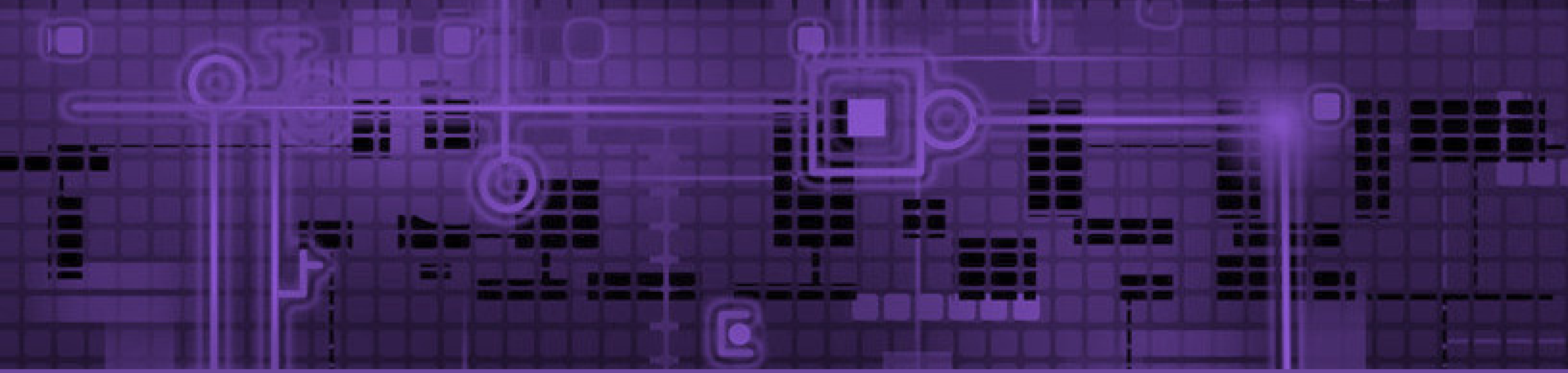


Direct-Bond-Copper Aluminum Nitride

Microchannel Heat Sink for IGBT Modules

The advancement in semiconductor technology has coerced engineers into looking for more innovative and effective methods to cool semiconductor devices with increasing power density. The continuing efforts towards the shrinking of the Metal Oxide Semiconductor Field-Effect Transistor (MOSFET) and the Insulated Gate Bipolar Transistor (IGBT) gate size have made it impossible for standard electronics packages and pure air-cooled devices 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 become the focus of research efforts to solve the thermal problem of high-power devices.

Power modules used in Hybrid Electric Vehicles (HEV) provide additional challenges for cooling IGBT modules, because they require low temperature differentials (20-30°C) between the die and the coolant, while simultaneously dissipating high heat fluxes. Although the thermal problem has been offset by advances in IGBT chip design, the cooling capabilities of present modules limit the device performance.

To solve the cooling problem of IGBT modules in HEV, two approaches have been studied by researchers to improve the effectiveness of power module cooling systems. One approach aims to reduce the thermal resistance by eliminating layers between the die and the cooling medium, decreasing the intermediate layer thicknesses, and increasing its thermal conductivity. The second approach focuses on increasing the efficiency of the heat sinks by reducing their thermal resistance.

Leslie [1] illustrated some thermal management concepts for high-power IGBT modules (see Figure 1). In the cooling setup of conventional IGBT modules, the top face of the chip is usually kept open for wire-bonding and electrical interconnections, while the backside is die- bonded to a direct-bond-copper (DBC) substrate. The copper DBC layer provides a platform for die attach and electrical connections while the aluminum nitride (AlN) layer provides electrical isolation. The direct-bond-copper (DBC) substrate is then soldered to a baseplate which is normally made of copper as a heat spreader. The heat flux is removed by a heat sink/cold plate which is attached to the heat spreader. Because each layer, solder joint and TIM add additional thermal resistance to the heat transfer path, this design is not very efficient for thermal management.

In Figure 1, Type 1, 3, and 4 concepts remove the heat spreader and bring cooling directly to the direct-bond-copper (DBC) substrate, which eliminates the thermal impedance caused by the heat spreader and its attachments. Types 4 and 5 work on improving the efficiency of the heat sinks by using a liquid-cooled microchannel structure.

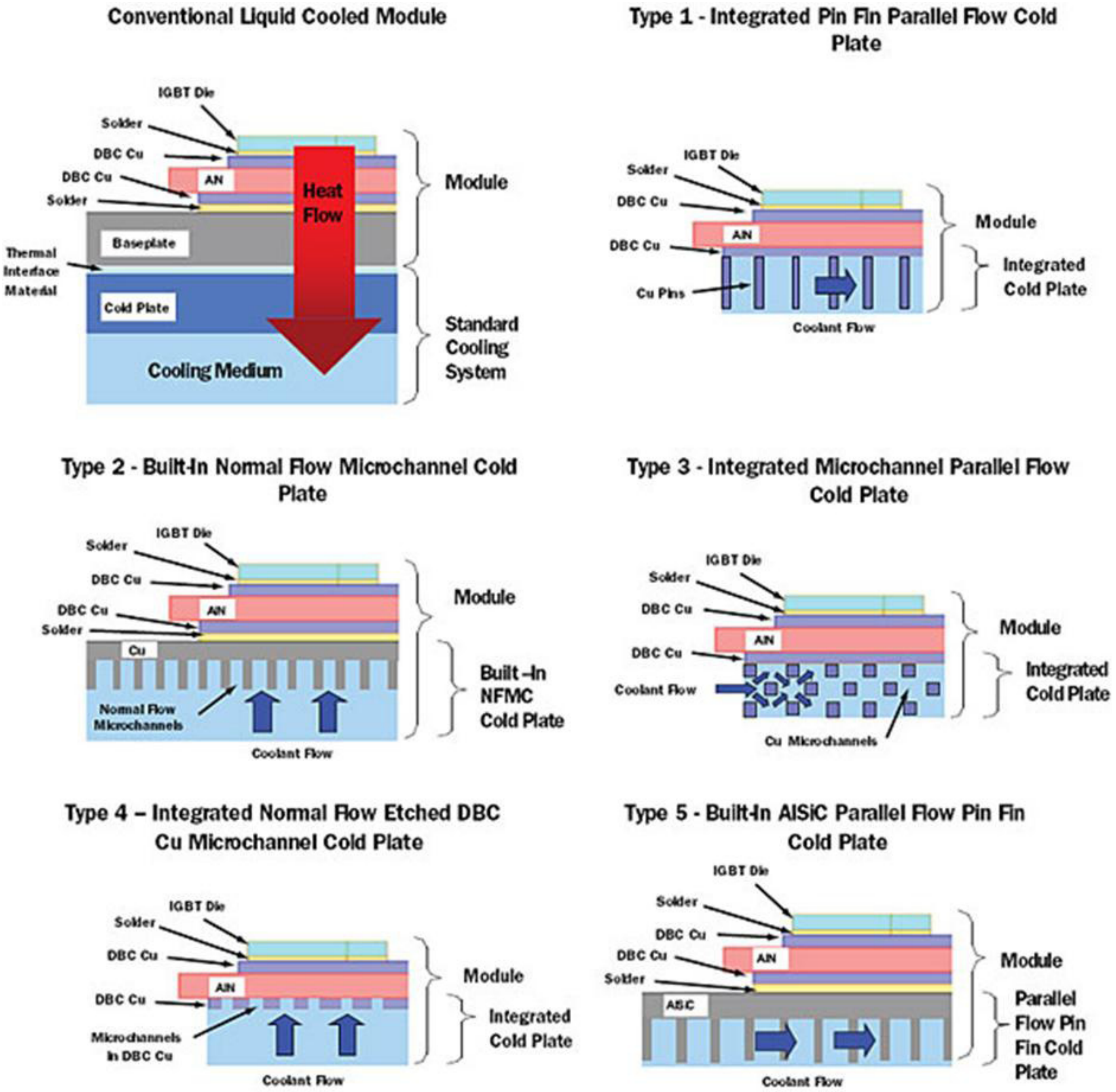
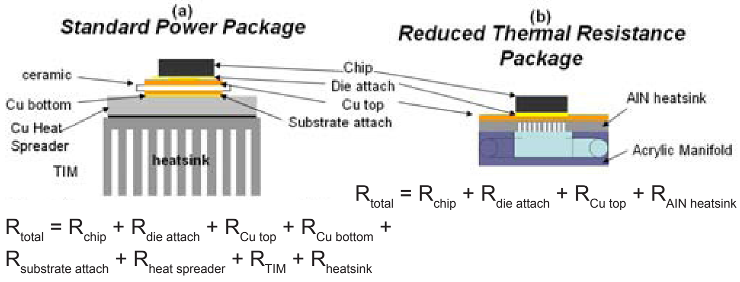


Figure 1. Cross Sections of IGBT Module Cooling Concepts [1]

Sharar et al. [2] proposed and tested a new direct-bond-copper aluminum nitride manifold-microchannel (AlN DBC MMC) cooling solution for IGBT modules in HEV. Their solution is illustrated in Figure 2. In their new method, the copper heat spreader is eliminated and the microchannels were directly machined onto the aluminum nitride substrate.

Figure 3 shows the cross section of the AlN DBC MMC. A direct-bond-copper aluminum nitride substrate with 304µm layers of copper on each side was chosen for the experiment. The copper was patterned on the topside for die attachment and in three parallel strips on the backside for stress relief. Two sets of 30 microchannels were cut by using a diamond-tipped dicing saw. Each channel had



$$R_{total} = R_{chip} + R_{die\ attach} + R_{Cu\ top} + R_{AlN\ heatsink}$$

$$R_{total} = R_{chip} + R_{die\ attach} + R_{Cu\ top} + R_{Cu\ bottom} + R_{substrate\ attach} + R_{heat\ spreader} + R_{TIM} + R_{heatsink}$$

Figure 2. Comparison of Thermal Resistance in a) Standard Power Package b) AlN DBC MMC Power Package [2]

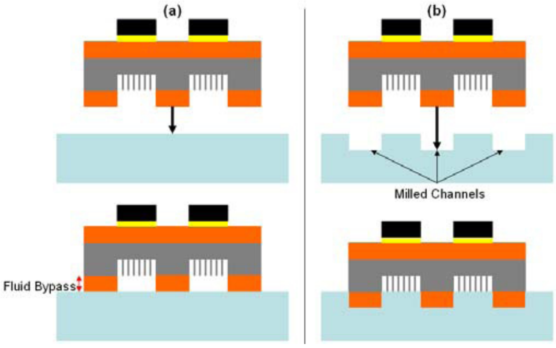


Figure 3. Cross-Section of AlN DBC MMC (a) without Milled Channels and (b) with Milled Channels [2]

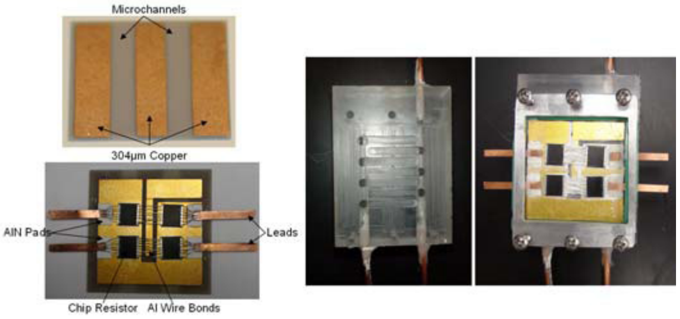


Figure 4. Fabricated AlN DBC MMC Test Device [2]

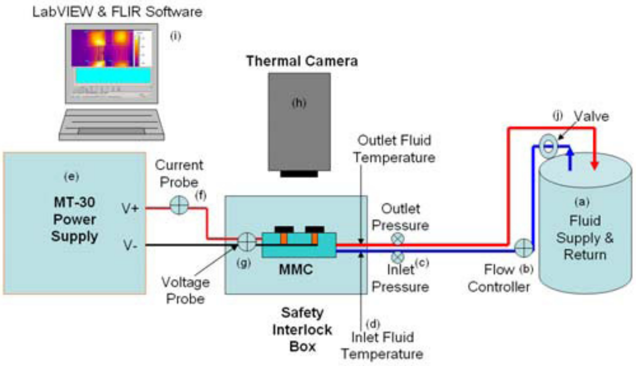


Figure 5. Schematic of AlN DBC MMC Experimental Setup [2]

a width of 250μm, a depth of 300μm, and a pitch of 350μm. To remove the fluid bypass, an acrylic manifold with three 330μm deep strips was used as a manifold back plate (see Figure 2 (b)). Figure 5 shows a completed AlN manifold microchannel cooler.

Sharar et. al [2] used the test setup shown in Figure 5 to conduct the thermal test for the AlN DBC MMC. Experimental data was obtained for the MMC device using 25°C de-mineralized water, 80°C demineralized water, 80°C 50% ethylene glycol and demineralized water (EGW), 80°C 50% propylene glycol and demineralized water (PGW), and 80°C 0.14% 4-5nm nanodiamond solution in 50% ethylene glycol and water.

Figure 6 shows the pressure vs. flow rate graph for different working fluids at different inlet temperatures. At 80°C, the demineralized water has the lowest pressure drop.

Figure 7 shows the thermal resistance vs. flow rate for all test conditions. The thermal resistance calculation is based on the average temperature across the coolest and best performing fluids. For all fluids, the thermal resistance decreases rapidly with an increase of the flow rate and begins to level off at higher flow rates. The water constantly outperforms other working fluids for the same volumetric flow rate.

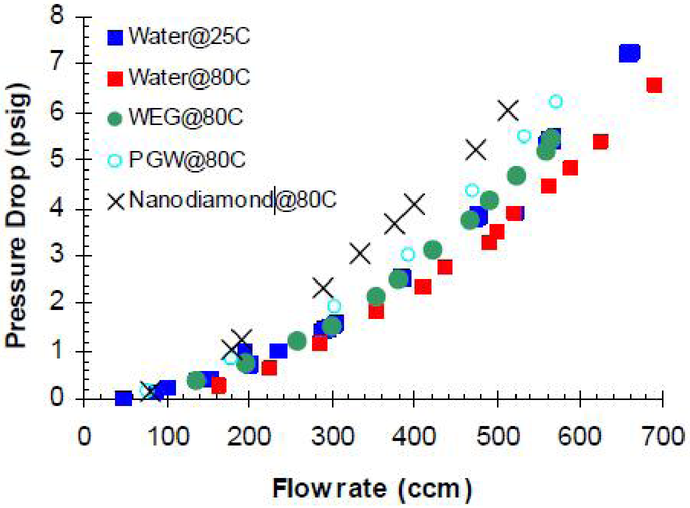


Figure 6. Pressure vs. Flow Rate for Different Cooling Fluids [2]

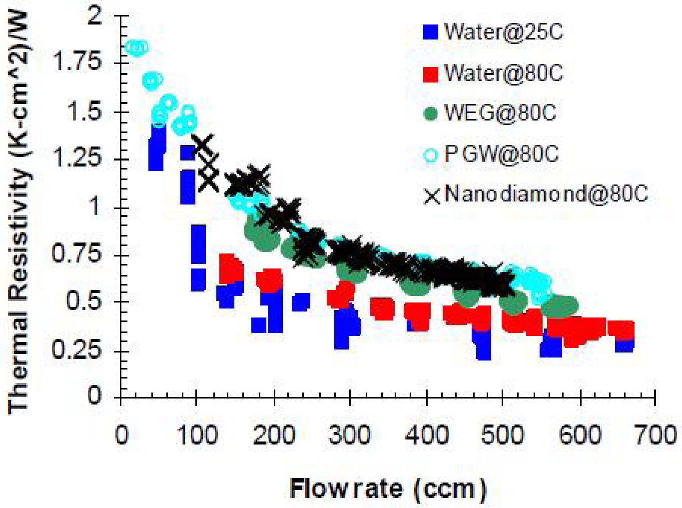


Figure 7. Thermal Resistance vs. Flow Rate for Different Cooling Fluids [2]

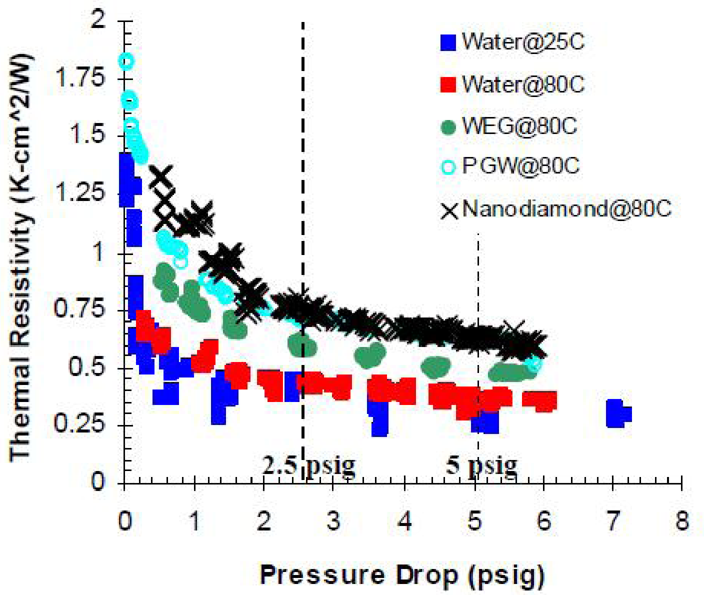


Figure 8. Thermal Resistance vs. Pressure Drop for Different Cooling Fluids [2]

Fluid	Rth@ 2.5 psig	Flowrate (ccm)	Rth@ 5 psig	Flowrate (ccm)
Water @ 25°C	0.413	386	0.316	548
Water @ 80°C	0.427	424	0.359	600
EGW @ 80°C	0.592	383	0.486	544
PGW @ 80°C	0.715	350	0.622	509
Nanodiamond @ 80°C	0.759	301	0.628	457

Table 1. Thermal Resistance (K-cm²/W) for Different Cooling Fluids at 2.5 PSI and 5 PSI [2]

As 5 PSI is the pressure drop threshold for most HEV applications, Figure 8 shows the thermal resistance of the MMC cooler with reference values at the upper limit of 5 PSI and half of the limit, 2.5 PSI. The average thermal resistivity values and flow rates for each fluid at the two reference values are listed in Table 1. Because the demineralized water generates less pressure drop and has less thermal resistance when compared with other fluids at same flow rate, it stands out as the best working fluid when comparing the thermal resistance at the same pressure drop. However, other working fluids demonstrated good thermal performance on MMC. For example, EGW and PGW were capable of 0.486 and 0.622 K-cm²/W at 5 psig and 80°C. The experiments conducted by Sharar et. al [2] show that the AlN DBC MMC is a very simple way to package the IGBT and can reduce the overall thermal resistance from the IGBT to ambient. In the test, the demineralized water showed the best performance. However, pure water cannot work under freezing conditions. So, the EGW would be a better choice for the HEV application. The PGW and nanodiamond solution in the EGW are less favorable choices for this application.

References:

1. **Leslie, S., "Cooling Options And Challenges of Semiconductor Modules", Electronics Cooling, November, 2006.**

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.**