HIGH-TEMPERATURE SiC PACKAGING FOR HEV TRACTION APPLICATIONS

K. Vanam[1], F. Barlow, B. Ozpineci[2], L. D. Marlino[2], M. S. Chinthavali[2], L. M. Tolbert[2], and A. Elshabini
Department of Electrical Engineering, University of Idaho
Email: fbarlow@uidaho.edu

[1]Micron Inc., Assembly R&D, Boise, Idaho

[2]Power Electronics and Electric Machinery Research Center
Oak Ridge National Laboratory
National Transportation Research Center

Abstract

A key issue with Hybrid Electric (HEV) and Plug-in Hybrid Electric Vehicles (PHEV) is the cost of these products relative to traditional vehicles. Currently in most cases, the fuel savings do not offset the initial capital expenditure associated with a hybrid. Therefore, an important goal is the cost reduction of these products in order to allow consumers to justify the purchase of these vehicles rather than traditional alternatives. One possibility that could contribute to this goal is the elimination of the additional coolant loop and associated hardware that is currently required to cool the power electronics in these systems. In many of these systems, the internal combustion engine (ICE) requires a coolant loop with a maximum outlet temperature of 105^{o} C and an additional loop is required at a lower temperature (typically 65^{o} C) for the power electronics. This lower temperature loop is required due to the inability of silicon devices and traditional packaging technology to operate reliably at high temperatures. The ability to operate silicon carbide (SiC) devices at much higher temperatures would enable the elimination of the second cooling loop and decrease the cost of these vehicles. In addition, for some applications a suitable packaging technology and SiC devices may enable air-cooling rather than liquid cooling and potentially even further reduced cost.

To that end, the researchers have developed a SiC packaging technology suitable for use in these applications. This technology allows the power devices to operate at 200+^{o} C junction temperatures and significantly reduces the cooling requirements that exist in traditional HEV applications. By allowing this higher junction temperature, the power electronics can utilize the same coolant loop as the ICE in a reduced size. This paper will report on this packaging technology and its use with SiC devices.

Keywords: Power Electronics, SiC, High Temperature Packaging

1.0 Introduction

In many power electronic products, the required heat sink and associated hardware can become quite large, heavy, and expensive relative to the silicon that it cools. This is in part because the silicon devices cannot reliably operate at high temperatures and are generally limited to 125^{o} C, or in some cases slightly higher. In contrast, SiC devices can operate at much higher temperatures and in some cases have been demonstrated at temperatures as high as 450^{o} C [1].

One example of this is the power electronics in a HEV or PHEV product. A close examination of one of the power electronic assemblies within one of these systems reveals that a significant amount of space and weight is consumed by the cooling system [2]. This takes the form of a separate cooling loop that operates at a lower temperature than the ICE coolant loop. This is necessary since the thermal resistance between the power devices and the coolant is too great for many of these products to operate reliably with 105^{o} C engine coolant. This lower temperature coolant requires an additional pump, hoses, and a radiator. These components add cost, weight, and complexity to the product. In contrast, SiC devices operating at 200^{o} C junction temperatures could utilize the same ICE coolant loop in an effective manner.

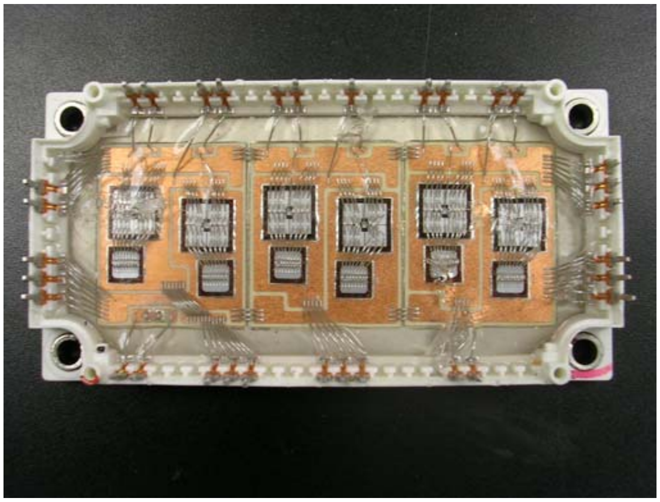

Figure 1: Top view of a commercially available 1200 V, 100A IGBT module with the plastic lid removed.

2.0 Limitations of Current Packaging Technologies

Packaging technologies have been found to be inadequate for many of these SiC devices due to fundamental temperature limitations. For example, a typical power module commonly used in industry today for power applications is shown in Figure 1. The base of this module is a metal plate that acts as a heat spreader and mounting plate to form an intimate contact between the module and a heat sink. One or more direct bond copper (DBC) substrates are then soldered to the heat spreader. These substrates utilize thick copper layers to provide electrical interconnections between individual power devices (diodes and IGBTs in this case). Historically the DBC surface was often plated with nickel, but the current industry trend is to bond the devices to the bare copper metallization on the DBC substrate. This bond is achieved with lead tin or equivalent solder to mount the die to the substrate and aluminum wire bonds to achieve the top side electrical connections on each die. Unlike most low power devices, high power devices are "active back" and require a low resistance path to both the backside power contact as well as to the top side power contact(s). Aluminum wire bonds are also used to interconnect the substrates in the module and provide electrical connections to the modules power pins. Finally, a plastic housing is attached to the module and the internal space is filled with a silicon gel. The housing protects the internal structures of the module and provides support for the metal pins or tabs that are used to interconnect the module to the outside world.

It has been recognized within the industry for a significant number of years that this traditional approach to power module packaging has a number of limitations, which include:

- Coefficient of thermal expansion (CTE) mismatch between base plates and the substrate.
- Solder void formation in die attachment and DBC to base plate bond.
- Reliability limitations and parasitic electrical effects caused by wire bonds.

A. Substrate Limitations

This thermal expansion mismatch between the Si or SiC power devices, with CTE values of 2.8 ppm/°C and 4.2 ppm/°C respectively, and the DBC substrate builds stress into the solder joint and can result in failure of the module. A similar effect can also be observed in the bond line between the substrate and the base plate. Stress in the die bond can be alleviated with compliant die attach materials or by matching the CTE of the substrate and power devices. In most modules, a combination of these techniques is utilized since many solders are available that are somewhat compliant in nature and still offer good electrical and thermal performance. In addition, DBC AlN is a reasonable CTE match to Si power devices and an excellent match to SiC power devices.

However, the substrate to base plate mismatch is much more difficult to eliminate in the traditional structure since the substrate options are limited by the need for a high thermal conductivity dielectric. It is technically possible to utilize base plate materials that are closely matched to the ceramic and therefore greatly improve the overall CTE match, but at an increased cost. A variety of materials such as aluminum SiC composite base plates (AlSiC), copper graphite metal matrix composites, and copper molybdenum have been developed and are used in the aerospace industry. However, the cost of these materials is significantly higher than the traditional nickel-plated copper base plate and, therefore, these technologies have not enjoyed wide spread adoption in the commercial markets.

Instead of using alternative base plate materials, a number of manufactures have developed power module assemblies that do away with base plate and associated solder interface completely in favor of pressure contact between the DBC substrate and the heat sink. Packages such as the SEMITOP™, SKiiPPACK™, and MiniSKiiP™ are examples of approaches developed by SEMIKRON International [3-6]. The basic idea is to provide uniform pressure over the DBC substrate in a manner that provides a solid contact between the backside of the DBC and a heat sink. Since the heat sink and DBC are not bonded together, they are able to expand and contract separately thereby alleviating stress that would otherwise build up due to thermal expansion differences in the two materials. Consistent uniform pressure is required to minimize the thermal resistance of the interface between the heat sink and the DBC substrate. Without this pressure, the thermal resistance would be very large and the power ratings of the modules would require considerable derating to maintain reliable device temperatures.

B. Wire Bond Interconnects

Wire bond failure is another key concern. A recent report illustrated that modules are very reliable if the junction temperatures are limited to 125°C [7]. However, increasing the junction temperature to 150°C creates a temperature difference between the device junction and the coolant loop (ΔTj) of 85°C. This much larger temperature difference has been shown to lead to wire bond lift-off in only 41,000–42,800 power cycles. At this point, the delamination in the solder joint between the DBC substrate and base plate was measured to be only 4.6% [7]. Therefore, wire bond lift-off and heel crack formation is a key limiting factor for power modules. The principal problem is the large CTE of the aluminum wire relative to the Si or SiC device. As the module expands and contracts due to thermal deviations in the wire, devices, and substrate, the wires flex and contract in response to these thermal excursions. In contrast, the changes in the devices and substrate are far smaller and the result is stress on the wire bonds. Poorly formed or mechanically damaged bonds may exhibit heel breaks at the location where the wire bends up from the die surface. This mechanical damage may be the result of inappropriate bond parameters, usually too much bonding force and ultrasonic power, or some other physical damage created during assembly or use. These heel cracks may not be visible after the initial assembly, but they grow in response to the stress created during the modules operation and may lead to premature failure of the module. However, for well formed bonds, the principal failure mechanism is wire bond lift-off where the bond comes loose from the die surface and leaves behind a thin layer of aluminum, followed by heel cracks created by CTE mismatches in the module [8]. It has been shown that this process of wire bond lift-off begins by crack formation in the bond weld near the die surface [9]. As the crack propagates, the current density is increased in the surrounding bond area ultimately leading to interruption of the current and lift-off of the wire from the die surface.

The industry has worked to eliminate the problems associated with wire bonds with novel assembly methods that make connections to both sides of the devices with solder or braze alloys. There is a wide variety of these methods, some of which are based on metal clips or structures [10], while other methods are based on ceramic [11] or polymeric interconnect structures placed on top of the device [12]. All of these methods seek to use alternative methods to make the top side electrical connections without wire bonds. However, none of these methods has been demonstrated for use at high temperatures.

C. Key Problems

With these concerns in mind, a number of key issues must be addressed in traditional packages in order to develop modules from SiC devices that can operate at high temperatures. Primarily the issues are:

- The effect of high temperature on the substrate material.
- Reliability of the conductor material and its adhesion to the substrate.
- Traditional die bonding materials are inadequate for extended use at 200° C and beyond.
- Wire bonds and bond metallurgy must be carefully considered.
- Encapsulation materials must be eliminated or be stable at high operating temperatures.

3.0 Flip Chip Power Package

In this work, the researchers have focused on two of the limitations of current packaging technology; die attachment, and wire bonding. The proposed solution to these problems is a flip chip variation of a SiC power package that can be cooled using spray or conventional cooling techniques such as a cold plate or heat sink. The viability of the proposed package was first implemented on a Si based device, diode (16 A, 600V), and later on a SiC based diode (75 A, 1200 V). The material selection and the packaging technology were vital for the high temperature and high voltage operation of the package. The SiC diode package was cooled using a cold plate for testing the integrity of the package and materials used. However, testing of the package using spray cooling with water is left for future work and the concept is presented here.

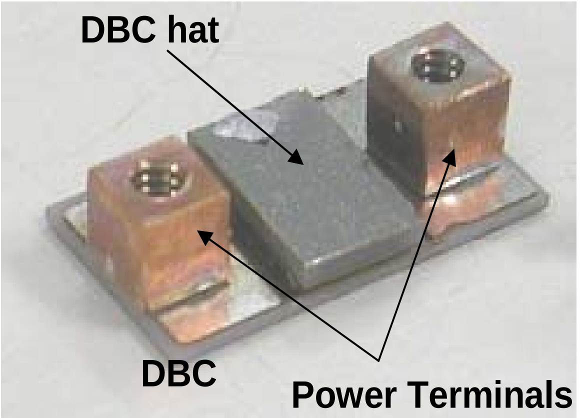

Figure 2: Flip Chip power package containing a 75A, 1200V SiC diode, shown without a metal base plate.

A flip chip power package is shown in Figure 2. It consists of a DBC "hat" that forms the top side connection to the diode's anode, and a second DBC substrate forms the bottom-side cathode connection. The Kovar legs complete the connectivity between the hat and the DBC substrate. While the power terminals used in this demonstration are very large, these structures were selected for convenience in testing the assembly rather than for their compact size. In practice, these individual die "packages" could be included inside a module such as that shown in Figure 1, but with traditional soldered tabs for external power connections.

A temperature hierarchy in solder selection is a key in realizing the package. High temperature solder balls (95Pb 5Sn) form the top side anode connection and 2 mil thick Indium alloy 209 preform (65sn 25Ag 10Sb) was utilized for bottom side device and base plate attachment. Alloy 209 has a melting point of 233 °C and once it melts forms, an alloy with the base metal on to which it reflows and subsequent reflow will be approximately 265 °C. Another alloy that is suitable for base plate attachment was Indium alloy 121 (96.5 Sn 3.5 Ag), which has a reflow temperature of 221 °C. Alloy 121 is a very good stress absorber and can be used with a pure copper base plate as opposed to expensive AlSiC or CuMo base plates. Apart from this, it has very good thermal conductivity, high fatigue & creep resistance, and high tensile strength.

Bare SiC diodes (75 A, 1200 V) were obtained from CREE Inc. for evaluation of the packaging methodology. The devices were composed of Al on the top side (anode) and Ni on the bottom side (Cathode) and would therefore require additional processing. The top side was plated with electro less nickel (EN) as described earlier [13]. The diode after the zincating process and EN plating is shown in figure 3.

The next step was to deposit a solder mask using bisbenzocyclobutene (BCB). The problem of handling individual bare diodes was resolved using a thermal release tape during deposition and patterning of the BCB. Figure 4 shows the SiC diode with 95/5 reflowed solder balls. There were more than 100 solder balls to handle the current rating of the device. Note that some of the balls are poorly formed; however, since all the balls are in parallel and some redundancy exists, the product is somewhat insensitive to this effect. These misshapen balls are also principally the result of the lack of availability of full wafers of these devices, and therefore the need to manipulate and apply under bump metallization (UBM) to individual bare die rather than entire wafers. This phenomenon would not occur in a production environment were full wafers would be bumped in a streamlined process.

The rest of assembly components are shown in Figure 5. The solder balls were attached to the DBC hat by again reflowing the solder balls and Kovar legs using a 2-mil thick 95Pb 5Sn preform. The DBC

Figure 3: A 75 A, 1200V SiC diode (left) after zincation, (right) after EN plating.

hat along with the SiC diode was attached to a DBC substrate using indium alloy 209. The solder bond between the substrate and the Cu base plate (125 mils thick) was also formed at this time. The proposed package can handle temperatures in excess of 200 °C and high voltage operation is possible by filling the gap between the top DBC hat and the substrate with a dielectric such as Teflon.

The package was tested using a cold plate (maintained at 37 °C) to confirm the feasibility of the package. The base plate of the SiC package was bolted to the heat sink and thermal grease was used between the base plate and cold plate. The test results are shown in figure 6. The I-V curves for the diodes were as expected. As direct access to the diode was not possible for thermocouple placement, a 62 mil diameter hole was drilled through the copper base plate and a thermocouple was positioned 50 mils below the long edge of the diode. This gave a rough estimate of the device temperature. This demonstrates the successes of the packaging methodology and selection of materials at elevated temperatures.

Figure 4: A bumped SiC diode prior to assembly into a prototype package.

4.0 Conclusions

A high temperature SiC power package has been developed which utilizes a flip chip configuration and solder attachment for interconnection to both the top and bottom side of the die. This package is capable of continuous operation with device junction

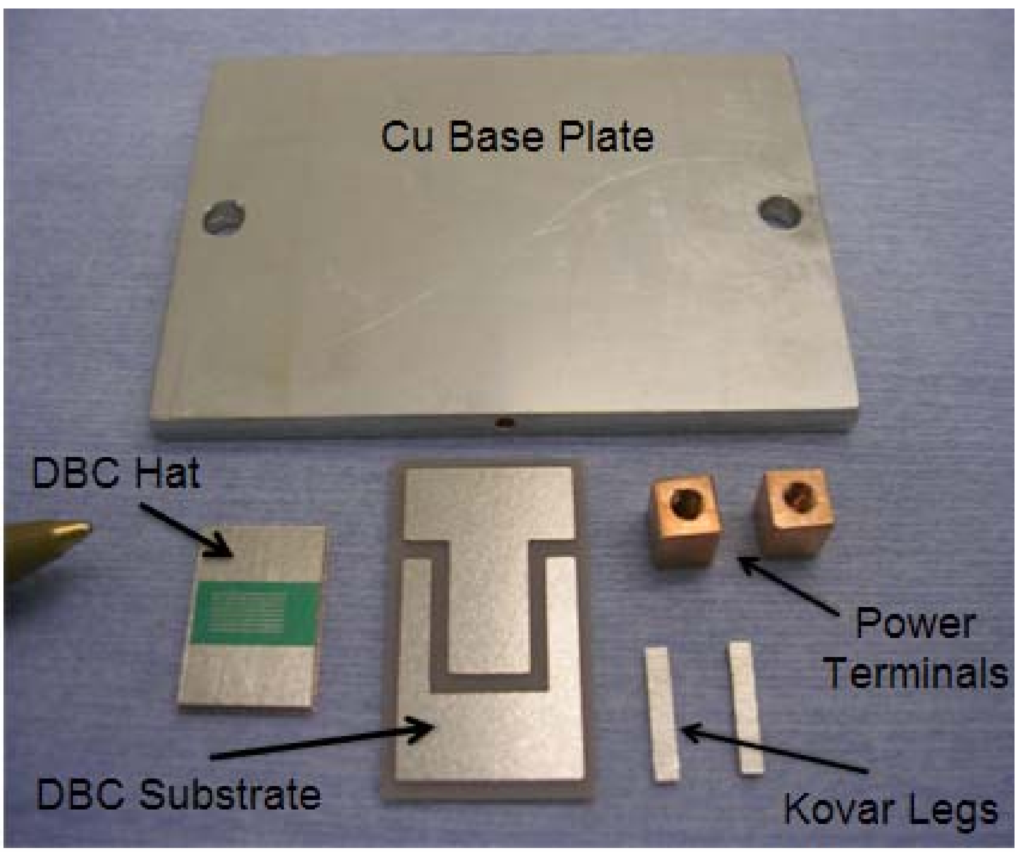

Figure 5: Package components.

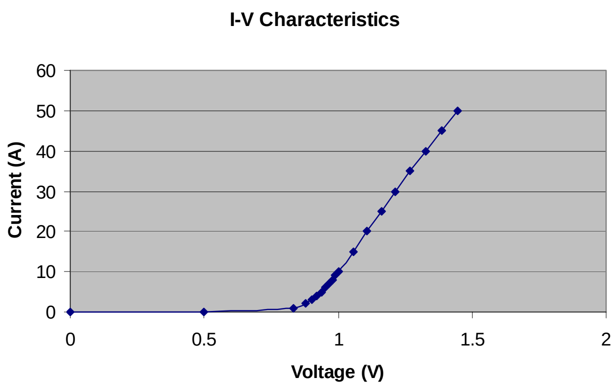

Figure 6: Measured package performance.

temperatures well above 200^o C. The elimination of wire bonds alleviates the reliability problems associated with the operation of the structures at higher temperatures. Through the selection of high temperature die attach materials, the limitations of traditional die attach materials has been eliminated.

5.0 Acknowledgement

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