

Cool Running Autos

Cooling of IGBT based power modules for Hybrid Electric and Electric Vehicles

It has been forecast that by 2020 there will be upwards of 10 million passenger and light truck vehicles sold annually that are powered entirely or in part by electric motors. Starting with the leadership of Toyota's first Hybrid car launched in 1997, significant progress in various power train electrification designs have been made by every major OEM, especially during the last five years.

By Thomas Sleasman and Birol Sonuparlak, Thermal Management Solutions, Rogers Corporation, Chandler, Arizona, U.S.

Today's Hybrid Electric Vehicle Power Module Market

Hybrid drive systems use a combination of an internal combustion engine (ICE) and one or more electrical motors (EM). Variations in hybrid drive systems depend on how the EM and ICE of a power train connect, and also when and at which power level each propulsion system contributes to powering the vehicle.

There are two types of HEV drive systems, series or parallel. The parallel system is currently used by almost all the major OEMs. Parallel hybrid systems can be further categorized as assist, mild and full hybrid. The Toyota Prius and the Ford Escape are examples of full hybrids, as they can run on just the ICE, the EM or a combination of both. Mild hybrids on the other hand do not run on EM only. The EM provides additional power as required while the ICE still provides the primary power for the power train. Honda's Integrated Motor Assist (IMA) is such a mild hybrid. A third hybrid drive system is the plug-in hybrid (PHEV). These should be increasingly popular in the future. PHEV allows the driver to choose the mode of operation. The driver can choose the EM mode of operation for short distance commuting or the independent ICE mode of operation for long distance driving. The PHEV's larger battery can

be charged using standard voltages from a typical power grid system.

Electric vehicles (EVs) are also receiving renewed attention. The electric motor (EM) is the only source of propulsion in EVs. Prior to 2003, most of the major OEM's, such as Chrysler, Ford, GM, Honda, Nissan and Toyota, produced a limited number of EVs. More recently, a Renault-Nissan alliance has started developing a complete range of 100% electric power trains with power ratings of 50kW to 100kW. Renault has already announced the final production design of two electrical vehicles, Fluence ZE and Kangoo ZE. The Fluence production plant will start manufacturing this sedan in the first half of 2011 at the Bursa OYAK-Renault plant in Turkey. Renault forecasts 100,000 vehicle sales over five years starting in 2011. The

Fluence will also be the first EV to test the Better Place battery swap concept in Israel.

HEV/EV Power Module Solutions

The efficient dissipation of heat generated by Insulated Gate Bipolar Transistor (IGBT) based power modules used to control these electric drive designs is critical to system quality and reliability. Design concepts such as integrating inverter, DC-DC converter and electronic control unit, along with reducing the number of IGBT power chips, are helping design engineers to lower the size and weight of the power train and significantly reduce the power train cost. Reducing the size and populating more components in a confined space increases the challenges of thermal management. Well engineered thermal management is required to cool electron-

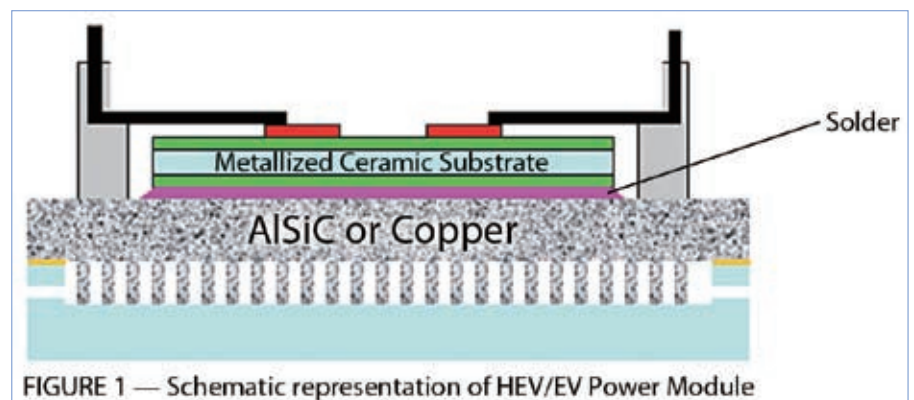


FIGURE 1 — Schematic representation of HEV/EV Power Module

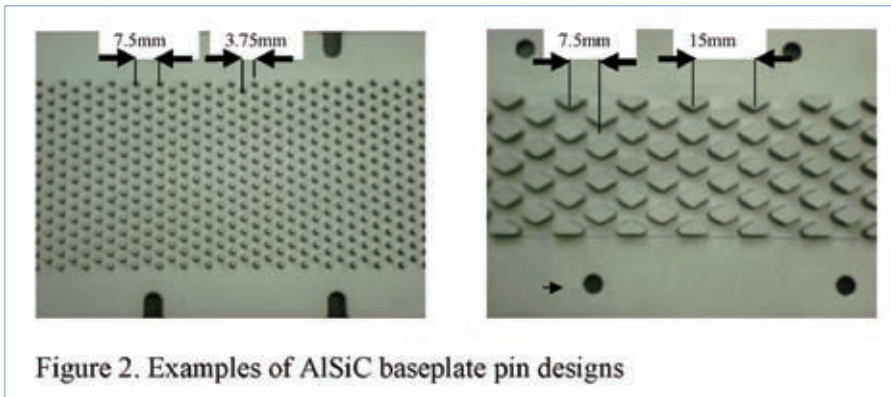


Figure 2. Examples of AlSiC baseplate pin designs

ics and maintain electrical performance within a given envelope of HEV/EV operation, and efficient thermal management provides long term reliability by minimizing thermally induced stresses.

The need to be light weight, smaller in size, more efficient in energy use, less costly and able to meet stringent automobile and transportation standards is being addressed today by manufacturers of direct liquid cooled Pin Fin IGBT base plates produced in copper and aluminum silicon carbide reinforced metal matrix composites. These products and their application to power electronics are mature, well known and, as we explore in this article, well positioned to realize the design goals of current and future Hybrid and Electric vehicles.

Today, most HEV/EV inverter systems use liquid cooled IGBT power modules for thermal management. Although there are still power module designs utilizing air cooled power modules in design and production, we believe that future IGBT power modules for HEV/EV applications will continue to use more direct liquid cooled IGBT modules and move heat away from these modules more efficiently. A schematic representation of IGBT power module with pin fin heat sink is illustrated in Figure 1.

Integrated Pin Fin, direct liquid cooling base plates eliminate thermal grease interfaces between the IGBT module and the heat sink. This is a performance advantage that is realized in HEV/EV IGBT power modules beyond the standard base plate technology currently used in power modules for Rail/Traction power IGBT modules. Today, 70 to 80% of standard power modules for HEV/EV use base plates. There are also power

modules on the market that do not use base plate solutions. These solutions also eliminate the solder joint between the DBC and base plate, and are present in such products as the SKAI IGBT System and Danfoss Shower Power® cooler system.

Today, pin fin heat sink material selection is made generally between copper and AlSiC materials. AlSiC pin fin designs used in HEV/EV IGBT power module applications are illustrated in Figure 2. While the majority of HEV/EV IGBT power modules in design today use pin fin base plates made from AlSiC MMC or copper, there are developmental designs that use 100% aluminum pin fin base plates. In these developmental designs, the thermal resistance of the IGBT module will be considerably reduced by eliminating the solder joint between the ceramic substrate and the pin fin heat sink. The long term reliability and the cost advantages of these developmental designs still need to be demonstrated.

Base Plate Selection Considerations

Selection of the base plate material is usually made based on the reliability requirements in the application as well as the choice of ceramic substrate materials. The properties of pin fin base plates and ceramic substrates used in IGBT power modules are listed in Table 1.

Ceramic substrate choices are silicon nitride, aluminum nitride and aluminum oxide. Considering that many HEV/EV applications require 15 to 20 years of useful life, AlSiC pin fin heat sinks joined to metalized aluminum nitride or silicon nitride substrates have become the preferred choice. This AlSiC heat sink/

ceramic substrate combination not only provides excellent thermo-mechanical stability due to the close CTE match between the AlSiC base plate and the ceramic substrates and maximizes long-term reliability, it also provides proper cooling of the IGBT chips.

A close CTE match between the ceramic substrate and AlSiC is a fundamental advantage in preventing any failure during thermal cycling. When thermal cycling power modules with copper base plates, almost all the interfaces, including the Si chip/DBC interface, are in danger of delamination, fatigue and crack propagation. These failure modes are accelerated when the ceramic is AlN due to this material's lower CTE. An alumina (Al_2O_3) substrate is generally preferred to AlN to reduce the probability of failure of a power module when a copper base plate is used. Due solely to the degree of CTE matching of the system, the heat dissipation performance of a power module with AlSiC base plates will remain consistent even after thousands of thermal cycles, while the thermal performance of power modules with copper bases will gradually decrease after each thermal cycle.

This restriction in selection of ceramic substrates translates into another potential shortcoming of power modules utilizing copper base plate technology. When properties are examined, the primary advantage of copper to AlSiC is copper's high thermal conductivity. However, when copper base plate is used with aluminum oxide substrates, heat dissipation through the base plate is reduced due to the presence of aluminum oxide as a thermal barrier between the IGBT chip and the copper base plate.

In contrast, AlSiC base plate power modules that use AlN as the ceramic substrate do not exhibit this problem. The high thermal conductivity of AlN and the inherent CTE compatibility between AlN and AlSiC, contribute to a high reliability design. When Si₃N₄ is selected as the substrate material instead of AlN, the thickness of the ceramic substrate can be reduced and the thickness of the copper layers can be increased. This is because Si₃N₄ is a much stronger material than AlN and Alumina. AlSiC/

Si3N4 will still provide the better solution than copper/Si3N4 solution for the same reasons described above.

Yet another design advantage for AlSiC base plate technology is the superior stiffness of AlSiC when compared to copper and aluminum. AlSiC materials' mechanical properties allow designers to reduce base plate thickness, allowing for reductions in Power Module space requirements. AlSiC plates remain flatter after ceramic soldering processing steps. Copper base plates change flatness more than AlSiC during soldering processes and also tend to relax over time as stresses are gradually released. It can take weeks for the stresses to completely stabilize after soldering. In contrast, the flatness in an AlSiC base plate becomes stable within a day or so. This predictability makes manufacturing of IGBT modules simpler and allows for better control in the assembly process.

	TC (W/mK)	CTE (ppm/K)	Density (g/cc)	Thickness (mm)
AlN Substrate	170	4.2	3.26	0.64
Si ₃ N ₄ Substrate	70 - 90	3.4	3.2	0.32
Al ₂ O ₃ Substrate	24	7.1		0.25 - 0.38
AlSiC Pin Fin Heat Sink	170 - 230	5-14	2.8 - 3.08	3
Copper Pin Fin Heat Sink	390	16.9	8.9	3

Table 1: Baseplate and ceramic materials used in IGBT power modules

Price Considerations

Although the performance advantages of AlSiC in HEV/EV applications are clearly understood, there are still misconceptions in terms of pin fin heat sink unit prices when AlSiC and copper are compared. Based on the flat or partially bowed IGBT base plate comparison between AlSiC and copper in traction applications, engineers can be lead to believe that AlSiC pin fin heat sinks would be 3 to 4 times more expensive

than copper pin fin heat sinks. In reality, manufacturing processes allow AlSiC pin fin heat sink and copper fin heat sinks to have costs that are very comparable. The manufacturing process costs of pin fin copper base plate are much higher than the stamped copper used in traction applications.

In conclusion, the engineered properties of SiC reinforced aluminum composites and net shape capabilities

to produce pin fin AlSiC composite parts have now been recognized by many TIER 1 suppliers for HEV/EV IGBT power module applications. AlSiC price concerns are being eliminated when companies think through designs that utilize the broad advantages of AlSiC pin fin heat sinks over traditional copper or aluminum materials.

www.rogerscorp.com