Performance and Reliability of SiC dies, Die attach and Substrates for High Temperature Power Applications up to 300°C

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Abstract

The recent commercial availability of silicon carbide power semiconductor devices are theoretically capable of operating at temperatures well beyond the limits of silicon devices and have generated an interest in developing high temperature capable packaging solutions to match. In this work, the performance and reliability of a number of commercially available silicon carbide power MOSFET dies from multiple vendors was determined for die temperatures up to 350°C. Although these results have demonstrated a number of aging effects and very high on-state resistances at high temperatures, it appears that these devices can perform reliably even in air atmospheres for 100 hours or more at 350°C. In addition, commercially available DBC type ceramic-based substrates have been evaluated for their thermal cycling performance and candidate high temperature capable die attach materials including silver sinter paste and tin and gold-tin pre-form based transient liquid phase types have also been evaluated. These results have demonstrated that the active metal brazed substrates, both copper and aluminium variants, in conjunction with the silicon carbide dies and silver sinter die attach may serve as the basis for high temperature power modules, and may be operated reliably in thermal cycled applications and in air atmospheres up to 300°C. Due to large threshold voltage shift of the SiC MOSFETs at these temperatures, it may be necessary to implement a negative gate bias capability.

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Keywords: SiC, DBC, AMB, high temperature reliability, aging, power substrates, die attach, Ag sintering, TLP
Introduction

The commercially availability of silicon carbide (SiC) MOSFET devices with their high energy efficiency and theoretical high temperature capabilities has generated much interest from within the power electronics community. The realisation that conventional power module packaging technology is not suitable for high temperature operation has also led many businesses to investigate, and some to develop, suitable packaging solutions.

In this paper, we present results from such an investigation, the aim of which was to determine the relative high temperature performances and reliability of some key materials that might be good candidates as building blocks for a high temperature capable scalable power module.

The performance and reliability of commercially available SiC MOSFETs has been determined up to 350°C, well beyond datasheet values. Their measured on-state resistive losses versus temperature have been used along with the thermal and mechanical properties of the candidate materials to model the temperature profiles for representative three-dimensional power module models. This modelling has aided in the understanding of the thermal conditions that the materials will be subjected to in the real application.

In addition, DBC type power module substrate materials have been procured from a number of manufacturers and evaluated for their relative thermal and mechanical performances, also up to 350°C.

Results from performance testing of silver sintering and transient liquid phase (TLP) diffusion soldering are also presented for the same high temperature thermal cycled environment and some of the process challenges discovered during this work are also disclosed.

Finally, a power module demonstrator comprising the materials with the best high temperature cycling performance has been assembled and tested.

The intended application for this high temperature power module is within the inverter system used to drive a hybrid electric vehicle (HEV) motor, and which is cooled using the same coolant circuit as the combustion engine. This sets the ambient temperature to approximately 100°C and the objective is a peak die temperature of 300°C which will reduce the need to over-engineer the cooling system to take account of only occasional high speeds or accelerations.

Experimental setup

Static electrical measurements of SiC dies have been carried out using a custom built probe station as shown in Fig. 1, connected to an Agilent device curve tracer. The probe station is capable of heating the dies to > 400°C. Bias test stressing was also carried out using the probe station and biasing was carried out using bench-top DC power supplies.

Fig. 1. Custom built high temperature die probe station, used for static temperature dependency measurements and bias stress tests. Custom made probes (P), die and dielectric liquid well (W), heater (H), micrometer probe height adjustment (M), air actuated well liftoff solenoid (A).

Fig. 2. Custom built fast passive thermal cycling chamber and substrate card holders, capable of cycling from 0-350-0°C in less than 10 minutes.
A passive fast thermal cycling oven was custom designed and built for this project in order to determine the relative performances of candidate materials. This was used to evaluate DBC-type and thick-film power substrate materials, three terminal high temperature passive device packages and relative die attach performances. The materials were placed in card slots or baskets, as shown in Fig.2. The materials were cooled to room temperature and removed for inspections every 10 to 50 thermal cycles, and were rotated to different positions within the chamber to account for small differences in the heat distribution.

Die attach samples were prepared on electroplated and electro-less plated copper blocks or DBC type substrates by the printing or dispensing of Ag sinter pastes or clamping of tin preforms in the case of TLP process using a purpose made clamping arrangement. An ATV reflow oven was used to provide the temperature profiles and gases to the die attach processes.

New and thermal cycled substrate and die attach cross sections were prepared for optical microscope and SEM inspections using standard metallographic preparation techniques, adjusted for ceramics, by embedding in epoxy, precision sawing and then polishing. Scanning acoustic microscopy (SAM) was also used to image through substrates to determine the extent of metal delamination (lifting or peeling).

**High temperature performance and aging of silicon carbide power devices**

The current generations of SiC MOSFETs under test here have not been completely validated above 150°C before. The goal here was to measure some important electrical characteristics at much higher temperatures, to see if high temperature operation is possible and, if so, how and how fast they degrade (age) and ultimately fail. Beside I-V characteristics, threshold voltage ($V_{T}$) temperature stability, and stability due to positive and negative gate bias at the maximum ratings are used by manufacturers and researchers to demonstrate device stability [1,2]. In this work, their stability was measured at temperatures up to 350°C.

Our results demonstrated that the three types of SiC MOSFET devices under test functioned correctly up to 350°C, with a small number of random failures occurring above 300°C. The on-state resistance increased almost linearly and with quite a large spread, from their room temperature values of around 100 mΩ to approximately 420-650 mΩ at 300-350°C. These numbers indicate that periods of high temperature operation must be limited if they are to be cooled using conventional means. As Fig.3 indicates, the high temperatures have more than halved the room temperature threshold voltage values, although the drain currents did not decrease significantly as might be expected. These results indicate that, for devices that have very low room temperature threshold voltages e.g. $V_T << 1.5 \text{V}$, false turn-on could be an issue at temperatures above 300°C. Positive bias stress tests (PBTS) conducted at 300°C and the die maximum gate voltages indicated a positive increase in $V_T$ approaching or just exceeding two times their room temperature values, as shown in Fig.3 inset. A negative gate stress at the maximum negative gate voltage and for the same time period decreased $V_T$, but not as far as its original value. These shifts in $V_T$ are thought to be due to charge trapping at defects within the SiC epitaxial growth layer on which the MOSFET source and gate structures are produced [3].

![Fig. 3. Threshold voltage ($V_T$) temperature stability and threshold shift due to positive and negative gate bias stress testing at 300°C (inset).](image-url)

A further aging issue has already been reported; the forward characteristic of the SiC MOSFETs degrade after long periods of isothermal heating at 350°C, seen as the gradual appearance of a rectifying characteristic at low drain-source voltages [4]. The precise mechanical reasons for this a currently under investigation, but are expected to be due to instability of the source and or drain ohmic contacts [5]. Of the three types of devices tested, this effect became significant after 24 and 70 hours for two types, and was only just becoming evident after 100 hours of isothermal heating for a third type.
High temperature thermal modelling of power modules incorporating candidate materials

The measured on-state resistance versus temperature up to 350°C was incorporated into a physics-based MOSFET device model to generate power losses for a range of drain currents that will be seen in the inverter motor drive application. These losses were then used as input into three-dimensional models of a representative power module package consisting of the materials under test in this project, including SiC dies, die attach and power substrates on a baseplate and heatsink, including the thermal and mechanical properties of every material in the layered assembly.

These profiles were then filtered to derive the period of time during these application conditions when the devices are at the temperature range of interest, above 150°C, as shown in Fig.5.

High temperature thermal cycling lifetimes and failure modes of power module substrates

Samples of candidate direct copper bond (DBC), and active metal brazed equivalents (AMB) including both copper and aluminium variants were procured from a number of different manufacturers. These power substrate materials were manufactured from a range of ceramic materials including aluminium nitride (AlN), aluminium oxide (Al₂O₃, Alumina), Alumina containing approximately 10% zirconium, and silicon nitride (Si₃N₄). These materials were passive thermal cycled in order to obtain their relative performances and lifetimes at temperatures up to 350°C. Two thermal cycles were chosen; one with the low temperature set to 100°C, our application coolant temperature, and the other to represent a more stressful thermal situation which might occur in cold weather when the system is first turned on. Both profiles reach a maximum of 350°C, slightly above our peak application temperature to accelerate testing. At least three of each substrate type were tested; it was discovered that there was very little spread of results for all substrate types tested.

The power substrate thermal cycling results are presented in Table-1. It can be seen that the copper/Si₃N₄ and aluminium/AlN substrate types have an almost order of magnitude greater lifetime than the other substrate types. Of these, the aluminium/AlN variant survived the longest. In fact, no delaminations of the aluminium from the ceramic or ceramic fractures have been detected during testing to date. However, we determined that the surfaces of these aluminium based substrates become extremely uneven, comprising of hillocks or ridges, followed by severe high amplitude cracking and then lifting of the nickel-phosphorous (NiP) platings, as shown in Fig.6. The appearance of hillocks is thought to be due to recrystallisation of the aluminium [8]. At the extremely high cycling temperatures used in this work, and the high peak to peak amplitude (Rₚ) measured, these issues are likely to be detrimental to the die attach and wire bond interfaces, although another author demonstrated that this was not the case for their lower temperature cycling [9].
Table 1: Power substrate lifetimes for two passive thermal cycling temperature profiles.

<table>
<thead>
<tr>
<th>Metal, thickness</th>
<th>Ceramic, thickness</th>
<th>Bond type</th>
<th>100-350°C lifetime</th>
<th>0-350°C lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu, 0.3 mm</td>
<td>AlN, 0.6 mm</td>
<td>DBC</td>
<td>50-100</td>
<td>12</td>
</tr>
<tr>
<td>Cu, 0.3 mm</td>
<td>AlN, 0.6 mm</td>
<td>AMB</td>
<td>~80</td>
<td>10</td>
</tr>
<tr>
<td>Cu, 0.3 mm</td>
<td>Al₂O₃, 0.4 mm</td>
<td>DBC</td>
<td>100-150</td>
<td>12-24</td>
</tr>
<tr>
<td>Cu, 0.3 mm</td>
<td>Si₃N₄, 0.3 mm</td>
<td>DBC</td>
<td>1210-1330</td>
<td>77-101</td>
</tr>
<tr>
<td>Cu, 0.5 mm</td>
<td>Si₃N₄, 0.3 mm</td>
<td>AMB</td>
<td>1095*</td>
<td>145-175</td>
</tr>
<tr>
<td>Al, 0.3 mm</td>
<td>AlN, 0.6 mm</td>
<td>AMB</td>
<td>1380**</td>
<td>990**</td>
</tr>
</tbody>
</table>

Notes: (a) samples still not failed to date. (b) hillocks and NiP plating cracks evident.

Fig. 6: Hillocks and subsequent brittle fracture of nickel phosphorous plating on surface of aluminium AMB substrates after 200 x 0-350°C cycles. Inset shows interferometer 3D image of surface and lifting of plating around hillocks.

Fig. 7: Typical failure mode for active metal brazed copper on Si₃N₄ ceramic; initial cracking of brazed interface followed by concoidal fracture of the ceramic and then crack propagation. Inset shows cross section view.

Fig. 8: SAM image illustrates typical fracture behaviour at high stress corners of the copper regions of DBC and AMB substrates.

Fig. 9: Plating cracks propagating into silver sinter die attach and under dies during high temperature cycling.

The main failure mode found for the copper based DBC and AMB substrates was concoidal fracture of the ceramic layer. Such a failure is shown in Fig. 7 for the AMB substrate type. The extent of ceramic cracking may be seen using scanning acoustic microscopy equipment, as Fig. 8 illustrates, although this type of failure may eventually be seen by eye as cracking at the interface followed by lifting of the copper regions, most often beginning at corners. The copper/Si₃N₄ AMB substrate types also suffered from surface roughening and cracking of NiP platings, but to a much smaller degree than the aluminium type, with no plating lift.

We also noted that these plating cracks propagated into the silver sintered die attach for AMB substrates with SiC dies attached as shown in Fig. 9, and under aluminium wire bonds as shown in Fig. 10. These plating cracks may not lead directly to failure of the die attach or wire bonds on their own due to their small areas compared to the footprints of the dies and wire bond feet. However, it is possible that these might become crack...
initiation sites and therefore contribute to reduced lifetimes along with thermal cycling stresses.

Fig. 10. Plating cracks propagating under wire bonds during high temperature cycling.

Thermal cycling lifetimes and failure modes of high temperature die attach solutions

The performance of pressure-less silver (Ag) sinter die attach paste and transient liquid phase (TLP) soldering, also known as solid-liquid inter-diffusion (SLID) and diffusion soldering, have been evaluated for their high temperature performance. A number of different TLP metal combinations were evaluated, using mostly 100% tin pre-forms sandwiched between either copper, silver, gold or nickel plating’s in the order of 10 µm thick. These all have the potential to provide low process temperature (< 230°C), high re-melt temperature (> 400°C) die attach solutions, when processed correctly.

These die attach assembly processes are not without their challenges; in this work, it was found that one of the main TLP process challenges was cleaning the surfaces of the delicate tin pre-forms and mating metal surfaces enough to limit voiding at the bonded interfaces. This voiding limited our ability to produce good bonds that would have enabled us to have provided good relative thermal cycling performances (lifetimes). The low viscosity of the silver sinter paste also presented an issue; the screen printed paste pushed out from under the die easily when the die was placed into position using a manually operated pick and place machine. In order to achieve a high enough bond-line thickness; this process probably needs to be carried out by an automatic machine that supports precision control of both applied pressure and die height.

Some reduction of voiding was apparent after thermal cycling of TLP samples, as shown in Fig.11. This is not surprising, since a uniformly distributed (stable) microstructure may take many hours or even days to fully homogenize [10]. Thermal cycling stresses may prevent a homogenized microstructure from forming as the most mobile atoms move away from regions of high stress like the bond interfaces. This process was far more evident at silver sintered die attach interfaces after cycling, as shown in Fig.12. Highly energetic silver atoms have migrated away from the highly (shear) stressed interfaces, clustering and leaving behind large voids (larger pores) at the bonded interfaces. This voiding will slowly increase the thermal resistance under the die and eventually lead to die lift-off failures. Table-2 shows the passive thermal cycling results for the sintered and TLP die attach solutions, which may be used as an indication for the lowest performance achievable.

Fig. 11. TLP die attach bond-lines before thermal cycling (top) indicating a high density of voids and (bottom) after 504 x 0-350°C thermal cycles.

Fig. 12. Movement of silver atoms during high temperature thermal cycling leads to aggregation of pores within the bulk and at the die attach interface.
Table 2 Measured passive thermal cycling lifetimes of high temperature die attach solutions.

<table>
<thead>
<tr>
<th>Die attach solution</th>
<th>Plating</th>
<th>Pressure</th>
<th>100-350°C lifetime</th>
<th>0-350°C lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag sinter paste</td>
<td>ENIG</td>
<td>N</td>
<td>~185</td>
<td>~185</td>
</tr>
<tr>
<td>Ag sinter paste</td>
<td>ENIG</td>
<td>Y</td>
<td>&gt;300</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Ag sinter film</td>
<td>Ag/NiP</td>
<td>Y</td>
<td>500 ~100</td>
<td>500 ~100</td>
</tr>
<tr>
<td>TLP (Sn)</td>
<td>E-Cu</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
<tr>
<td>TLP (Sn)</td>
<td>E-Ni</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
<tr>
<td>TLP (Sn)</td>
<td>E-Ag</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
<tr>
<td>TLP (Sn)</td>
<td>E-Au</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
<tr>
<td>TLP (80AuSn)</td>
<td>E-Au</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
<tr>
<td>TLP (SnAgSn)</td>
<td>E-Ag</td>
<td>Y</td>
<td>&gt;504</td>
<td>&gt;504</td>
</tr>
</tbody>
</table>

High temperature power module demonstrator

In order to prove the performance and reliability of the best candidate materials together, a power module was constructed as shown in Fig. 13. This was passive thermal cycle tested using the 0-350°C thermal profile. The results, summarised in Table 3, showed that the lifetime of the module actually exceeds the lifetime of the individual components. We attribute this mainly to the addition of a ring frame, and its stiffening effect, which limit the displacements of the copper/SiC AMB substrate to which it is bonded.

Conclusions

This work has demonstrated the high temperature performance of a range of candidate power module packaging materials that may be used to provide the foundations for the operation of SiC MOSFET devices up to a peak temperature of around 300°C. Some SiC power MOSFET devices were proven to be capable of operating reliably even after isothermal heating at 350°C for 100 hours. The copper/Si3N4 and aluminium/AlN substrate types provide approximately an order of magnitude improvement over their Alumina and AlN DBC counterparts; they have been shown in this work to be able to withstand more than 100 x 0-350°C and more than 1000 x 100-350°C cycles before failing by concoidal ceramic fractures and severe plating cracks respectively. Pressure-less Ag sinter die attach was also evaluated, and shown to survive for slightly longer than the substrate materials at these temperatures, eventually failing by die lift-off as a result of pore aggregation at the die attach interfaces. TLP die attach samples contained a very high density of voids at the bond interfaces due to insufficient and difficult to achieve levels of surface cleanliness. However, this die attach process showed promising thermal cycling results, both reducing voiding in some cases and all TLP sample types surviving 504 x 0-350 °C cycles without failure. The TLP solutions may provide the basis for a more resilient high temperature thermal cycling capable solution than pressure-less Ag sintering paste which has demonstrated pore aggregation under these thermal cycling conditions, especially if a cleaner and automated TLP process can be implemented.

Together, these solutions may be combined to form the basis of scalable high temperature SiC device based power modules, as we have demonstrated. Based on our automotive application modelling work which demonstrated that the peak die temperature only exceeds 250°C for 10% of one Artemis driving mission cycles and barely ever reaches 300°C, we estimated that the lifetime of a power module under these conditions may exceed 2,500 hours [11], which could equate to 10 years of driving. If the peak temperature can be reduced to 250°C, say, the lifetimes are likely to be 10 to 100 times higher.

![Fig. 13. Power module demonstrator constructed from the highest performance materials including SiC dies, Ag sinter paste and SiN4 copper AMB substrate. Inset shows minor pad lifting after 640 x 0-350°C thermal cycles.](image)

Table 3 Power module thermal cycling results.

<table>
<thead>
<tr>
<th>Number of 0-350°C cycles</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>164</td>
<td>3 of 4 inside corner pads beginning to peel</td>
</tr>
<tr>
<td>260</td>
<td>Few braze cracks on outside finger pads</td>
</tr>
<tr>
<td>340</td>
<td>Few cracks around sides of ring frame</td>
</tr>
<tr>
<td>485</td>
<td>Cracks at outer corners of ring frame</td>
</tr>
<tr>
<td>525</td>
<td>Sinter paste fillets cracking</td>
</tr>
<tr>
<td></td>
<td>5x non-destructive die shear test – all passed</td>
</tr>
<tr>
<td>600</td>
<td>Pads along inside of ring frame beginning to lift</td>
</tr>
</tbody>
</table>
References


