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High-Temperature Die-Attaches for SiC Power Devices

Amandine MASSON¹, Cyril BUTTAY¹, Hervé MOREL¹, Christophe RAYNAUD¹,
Stanislas HASCOET¹ and Laurent GREMILLARD²

Université de Lyon, CNRS, INSA-Lyon, ¹ Laboratoire Ampère UMR 5005,

² Laboratoire MATEIS UMR 5510, F-69621, Villeurbanne, France

Phone: +33 (0)4 72 43 82 38

Fax: +33 (0)4 72 43 85 30

E-Mail: amandine.masson@insa-lyon.fr

URL: <http://www.ampere-lyon.fr/>

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Keywords

« Packaging », « High temperature electronics », « Silicon carbide », « Reliability », « Nanotechnology »

1 Abstract

SiC devices have been substituted to Si dies for high temperature applications. However, classical packagings are not adapted for harsh environment and new solutions for back-side die attach must be envisaged. In this paper, theoretical basis and results for nano-silver sintering Transient Liquid Phase Bonding will be presented.

2 Introduction

More electric aircraft programs have been launched to lighten aircrafts in order to reduce fuel consumption. The objective is to substitute hydraulic and pneumatic networks by power electronic systems which will be installed in hot areas. SiC power devices can operate at high temperature and are now commercially available, but all the environment of the die must be adapted for high temperature applications: the classical modules (see figure 1) must be completely modified.

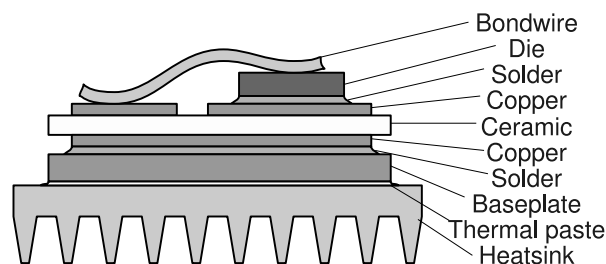


Figure 1: Schematic representation of a power module

Die-attach is one of the technological barriers for the production of high temperature modules. The classical bonding technology uses solder, which must remain solid over the whole operating temperature range. Furthermore, the reliability of the attach is directly linked to its operating temperature: as this operating temperature approaches the melting temperature, the mechanical properties of the solder joint degrade. The ratio between the melting temperature (T_m) and the operating temperature (T_o) is called homologue temperature and it should not exceed 0.8 [1] for power electronic applications.

$$T_h = \frac{T_o[K]}{T_m[K]} \quad (1)$$

For high temperature applications (e.g. T_o max = 300°C or 573 K), this would require a soldering alloy with a very high melting temperature (in our example $573/0.8 = 716$ K or 443°C). This is higher than the melting point of the most common high-temperature solders (such as gold-germanium or gold-silicon). Furthermore, a high temperature soldering process generates a high level of residual stress during cooling-down. The purpose of this work is to study alternative backside die attaches for SiC devices in harsh environment and to evaluate their reliability: two Low Temperature Joining Techniques, Nano-Ag sintering and Transient Liquid Phase Bonding, will be presented. For both techniques, the melting point of the bonding joint is much higher than the processing temperature. This means that, contrary to solder the operating temperature of these techniques can exceed the processing temperature (reducing the residual stresses) while remaining much lower than the melting temperature (increasing the mechanical performance). Different experiments have been made principally at the CPES [2, 3] to determine the most accurate conditions for the realization of joints with Ag nanopastes. It appears that best strength in shear-test are obtained for sintering time of 285°C, heating rate of 20°C/min, holding time of 60 minutes and Ag coating of the die. The present work will focus on the influence of DBC state surface and of the paste deposit on the joint reliability.

3 Theory

3.1 Nano-Ag sintering

Sintering pastes have been developed for die attach applications [4, 5, 6]. They all use silver as the base material, as it offers very high thermal and electrical performance, is simple to process (no need for vacuum or special atmosphere) and its cost is acceptable. All the pastes differ by the size and shape of the silver particles, as well as by their organic contents (binder, dispersant, coating...).

3.1.1 Theoretical considerations

Sintering is a well-known technology for producing bulk material by heating some powder under its melting temperature: sintering is now used for many materials, including metals [7, 8]. During the process, densification occurs and the dimensions are reduced (see figure 2). Different kinds of sintering can be described (with or without pressure, with or without additives, at solid or liquid state). In the sintering technique described in this paper, the particles remain solid during all the process, so only the solid state sintering will be considered below.

The sintering process can be described in three successive stages:

- debinding, which takes place before sintering: it consists in the volatilization of the binders which coat the particles to sinter. Debinding is an essential step which prevents the formation of voids in the bulk material
- sintering, which is the step of densification where particles are getting bigger and the number of internal voids decreases
- light dilatation can occur after sintering in case of recrystallisation after sintering (for metallic materials in particular)

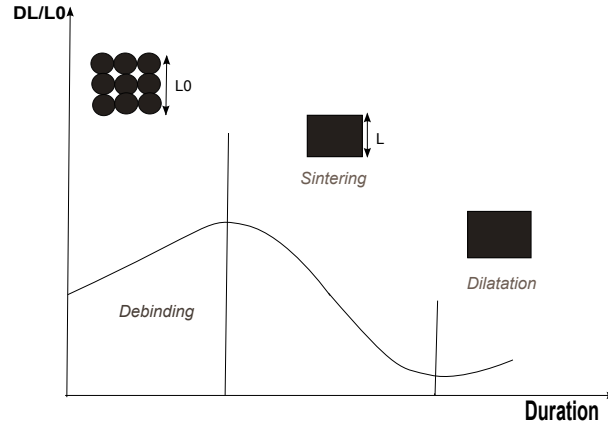


Figure 2: Schematic representation of the sintering process

The quality of the sintering is defined by its porosity (p , which must as low as possible). Porosity is the ratio between the volume of the voids (V_v) and the volume of the final piece (V_T).

$$p = \frac{V_v}{V_T} \quad (2)$$

After debinding, two processes are in competition: sintering and grain growth (which correspond to the grouping of powder with persistence of large voids in the structure) [8]. The driving energy of sintering is the reduction of the free enthalpy (ΔG) of the system: when ΔG is negative, sintering can occur. ΔG is a physical function which is used for describing the evolution of a system at temperature and pressure constant. G is dependant of H , function enthalpy, which measures the total energy of a system and to S , the entropy, which characterizes the agitation of a system at the macroscopic scale.

3.1.2 Effects of the sintering parameters

Different experimental parameters have an influence on the kinetics of sintering process:

- the temperature: process duration decreases when temperature increases
- the pressure: instering temperature decreases when pressure decreases
- the size of particles: sintering time is reduced when the size of particles decreases

Influence of the size particles follows Herring's law where r_1 and r_2 the radius of each entity at the beginning (time t_1) and at the end of the process (time t_2), m is a constant which depends on the type of sintering (between 4 and 8).

$$\frac{t_1}{t_2} = \left(\frac{r_1}{r_2} \right)^m \quad (3)$$

From this equation, it is obvious that smaller particles will sinter much faster. This can be used to reduce the process temperature and pressure. In some cases, sintering at room temperature becomes possible [9]. According to the Herring's law, it can be seen that the duration of sintering can be drastically reduced when the size particles decreases.

Nano Ag pastes have been developed for sintering application because Ag is an appropriate metal for die backside attach (excellent mechanical, thermal and electrical properties, high melting temperature) and the nano-size is adapted to low temperature process requiring little or no pressure (a few MPa). In contrast, pastes based on micron-scale particles require pressure of up to 40 MPa[4] to be applied during bonding. This requires a very specific tooling not to break the dies.

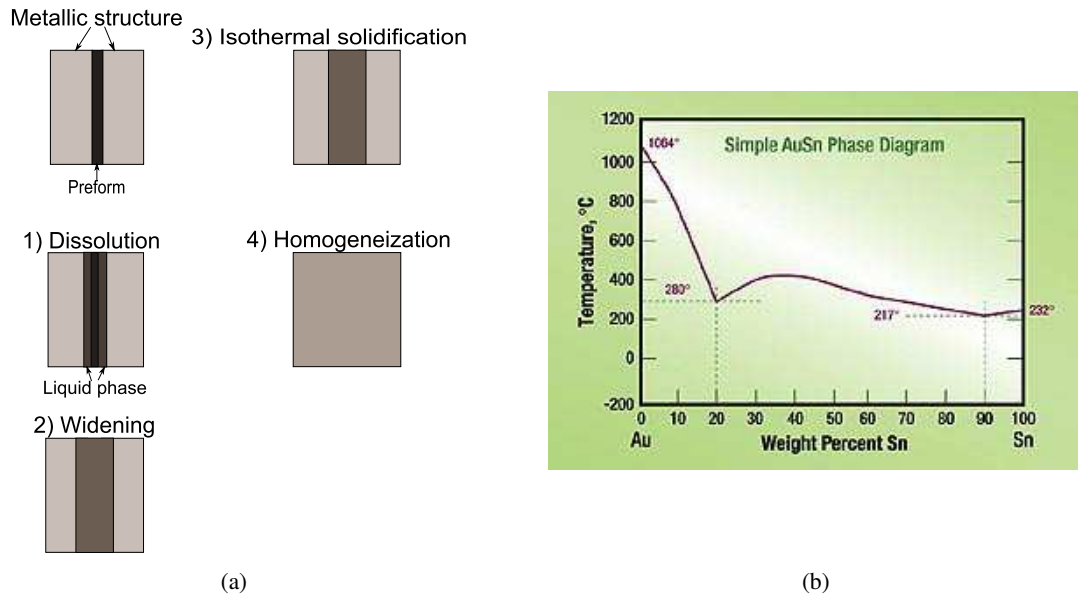


Figure 3: Schematic representation of the TLPB process (a), after [10] and binary diagram AuSn (b)

3.2 Transient Liquid Phase Bonding

Transient Liquid Phase Bond (TLPB) is a technique based on the diffusion at moderated temperature of a thin metallic preform (with a relatively low melting temperature) into two thicker layers (which have a high melting temperature, and remain solid during the process): it results in a joint which composition is homogeneous and which has a higher melting point than that of the preform [10].

Four steps can be described in the TLPB process:

- dissolution of the preform: formation of a liquid phase at the interface (see figure 3(a)). The liquid phase can be formed when the melting point of the preform is exceeded or when the melting point of a new alloy is exceeded.
- widening: the liquid phase is filling the voids and the contaminants are dissolved
- isothermal solidification: diffusion of the liquid in the structure
- homogeneization of the joint

Temperature, duration, width of the preform and state surface of the substrate are the most important parameters which can influence the TLPB process. The maximal joint width can be empirically summarized as a function of time and temperature on a TTT diagram [11, 12].

TLPB process is commonly used for the realization of AuSn joint [13]. The assembly (Au/AuSn20/Au) is heated up to the melting point of AuSn20 at 534 K, and after diffusion and homogenization, a new alloy (AuSn6) is obtained (see figure 3(b)). Its melting temperature is 1340 K as it can be seen on the binary phase diagram of Au/Sn. Other compositions of joints such as CuSn, AgSn, AuIn can also be used in TLPB technique [14].

4 Experimental procedures

In this section, we describe implementations of the silver sintering and TLPB techniques as a replacement to solder for power dies. As silver sintering is compatible with both the back metallization of the dies and the copper of a DBC substrate, we were able to perform a detailed study of die-to-substrate bonding. The chosen TLPB technique (AuSn/Au), on the contrary, needs thick gold metallizations to be applied on the parts to be bonded. This requires special dies to be developed (more details are given below), and is the reason why only preliminary results can be presented here.

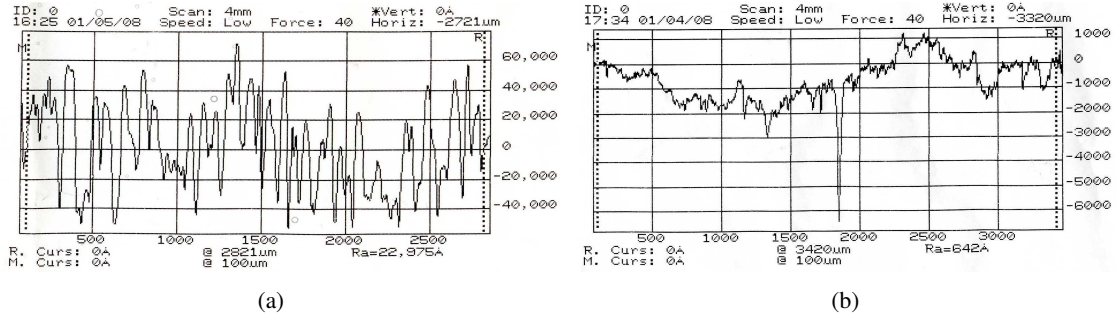


Figure 4: Profilometer measurements of the DBC substrate as delivered (a) and after polishing (b). The vertical scale is in Å and the horizontal in μm .

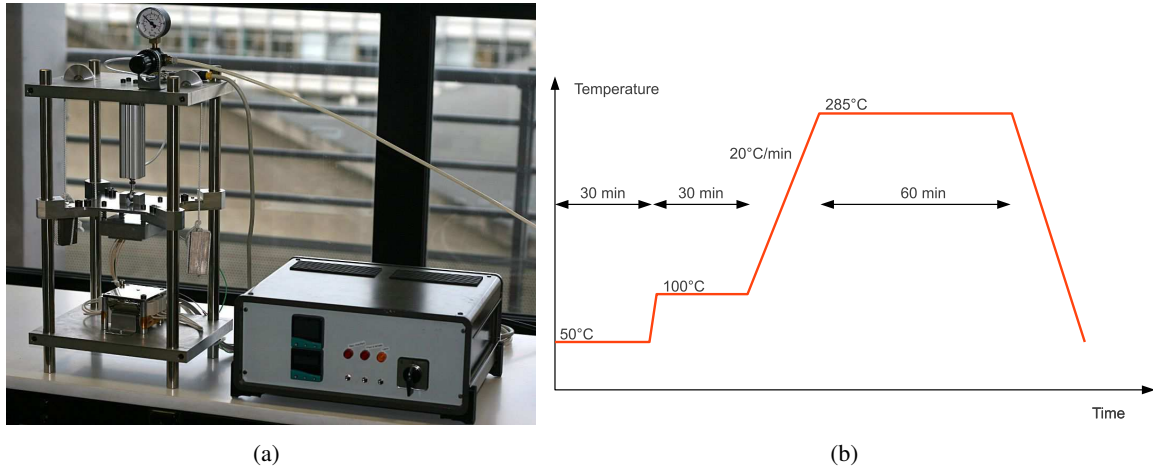


Figure 5: The press used for all the assemblies described in this article (a) and the temperature profile used for the die attach by nano-Ag sintering (b)

4.1 Nano Ag die-attach

As described above, a paste with nano-scale particles was selected in order to reduce the pressure required during bonding. The Nano Ag paste from NBE Tech [6], containing additives (binder, dispersant, thinner) and nano Ag particles (8-12 nm), was used for the attach of SiC devices (SiCED diode, 2.7×2.7 nm) and Direct Bonded Copper substrates. Different types of DBC have been used for this study:

- commercial DBC (Curamik) with $300 \mu\text{m}$ Cu metal bonded on 0.6 mm alumina.
- the same substrate, after mechanical polishing of the copper metallizations (35 down to $1 \mu\text{m}$ diamond grit), to reduce its surface roughness. Surface profiles of the un-polished and the polished substrates are given in figures 4(a) and 4(b) respectively (and the measured arithmetic rugosity is respectively of $2.3 \mu\text{m}$ and 64 nm)
- commercial DBC with Ni/Au finish (also from Curamik)
- silicon nitride substrate, with a Ni/Au finish (Denka)

4.1.1 Sintering

The DBC substrate is first deoxidized in H_2SO_4 (96 %) during five minutes and rinsed with deionized water. For both the DBC substrate and the SiC die, organic contaminants are removed in an ethanol solution during 3 minutes: agitation is provided using an ultrasonic bath.

Immediately after the preparation of the substrate, Ag nanopaste is deposited on a ceramic metallized substrate by screen printing (50 or $100 \mu\text{m}$ thick) and the die is placed on the Ag deposit.

The temperature profile followed is made of three steps (figure 5(b)): at 50°C and 100°C, the binders vaporize whereas sintering process takes place at 285°C. After sintering, the system cools down naturally, so the overall cycle time is around 3 hours.

The entire process is realized in air, under uniaxial pressure using the press visible in figure 5(a) (6 MPa). Both platens of the press are equipped heating elements, providing a uniform heating of the assembly. The pressure is controlled by pneumatic actuator and a pressure regulator.

4.1.2 Characterisation of the joint

For each test configuration, 6 or 7 assemblies were realized: 1 for microscopy inspection (this sample was encapsulated in resin, cut, and polished), the remaining for mechanical test (assessment of the shear strength). Shear-test is a very common way for evaluating the mechanical properties of a joint: a force is applied on the joint of the assembly and the force required for removing the die from the substrate is measured (6(a)).

The objective of the shear test is to evaluate the reproducibility of the bonding process. The process is considered reproducible if there is little dispersion in the shear force required to remove the dies from their substrates. For each sample, an optical observation of the fracture surfaces is performed, in order to determine if the fracture occurred within the silver joint, or at the interfaces.

4.2 TLPB AuSn

As mentioned above, for the TLPB technique selected (using Sn or AuSn as the liquid phase, and thick Au layers as the solid phases), it was not possible to use commercial dies or substrates. This forced us to develop some specific test vehicles. Two batches of test vehicles were made, based on 4 inches silicon wafers:

- layers of Ti (5 nm), Ni (100 nm) and Au (500 nm) were deposited on the first batch of two wafers, before the electroplating of a thick gold layer (10 and 20 μm)
- The second batch received a layer of tungsten (300 nm) and a layer of gold (100 nm) (both by sputtering), before the gold electroplating (10 μm)

The use of silicon wafers instead of silicon carbide was dictated by the Au electroplating equipment of the CNM (Barcelona), which could only accommodate 4 inches wafers (and most SiC wafers are limited to only 3 inches). However, in our experiment, the wafers are only used as substrates, and have little influence on the bonding process. Silicon has a coefficient of thermal expansion close to that of SiC (2.6 and 4 ppm respectively).

The wafers were then singulated in 5×5 mm dies.

For our tests, these dies were assembled by pairs using the press in figure 5(a), and two different preforms: 6 μm -thick Sn foil or 12.7 μm thick AuSn eutectic preforms. A large number of samples have been realized for different durations and temperatures of process in order to experimentally study the influence of each parameter on the joint quality. As the assembly consisted of two 5×5 mm dies, without any substrate, it was not possible to perform shear testing. The results presented here are based on microscope observations only.

5 Results and discussion

5.1 Nano Ag Sintering

To determine the most appropriate process parameters, different configurations were tested (table I). The effect of the following parameters was studied:

- state surface effects of the DBC
- nature of the metallization (Cu or Cu with a Ni/Au plating)

Table I: Test matrix

Series	thickness	substrate	bonding pressure	remarks
A	50 μm	Raw DBC	6 MPa	cleaning in U.S. bath manual scrubbing to get good die-paste contact
A'	50 μm	Raw DBC	6 MPa	
B	50 μm	Raw DBC	6 MPa	
C	50 μm	Au-finished DBC	6 MPa	
D	50 μm	Au-finished Si_3N_4	6 MPa	
E	50 μm	polished DBC	6 MPa	
F	100 μm	Raw DBC	6 MPa	two-step screen printing
J	50 μm	Raw DBC	0.7 MPa	
N	50+50 μm	polished DBC	6 MPa	
O	50+50 μm	Raw DBC	6 MPa	

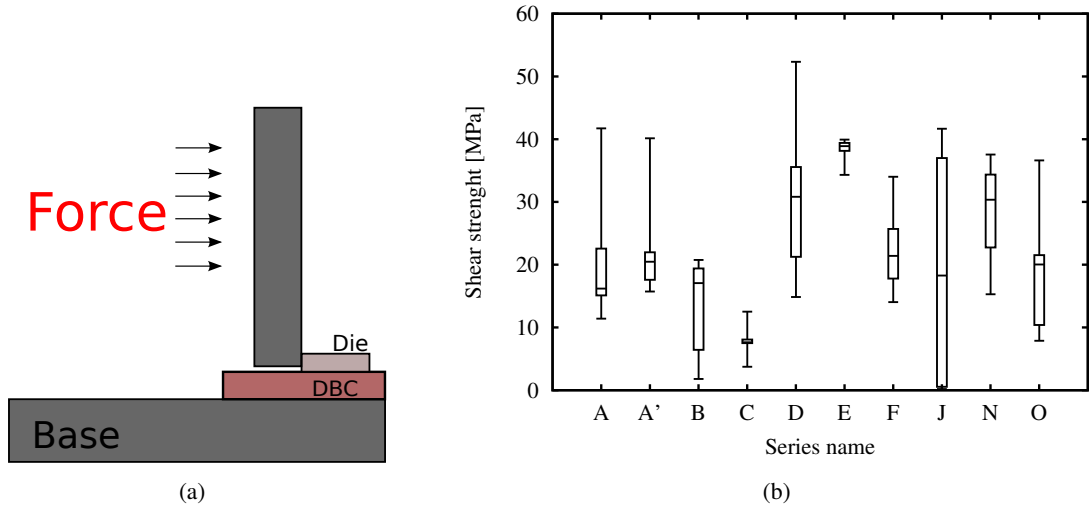


Figure 6: Schematic of the shear test (a). Box-and-Whisker plot of the shear-tests performed (b). The description of the series is given in table I.

- thickness of the deposit (50 or 100 μm , as well as the effect of depositing 50 μm twice with a drying stage in-between).
- pressure during assembly (pressure-less assembly was not studied, as preliminary tests showed very poor bonding)

Note that more than sixty prototypes have been realized, and for each of them, a die attach was achieved. The results of the shear tests are visible in figure 6(b).

Series A correspond to a cleaning process in which the parts to be assembled were cleaned by dipping them in the chemical solutions only. From series A', and for all subsequent series, it was decided to use an ultrasonic bath for the ethanol cleaning.

Comparison between groups A' and E shows clearly the importance of DBC state surface on the reproducibility of results and on mechanical resistance of the die-attach.

In fact, the dispersion is very small in group E (polished DBC) and the average shear-test resistance is much higher than for group A'. The difference in shear strength and the dispersion between the samples of series A' can be explained by the thickness of the silver joint. As can be seen in figure 7, for the sample from series A', the thickness of the silver layer is comparable to the rugosity of the substrate. This means that in some places, the copper is in direct contact with the die. For series E, thanks to the polishing, the silver layer is much thicker than the surface rugosity.

In both cases of figure 7, note that the final thickness of the silver joint (in the order of 10 μm or less) is much less than the thickness of the fresh paste deposit (50 μm). This is due to the elimination of the organic content of the paste, to the sintering, but also to the spreading of the paste caused by the pressure:

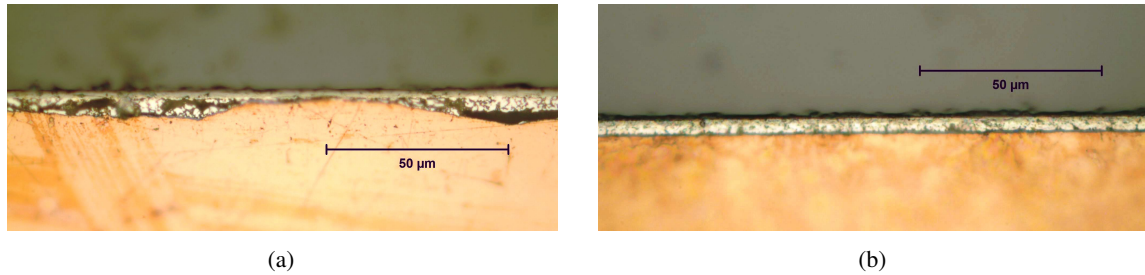


Figure 7: Optical pictures of a bonding joint from series A (a) and E (b)

after assembly, silver beads can be seen around the die, indicating that some of the paste has flowed from under the die. This explains the poor performance of the samples from series B, where a light (manual) scrubbing of the die was performed on the paste deposit to get good wetting of the die backside with the silver paste: this resulted in an even thinner silver layer, hence a very poor adhesion.

Samples from groups C and D have been realized with two different substrates: the first with a DBC (Alumina/Copper), the second with a Si_3N_4 /copper substrate: the rugosity of DBC coated Au is $0.98\mu\text{m}$ and $0.52\mu\text{m}$ for Si_3N_4 substrate. In both cases, the substrates were provided by their manufacturers (resp. Curamik and Denka) with a Ni/Au finish on the copper layers. As it can be seen in figure 6(b), the results are very different. For series C, the shear strength was found to be very low, whereas for series D, it was on average better than that of series A' (on raw copper), although with a large dispersion. This dispersion could be caused by the surface roughness of the samples (it was not possible to polish them without removing the Ni/Au plating).

One conclusion that can be drawn from series D, however, is the effect of a very thin layer of gold: preliminary tests showed that no bond could be achieved with silver sintering on a nickel surface. The substrates from series C and D both have a thick layer of nickel (several microns), coated with a very thin (around 50 nm) of gold. The relatively high shear strength of series D shows that this thin layer of gold is enough ensure a good die attach despite the nickel layer underneath.

Series F, J, N and O were two attempts to obtain a thicker silver layer, in order to overcome the rugosity issues described with un-polished substrates:

- For series E, a $100\mu\text{m}$ -thick screen was used to print the paste. No noticeable change in the silver joint was observed, meaning that the additional volume of paste flowed out during the pressing.
- For series F, a lower pressure setting was selected (0.7 MPa against 6 MPa for all other series), in order to reduce the “squeezing” of the paste. This produced a very unreproducible bond, with some samples barely bonded. This was probably caused by a poor contact between the dies and the paste.
- For series N and O, a two step deposit was performed, as advised with large-area bonds [15]: $50\mu\text{m}$ of paste were deposited, and then dried. Following to this drying, a fresh layer of paste was deposited using the same screen, and then the die was placed on top of the deposit, and the sample was sintered using the profile in figure 5(b)

As a conclusion, it appears that series E was the most reproducible, and exhibited a high shear strength, close to 40 MPa (i.e close to 30 kgf to shear a $2.7\times 2.7\text{ mm}$ die). It appears that bare copper substrates can be bonded using the nano-Ag paste. Copper oxidation could explain some of the dispersion in shear strength (the fracture surfaces of some samples show oxidized copper), but as can be seen with series E, not all series were affected. The surface roughness, on the opposite, is a very important parameter.

The parametric study of nano-Ag sintering has demonstrated that the most appropriate experimental parameters for joining SiC die with silver metallization with DBC substrate are:

- polished DBC
- thin layer of Ag nanopaste ($50\mu\text{m}$)
- sufficient pressure (in our case 6 MPa)

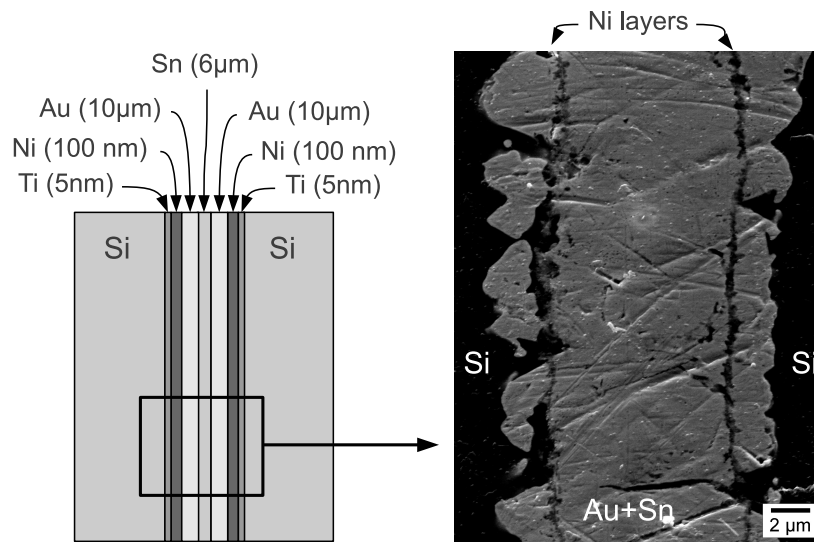


Figure 8: Structure of a sample using a Sn Preform before assembly (left), and the resulting Scanning Electron Microscope (SEM) image, showing the presence of gold in the silicon wafers

5.2 TLPB results

The parameters used for this study are:

- temperature: 235, 300 or 350°C
- preform material: Sn or eutectic AuSn
- assembly duration: 5, 30 or 60 minutes

With the Sn preform, a bond was achieved in all cases, except for the test at 235°C and 5 minutes. The melting point of AuSn being higher (281°C), 235°C is not enough to have a liquid phase, and therefore to start the TLPB process.

Element analysis (Energy Dispersive X-ray spectroscopy) revealed the presence of oxygen in the samples bonded using a single foil of tin, whereas no oxygen could be detected for the samples assembled using an AuSn preform. The bonding was performed in air, without any specific de-oxidation of the preforms. Therefore, in our case it should be preferable to use AuSn as the melting layer.

For the tests performed at 360°C, the microscope observations revealed not only a diffusion of the Sn in the Au layers, but also a spreading of the Au layers in the silicon wafers (see figure 8). This shows that nickel does not constitute an efficient diffusion barrier for gold at high temperature. Furthermore, AuSi has a eutectic at 354°C, lower than the 360°C of our experiment. This means that a liquid phase occurred in the silicon. In other samples (not shown here), up to 40 % silicon was found in the bonding joint, meaning that the AuSi liquid phase occurred on both sides of the Ni barrier.

To overcome the limitations of the nickel-based test vehicles, a second run was made, using tungsten as the diffusion barrier [3]. Two silicon wafers received layers of tungsten and gold by sputtering, followed by a thick electrodeposited layer of gold (10 μm).

Tests performed in a vacuum oven showed that these wafers could withstand over an hour at more than 600°C without any noticeable diffusion.

However, metallization peel-off was observed during the dicing of the wafers. This is probably due to the high level of mechanical stresses in the thick metal layer. Studies are ongoing to evaluate the effect of annealing on the metallization bond strength.

Conclusion

Two die attach techniques have been presented. They are compatible with the high temperature operation of power semiconductor devices.

Silver sintering, and in particular Nano-Ag, is the most mature, as it can be used with commercial substrates and dies. The results presented in this paper (especially the bond shear-strength) are comparable or exceed those available in the literature[2]. It was shown that by carefully choosing the process parameters, a very reproducible bond could be achieved. However, to obtain this good reproducibility, it was necessary to mechanically polish the substrates. This is not desirable, as it increases the cost of the substrates, and could prove difficult to do on large substrates, as they are not perfectly flat. Other solutions may include using a substrate with brushed copper (easier to perform than polished surface) or reduce the assembly pressure (in order to reduce the “squeezing” of the paste). They are currently being investigated.

The TLPB technique selected (AuSn), on the contrary, cannot be applied to off-the-shelf devices, as it requires them to have a thick gold metallization layer. It was shown that a good diffusion barrier (tungsten) is necessary. The adhesion of the metal layer to the wafer is not yet satisfying, and is still under study.

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