

SiC & GaN Die Attach for Extreme Environment Electronics

Srikanth Kulkarni, Fred Barlow, Aicha Elshabini, and Rick Edgeman[†]

Department of Electrical Engineering

[†]Department of Statistics

University of Idaho

Email: fbarlow@uidaho.edu

Abstract

It has been demonstrated that wideband gap devices fabricated from SiC, or GaN grown on SiC, can operate over a much wider temperature range than traditional silicon or GaAs devices. However, most of the packaging technology in use to today was developed for silicon or GaAs devices and much of this technology is fundamentally limited in its temperature range. For example the common die attach solders in wide spread use melt below 300°C, and are therefore inadequate for many of these new wide band gap devices some of which can operate above 400°C. Therefore, new technologies are needed to enable the wide spread use of these new devices at elevated temperatures. In particular suitable die attach methods are a key concern since many of these new devices are intended for power or microwave circuits and therefore utilize active die backs. Regrettably there is little long-term reliability data in the literature that can be used to evaluate die attach materials for these applications.

This paper seeks to address this fundamental problem by providing reliability data on a number of die attach materials that are suitable for operation of these devices in excess of 200°C. Baseline shear-strength data for solders and adhesives suitable for high temperature die attach will be presented as well as data on accelerated aged samples of SiC devices bonded to typical substrate materials. Aging of the samples will consist of both high temperature storage as well as thermal shock.

Keywords: *Die Attach, GaN, SiC, Extreme Environments*

1. Introduction

Wideband gap semiconductors, such as SiC and GaN, have significant potential for fabrication of devices that can operate in extreme environments. In particular the wideband gap allows these materials to continue to operate at temperatures well beyond the capabilities of conventional semiconductors such as silicon and GaAs. For example it has been demonstrated that power devices fabricated from SiC can operate as high as 450 °C for short periods of time, and GaN devices are attractive for microwave applications which in some cases may also benefit for higher junction temperatures. However, traditional packaging technologies have been developed for low temperature applications and in most cases cannot be directly applied to these higher operating temperatures. For example, the solders

or adhesives commonly used for die attach in most electronic products either melt or fail at temperatures below the desired operating temperature of some of these wideband gap devices. The net result is that these new devices create a host of problems from a packaging perspective including die attach, wire bonding, and encapsulation.

This paper focuses on the key problem of identifying a reliable high temperature die attach for SiC devices operating at ~200 °C junction temperatures. SiC is an interesting material since not only are a variety of power devices currently made from this material, but it is also one of the possible substrates on which GaN devices can be grown. In the GaN case, the SiC acts as a substrate or carrier for the GaN device(s), but die attach materials suitable for SiC power

Table 1: Properties of Die attach materials.

Solder	Composition	Sol	Liq	CTE	E.C.	T.C.	Tensile St.	Shear St.	E
Sn/Cu	97/3	227	335	19 ²	-	-	6,4200 ³	2,383	41 ²
Pb/Sn	89.5/10.5	275	302 ⁵	29 ⁵	8.9 ⁵	0.25 ⁵	4,400 ⁵	2,400 ⁵	19.064
Pb/Ag	97.5/2.5	303 E		23	8.6 ⁵	0.26	4,400 ⁵	2900 ⁵	-
Pb/Ag/Sn	97.5/1.5/1	309 E		30 ⁵	6 ⁵	0.23 ⁵	4,420 ⁵	-	13.28
Pb/In	81/19	260 ⁵	275 ⁵	27 ⁵	4.5 ⁵	0.17 ⁵	5,500 ⁵	~3,500 ⁵	-
Pb/In/Ag	90.0/5/5	290	310	27 ⁵	5.6 ⁵	0.25 ⁵	5,730 ⁵	3,180 ⁵	-
	92.5/5/2.5	300	310	25 ⁵	5.5 ⁵	0.25 ⁵	4,560 ⁵	2,830 ⁵	-
Au/Ge	88/12	356 E		13 ⁵	-	0.44 ⁵	26,835 ⁵	26,825 ⁵	72.689 ⁵
Au/Sn	80/20	280 E		16 ⁵	-	0.57 ⁴	40,000 ⁵	40,000 ⁵	60.287 ⁵
[†] P1011	Silver	N/A		32 (225)	Conductor	0.0274	-	1,700	-
[†] 377H	Graphite	N/A		56 (200)	Insulator	0.0044	-	3,400	-
[†] 430	Copper	N/A		28 (144)	Conductor	0.0134	-	1,700	-

[†]EPO-TEK® Superscripts denote the source of the value as listed in the reference section of this paper.

devices would be suitable for these GaN devices as well.

2. Die Attach Materials

For the die attach, solders, adhesives and adhesive films are available bonding materials [1-4]. Solders have very good electrical and thermal conductivity as they are metal alloys. Soldering however, can be more expensive than adhesives considering issues such as the cost of the solder, and a more complex fabrication process in some cases. A number of properties of die attach materials should be taken into account while considering the options for a given application. Some of these include; electrical and thermal conductivity, coefficient of thermal expansion (CTE), shear strength and young's modulus (E). The properties of the materials that have the greatest potential for high temperature operation are given in Table 1 [5-10].

After considering several applicable materials, 92.5Pb/5.0Sn/2.5Ag solder alloy and EPO-TEK® P1011 adhesive were chosen for the die-attach application in this work. While these materials may not be ideal for all applications, they enable operation above 200 °C and for some applications that is a key goal.

Adhesives, such as epoxy or polyimide, are polymers that have low electrical conductivity (E.C) and thermal conductivity (T.C). To improve the conductivity, the polymers are often filled with metals such as silver. Small particles of metal are suspended in a polymer matrix and provide superior electrical and thermal conduction. These types of adhesives are widely used for die attach in applications where the dice do not have active conductive backs and the thermal dissipation per die is limited. In high power applications, adhesives have not found wide application because they have much lower thermal and electrical conductivity when compared to solders.

EPO-TEK® P1011 is a silver filled polyimide with a maximum continuous service temperature of 225 °C. This adhesive was selected among other possible adhesives, based on the properties shown in Table 1.

3. Experimental Procedure

For assessment of the solder 92.5Pb/5.0In/2.5Ag and the adhesive EPO-TEK® P1011, in die attach applications for SiC or GaN grown on SiC dice, a 4H-SiC wafer was prepared and cut in to test sample dice. The parts were not metalized on the top surface, but the bottom

surface was metalized using an aluminum and titanium alloy to form an ohmic contact to the SiC, followed by a copper and then a nickel layer. The aluminum titanium alloy was prepared in a standard manner as is commonly done with SiC wafers to ensure that these test samples were representative of real devices.

These dice were divided into two groups for attachment with solder and adhesive. The die attach process for solder and adhesive are independent from one another hence, separate but similar randomization models were used for both the processes to ensure consistent results.

After the dice with each attachment process were prepared, they were further divided into three groups. The samples in the first group, called the control group were tested at the same time to give the shear strength of the die attach without any accelerated aging treatment. The second group of samples was treated with high temperature storage (HTS) and the samples in the third group were treated with thermal shock testing (TST). The samples from each treatment were then independently shear tested to study the change in the strength due to the accelerated aging treatments.

Adhesive Die Attach Process

Adhesive P1011 is a silver filled polymer that has a thixotropic index of 1.9 and viscosity greater than 8,000 cPs at room temperature. Hence, the adhesive does not flow significantly when dispensed on a surface. The whole process

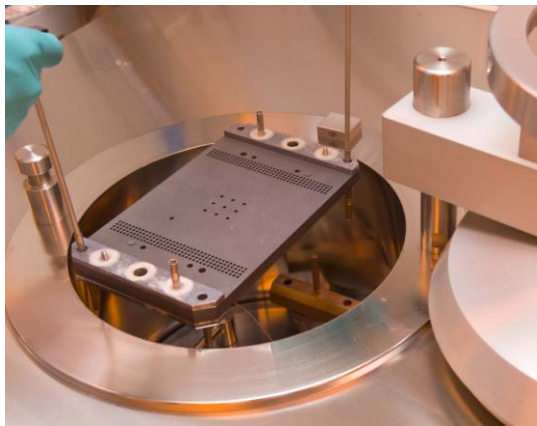


Figure 2: Graphite fixture used to produce the die attachment samples with solder.

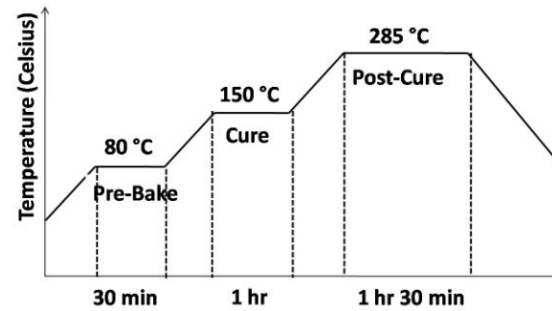


Figure 1: Temperature profile for adhesive P1011 curing cycle.

of adhesive dispensing and curing was done in air. The substrate used for the die attach samples was Direct Bond Copper (DBC) on alumina. Two SiC test dice were bonded to each DBC substrate.

Sample Preparation

DBC substrates were diced from pieces of 1" x 1" into squares of dimensions 0.25" x 0.25" with a DAD320 dicing saw. These substrates are 40 mils thick with 16 mils of alumina sandwiched between copper layers that are each 12 mils thick. The DBC were then cleaned by etching in 10% hydrochloric acid for 90 sec followed by rinsing in DI water to remove traces of acid, and then a final cleaning with isopropyl alcohol.

After the DBC substrates were cleaned, adhesive was dispensed in two locations on the surface with a manual I&J Fisnar Inc., JB1113-LF dispensing system. Two SiC dice were then placed on the dispensed adhesive to form one assembly. Nine such assemblies were made that formed a batch of adhesive assemblies. Each batch of assemblies was cured in a furnace with a temperature profile as shown in Figure 1. Adhesive samples were made in nine batches to produce a total of 81 samples.

Solder Die Attach Process

Identical DBC substrates were diced and cleaned in using the same process as described above. Solder preforms were cut from a ribbon using a punching machine with a 1.2 mm x 1.2 mm square punch. Due to the nature of this process, the preforms were then flattened by application of 5 PSI of pressure by a press with heated plates that were maintained at 80°C. The

preforms were then rinsed in isopropyl alcohol before they were used in the soldering process.

The solder attach process was performed with the aid of a vacuum soldering system; a Scientific Sealing Technology (SST) 3130. The soldering process was carried out in a reducing atmosphere composed of 5% Hydrogen to decrease the chances of oxidation during solder reflow. In addition, no liquid flux was used and the reducing atmosphere served as the fluxing agent. A fixture, as shown in Figure 2, made of graphite was used to hold nine DBC substrates, eighteen solder preforms and the SiC dies in place during the soldering process. Two dice were bonded to each piece of DBC with one solder preform per die. This fixture serves to register the parts during the solder process and also serves as the source of heat since current flows through the graphite to heat the samples.

Since this is fundamentally a batch process, nine samples were produced in each batch. The soldering process was carried out in a 95% N_2 /5% H_2 filled environment. Vacuum was first created in the chamber of the soldering system, and then the chamber was flushed with pure nitrogen or the 95% N_2 /5% H_2 mixture. This process was repeated twice to flush as much oxygen, water vapor and other contaminants from the chamber as possible. As an added precaution, each batch of solder assemblies was first run through a cleaning profile to remove thin layers of oxide on the surface of the assembly, and to ensure low oxygen content within the chamber. The temperature and the pressure profiles used in the cleaning process are shown in Figure 3. After the cleaning process,

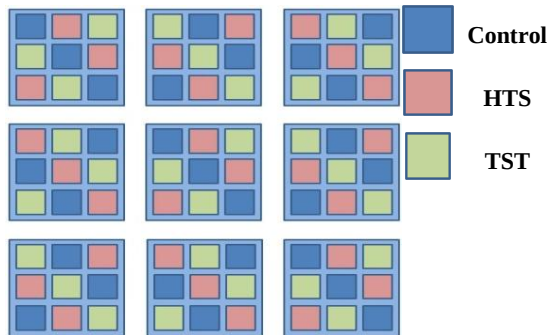


Figure 5: Latin Square Randomization (LSR) model.

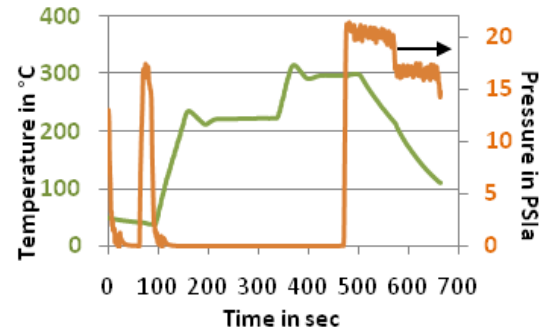


Figure 3: Temperature and Pressure profile for assembly cleaning in SST 3130 system.

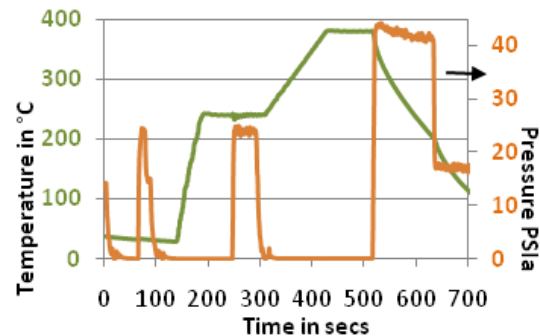


Figure 4: Temperature and Pressure profile for solder reflow in SST 3130 system.

the chamber vacuum was maintained and the batch of assemblies was then immediately run through a reflow profile complete the solder process. The temperature and pressure profile used in the reflow process are shown in Figure 4.

Randomization Model

To ensure consistent results throughout the experiment, the samples that were produced in batches were divided into groups for treatment based on the Latin Square Randomization (LSR) model. A graphical representation of LSR model is as shown in Figure 5.

In the preparation of each batch, the samples were arranged in a 3 x 3 matrix during the reflow or the curing process. Each batch of samples produced was divided into three groups with three samples in each group. These three groups included at least one sample from each row and column. From nine batches of solder samples and nine batches of adhesive samples,

54 substrates samples were allocated to each of the three groups (27 solder attach, 27 adhesive attach).

The first group, or control group, was shear tested without any treatment. The second group underwent HTS prior to shear testing, while the third and final group underwent TST prior to shear testing. Each of the two treatments (HTS & TST) was carried out in six steps and nine die attach samples were shear tested after each step. For HTS the steps were increasing amounts of hours at the high temperature, and for the TST samples the steps were the increasing number of cumulative thermal shock cycles.

After treatment, all samples were sheared using a Xyztec Inc. Condor 70 shear tester equipped with a 1.5 mm wide tool.

Accelerated Aging

To assess the effect of exposure of samples to thermal shock and high temperature for long durations, the samples were subject to high temperature storage and thermal shock test treatments. Both the treatments were carried out in air and no measures were taken to prevent oxidation during these treatments.

High Temperature Storage

Twenty seven samples (54 dice) of solder and an additional 27 samples (54 dice) of adhesive die-attach were subject to HTS to assess the effect of exposure of the die-attach to high temperature for long duration of time. HTS was carried out at 200°C in a Yamato DKN 400 forced convection oven. Three thermocouples were used to monitor the temperature of the samples during the HTS. This testing was conducted in six steps of 100, 250, 400, 600, 800 and 1000 hours. After each step, nine dice were sheared and their shear strengths were recorded.

Thermal Shock Test

The third group of twenty seven substrates (54 dice) of solder and an additional twenty seven substrates (54 dice) of adhesive samples were subject to TST to assess the effect of thermal shock due to sudden rise or fall of temperature of the samples. TST was carried out in an Espec TSE-11-A thermal shock chamber. Five

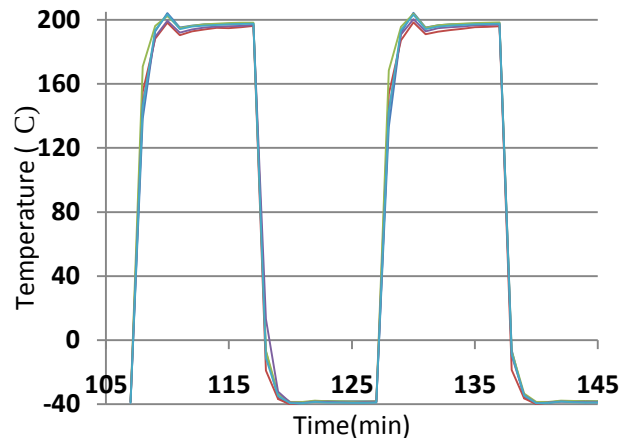


Figure 6: Temperature of samples recorded during TST

thermocouples were used to monitor the temperature of the samples during the test.

The TSE-11-A is an air-to-air thermal shock machine with two chambers. The upper chamber is a high temperature chamber that was maintained at 200°C and the lower chamber is a cold chamber that was maintained at -40°C. All the 54 substrates (27 solder, 27 adhesive) were loaded into a tray that moves between the top and the bottom chamber to expose the samples to thermal shock. The time taken for transition of temperature of the samples from one extreme to another was set to 3 minutes. The duration of time for which the samples were held in each chamber was set to be 10 minutes. A sample of the temperature profile recorded from the samples during the TST testing is shown in Figure 6.

TST was conducted in six steps of 100, 250, 400, 500, 750 and 1000 cycles. After each step, nine dice were sheared and their shear strengths were recorded.

4. Results & Conclusions

The shear strength data for all three groups is tabulated in table 2 for the solder samples and table 3 for the adhesive samples. This same data is also plotted in figures 7 and 8 for the solder samples, and figures 9 and 10 for the adhesive samples.

It is interesting to note that no failures of the solder samples were observed after any of the

Table 2: Shear strength of solder die attach samples measured in KgF.

Control Group						
No. of Dice	Mean	Range	Std. Dev.			
54	2.846	7.062	1.578			

Thermal Shock Test Group						
No. of Cycles	100	250	400	500	750	1000
No. of Dice	9	9	9	9	9	9
Shear Strength	3.308	3.407	2.017	2.452	2.282	1.890

High Temperature Storage Group						
No. of Hours	100	250	400	600	800	1000
No. of Dice	9	9	9	9	9	9
Shear Strength	3.3	2.601	4.179	4.454	2.833	4.021

Table 3: Shear strength of adhesive die attach samples measured in KgF.

Control Group				
No. of Dice	Mean	Range	Std. Dev.	
54	2.444	3.369	0.558	

Thermal Shock Test Group						
No. of Cycles	100	250	400	600	800	1000
No. of Dice	9	9	9	9	9	9
Shear Strength	2.128	1.735	0.846	Fail	Fail	Fail

High Temperature Storage Group						
No. of Hours	100	250	400	600	800	1000
No. of Dice	9	9	9	9	9	9
Shear Strength	1.736	2.599	2.173	2.481	-	-

accelerated aging tests. All of these samples were shear tested and all of the samples failed during this shear testing in the solder itself and not at the interface between the solder and the substrate or between the solder and the die metallization. This indicates that the bond between both the copper metallization on the substrate the die metallization is stronger than the solder itself, which is the ideal result. Also this indicates that the adhesion between the metallization on the die and the SiC itself is adequate. SiC is somewhat difficult to metalize and the authors have observed problems with

adhesion in some commercially made prototype die lots.

A decrease in the overall strength of the solder attach was observed during thermal shock, but not during HTS. While the drop during TST was statistically significant, it is believed that the strength of the bonds is still adequate for many applications even after 1000 hours of these rather harsh TST conditions. SEM / EDAX analysis was unable to identify any significant change in the structure of these solder samples after testing.

In contrast while the adhesive performed very well under high temperature storage, it failed the TST testing phase. Even after 600 hours of HTS testing at 200 °C there was no statistically significant change in the shear strength of the adhesive samples, and all of the samples failed in the adhesive itself during shear testing. However, the TST results demonstrate a sharp and statistically significant drop in the shear strength of this set of samples. As can be noted in table 3, as well as in figure 9, these samples began to fail the TST test after only 600 cycles. These failures were the result of the die coming loose from the substrate and the failure was in the adhesive itself.

The conclusions drawn from this data are that 92.5Pb/5.0Sn/2.5Ag solder is an excellent choice for SiC die attach on DBC substrates as long as the maximum junction temperature is limited. While this work was only conducted to 200 °C, it is believed that this solder can be extended to higher continuous operating temperatures in this role. In contrast, while this particular adhesive shows great promise in terms of its ability to withstand high temperatures for extended periods of time, it cannot withstand the TST conditions applied in this work. This may be a result of the relatively large CTE of the DBC substrate relative to the SiC dice.

5. References

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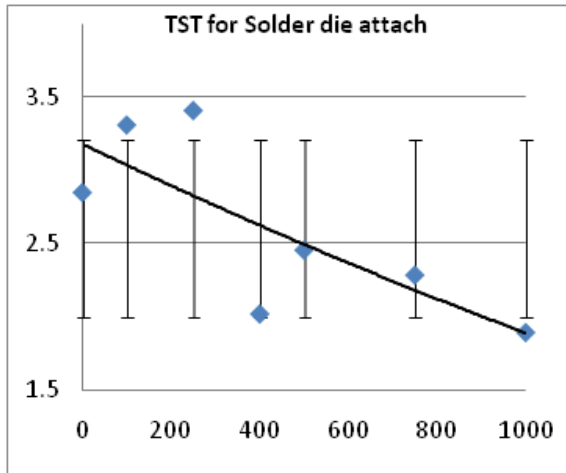


Figure 7: Results of thermal shock test for samples with solder die attach.

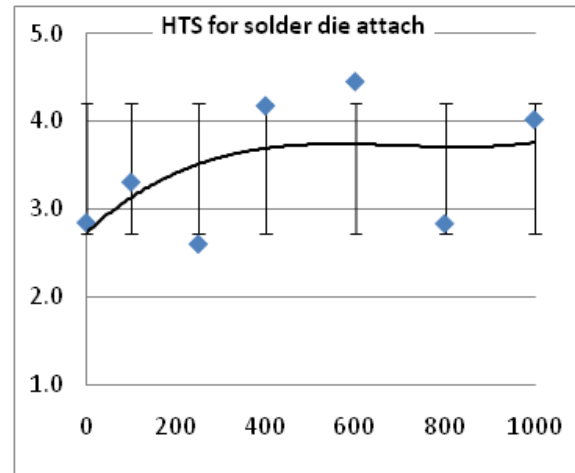


Figure 8: Results of high temperature storage for samples with solder die attach.

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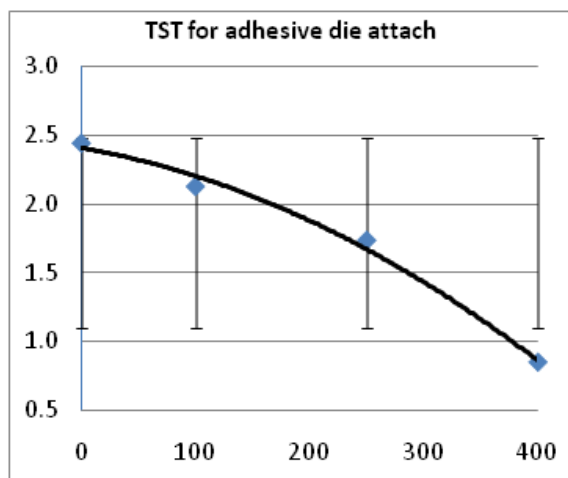


Figure 9: Results of thermal shock test for samples with adhesive die attach

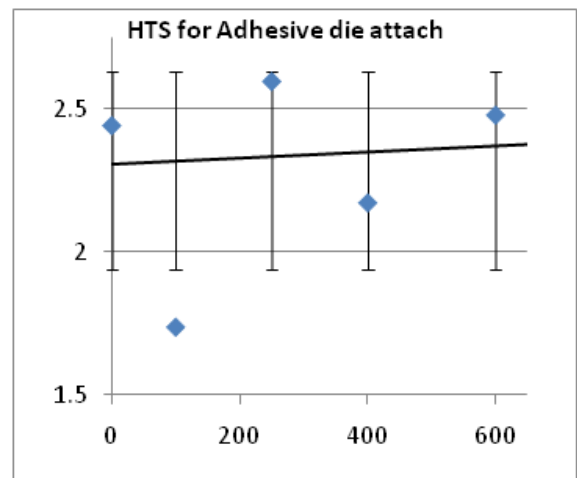


Figure 10: Results of high temperature storage for samples with adhesive die attach