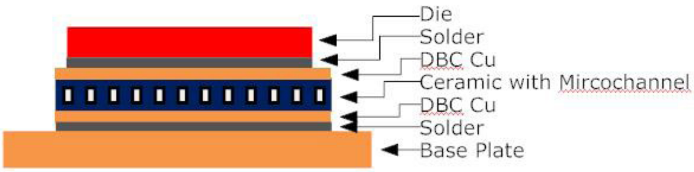


Figure 4. IGBT Module with Integrated Substrate Microchannel Heat Sink

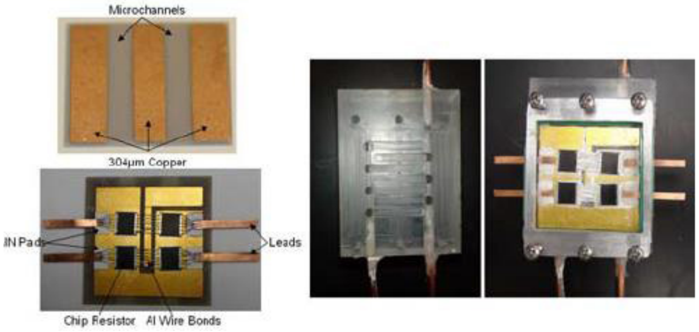


Figure 5. Direct-Bond-Copper Aluminum Nitride Manifold-Microchannel Heat Sink [2]

By doing so, the thermal resistance of the IGBT module is reduced to,

$$R_{ja} = R_{die} + 2R_{solder} + 2R_{DBC} + R_{substrate}$$

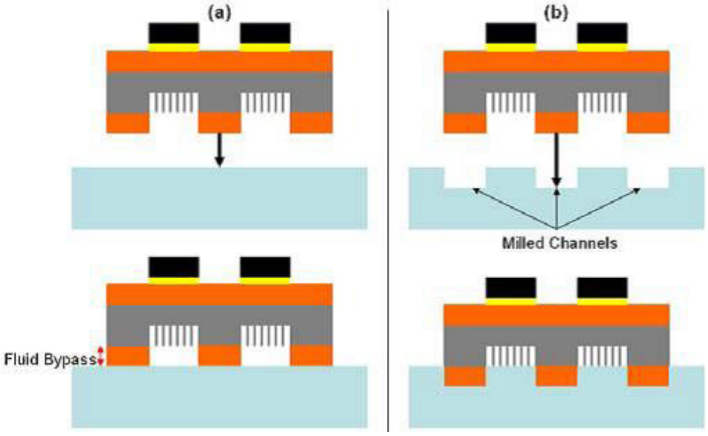


Figure 6. Cross-Section of Two AlN DBC MMC [2]

The overall thermal resistance will be reduced by ~30% when compared with the original design. The substrate is generally made of thermally conductive ceramics, such as aluminum oxide (AL_2O_3), beryllium oxide (BeO), aluminum nitride (AlN), etc. Figure 5 shows the direct-bond-copper aluminum nitride manifold-microchannel (AlN DBC MMC) cooling solution for IGBT modules in an electrical vehicle proposed and tested by Sharar et al. [2]. The cross-sections of two different microchannel heat sinks are shown in Figure 6. The microchannels are chemical etched on the AlN substrate. The tests conducted by Sharar et al. [2] show that the thermal resistance of the heat sink can reach 0.25°C.cm^2/W at a flow rate of 0.6 liter/min, which is very impressive at such a low flow rate.

The ultimate solution for high-power devices is integrating the liquid cooling into the die, as is illustrated in Figure 7. In this case, the microchannels are directly etched on silicon die. In this configuration, the cold water inside the microchannel will directly cool the die, which eliminates all the conduction resistance associated with all the layers.

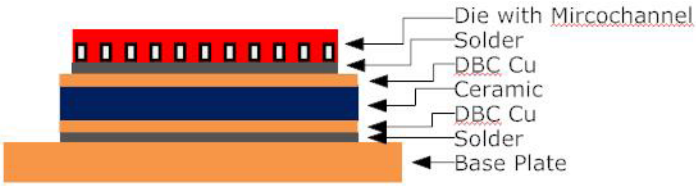
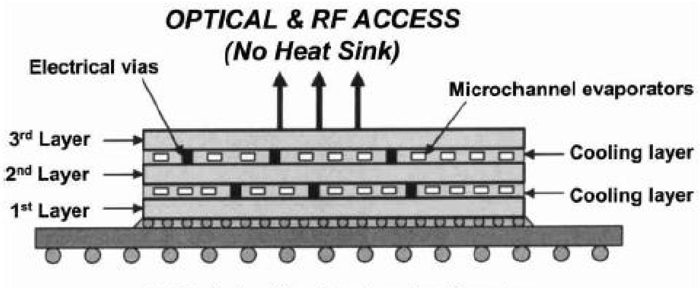


Figure 7. IGBT Module with Integrated Die Microchannel Heat Sink

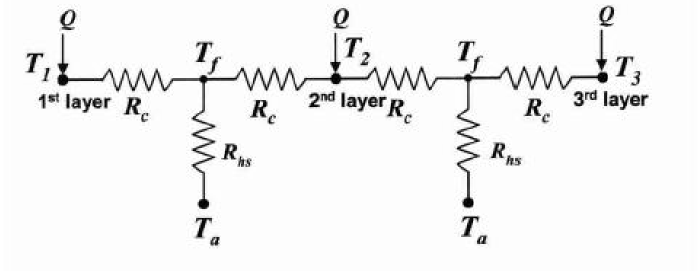
The thermal resistance of the IGBT module from die to ambient is,

$$R_{ja} = R_{die} + R_{microchannel}$$

The overall thermal resistance only includes two terms: the conduction resistance of die and the convection resistance of the microchannel. The concept of integrating a microchannel into a die has been proposed by many researchers for 3D chips. For example, Koo et al. suggested the use of integrated microchannel cooling for a three-dimensional die (see Figure 8). Nobody has integrated such microchannel in real IBGT module.



(a) 3D circuit with a microchannel cooling system



(b) Thermal circuit for microchannel cooling

Figure 8. Conceptual Schematic of A Microchannel Cooling Network for a 3D Die [3]

By integrating the microchannel into the die, it is estimated that the overall IGBT module thermal resistance will be reduced by ~50%, which means that the power density of the IGBT can be doubled at the same operating conditions.

We have seen the huge differences in thermal resistance made by integrating the microchannel into the IGBT module in different levels. However, there are some technical challenges that exist for applying such a technology. Etched microchannels have a small size, which benefits heat sink thermal performance, but this induces a large pressure drop and is prone to fouling. The piping, routing and preventing leakage of microchannel embedded in the die needs the cooperation of system engineers, mechanical engineers, die designers and thermal engineers. It is a system design work and must be tailored and customized for each IGBT module.

References:

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2. Sharar, D., Jankowski, N., and Morgan, B., "Thermal Performance of a Direct-Bond-Copper Aluminum Nitride Manifold-Microchannel Cooler" Semiconductor Thermal Measurement and Management Symposium, 2010. SEMI-THERM 2010. 26th Annual IEEE.

3. Koo, M. J., Im, S., Jian, L., "Integrated Microchannel Cooling for Three-Dimensional Electronic Circuit Architectures", Journal of Heat Transfer, January 2005, Vol. 127 p49-p58.