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Die attach using silver sintering

practical implementation and analysis

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ABSTRACT. Silver sintering is a promising alternative to high melting point (HMP) solders which contain lead. Indeed, it offers better thermal and electrical properties, and can operate at higher temperature. Currently, several implementations of this technique are available, based on various silver particles sizes and sintering additives. This paper presents a review of the different implementations, and gives practical details about one of them, based on silver nanoparticles. One specific aspect is highlighted: the metal finish of the DBC substrate. It has a major impact on the quality of the sintered joint: with some finishes, the adhesion is excellent (more than 50 MPa), while it is poor with some others (lower than 10 MPa).

RÉSUMÉ. Le frittage d'argent est un candidat prometteur pour remplacer les brasures haute température au plomb. Il offre en effet de meilleures performances thermiques, électriques et fonctionne à plus haute température. Actuellement, plusieurs solutions existent, basées sur des particules d'argent de tailles différentes et l'ajout d'additifs de frittage. Ces solutions diffèrent par leur procédé de mise en œuvre. Cet article présente un état de l'art des différentes techniques, puis détaille la mise en œuvre de l'une d'entre elles, basée sur des nanoparticules. Un point particulier est mis en évidence: la finition métallique des substrats DBC. Cette finition a un effet majeur sur la qualité du joint fritté: dans certains cas, l'attache est excellente (tenue mécanique supérieure à 50 MPa), alors que dans d'autres, elle est inférieure à 10 MPa.

KEYWORDS: power electronics packaging, silver sintering, high temperature.

MOTS-CLÉS: packaging en électronique de puissance, frittage d'argent, haute température.

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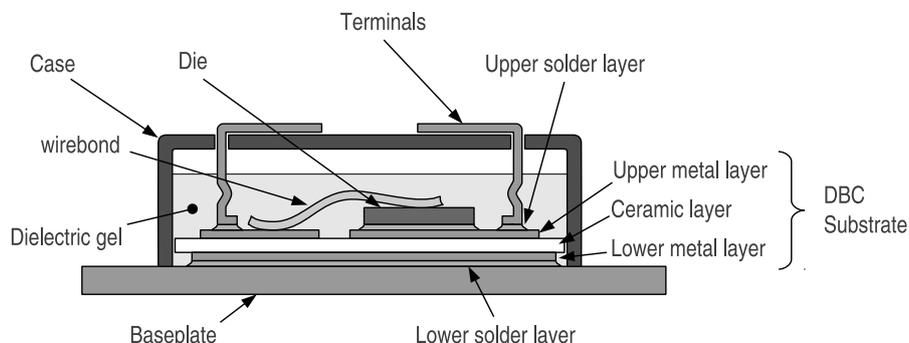


Figure 1. Structure (cross-section) of a classical power module.

1. Introduction

The vast majority of the power semiconductor dies are secured to a substrate using solder (see the structure of a classical power module in Figure 1). In most cases, a solder alloy with a high lead content is used (these alloys are referred to as High Melting Point, or HMP). Many studies are focused on replacing these alloys, for they are toxic, not reliable enough or because a higher operating temperature is requested. One of the most promising alternatives is based on silver sintering.

In addition to its mechanical purpose (securing the die to the substrate), the die attach layer must provide an efficient thermal and electrical path to the die. As a result, only metallic materials (pure metals or alloys) can achieve the thermal and electrical conductivity required. The performances offered by the conductive glues used in microelectronics as a die attach material are not sufficient for power applications.

The first studies on silver sintering as a die attach technique date back from the end of the eighties, at Infineon (Schwarzbauer, Kuhnert, 1991). Since 2000, there has been an increasing interest on this subject, with the availability of silver pastes based on nanometer-scale particules (Bai, 2005), and of power modules manufactured using silver sintering (Göbl *et al.*, 2006).

A review of the silver-sintered die attach techniques will be presented in the first section of this article. Then, we will describe a practical implementation of one of them, based on silver nano-particles (section 3). Finally, we will discuss the effect of the substrate surface on the bonding quality.

2. Review of silver sintering die attach

Sintering is a method to form a cohesive material from compacted powder using heat (Bernache-Assollant, Bonnet, 2005). This means that sintering starts with

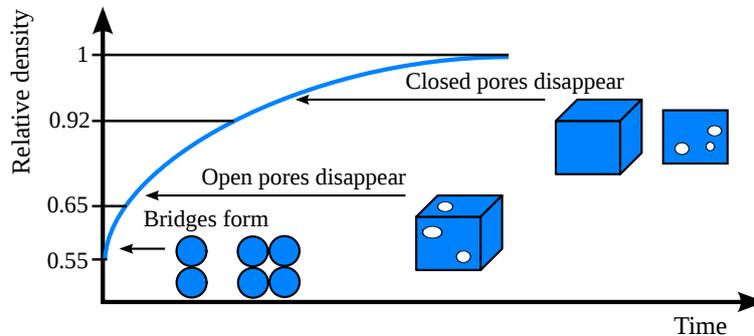


Figure 2. Evolution of the relative density during the sintering process (Bernache-Assollant, Bonnet, 2005).

a powder and ends with a single, solid part. Compared to soldering, sintering does not require a phase change. The links between particles are governed by diffusion mechanisms to form first a porous material, and then to reduce the porosity (Figure 2).

Although diffusion mechanisms are activated by the temperature, there is no need to reach the melting point of the material (as it is the case for soldering). As a consequence, sintering can occur at moderate temperature: in the case of silver, which has a melting point of 961°C , most sintering processes are performed below 300°C . Therefore, it becomes clear that process and operating temperature are decorrelated in the case of silver-sintered die attaches: while a solder can only operate below its melting (process) temperature, a sintered die attach can operate both below and above the sintering temperature.

Another difference between sintering and soldering is the behaviour of the bonding material during assembly: as the silver remains in the solid state during the sintering process, there is no macroscopic displacement such as wetting or capillary effect that can be observed when a solder alloy melts. These mechanisms are useful to compensate for uneven substrates or solder paste deposits. This means that silver sintering is sensitive to the quality of the elements to join, to which an extra care shall be given.

Among the metals available for the sintering process, silver has many advantages (which explain why it is also used in many solder alloys): it has the highest thermal and electrical conductivity of all metals ($429 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and $63 \text{ S}\cdot\text{m}^{-1}$ respectively); it is non toxic and hardly sensitive to oxidation. This means that the sintering process can be performed without a protective atmosphere.

The sintering process is controlled by three main parameters: the sintering temperature, the duration of the sintering soak, and the mechanical pressure applied on the particles. Indeed, applying a pressure forces the particles into contact and improves the diffusion mechanisms. Nevertheless, most of the bonding equipment currently in

use (ovens) are dedicated to soldering and do not allow to apply any pressure on the parts to join. Therefore, there is a need for a pressureless sintering process. This is why two main trends can be observed: on the one hand, pressure-assisted processes that can achieve very dense sintered joints; and on the other hand pressureless processes, which can be slower or achieve lower density joints, but can be performed in standard ovens.

2.1. Pressure-assisted sintering

This is the most advanced process, as it has been used on the production lines at Semikron (Göbl *et al.*, 2006) for a few years. This is the outcome of a development started more than 20 years ago, patented in 1989 (Schwarzbauer, 1989). One of its advantages is to use relatively coarse silver particles (micrometer-scale, 15 μm in the case of (Schwarzbauer, 1989)), which are easier to produce. The process temperature is moderated (240°C), but the pressure applied on the dies is fairly high, around 40 MPa (Göbl *et al.*, 2006). This corresponds to a force of 4000 N for a 10×10 mm² die. The tooling used to exert the force must therefore be carefully designed to avoid breaking the dies during the process (Göbl, 2007).

2.2. Low-pressure or pressureless sintering

The sintering kinetics is governed by the Herring law (Bernache-Assollant, Bonnet, 2005): two powders, with a particle radius size of r_1 and r_2 respectively will achieve the same state of sintering in respective times t_1 and t_2 related by the following relationship:

$$\left(\frac{r_1}{r_2}\right)^m = \frac{t_2}{t_1} \quad (1)$$

Where m is an integer constant (2 to 4), which is defined by the transport mechanism occurring during the sintering (gaseous transport, volume diffusion, surface diffusion. . .). It is clear from (1) that small particles will sinter much faster than larger ones. This allows for a reduction in the sintering temperature or in the required pressure. In extreme cases, particles with a few nanometers in diameter will be so reactive that they can sinter at room temperature, without the application of any pressure (Wakuda *et al.*, 2010).

Such nano-particle based pastes are available from several manufacturers: NBETech (Nanotach, (Bai, 2005)), Cookson (Argomax) or Henkel (SSP2000). All these pastes are intended for sintering at 250 to 300°C, with low (<5 MPa) to no pressure (natural sintering, in an oven).

2.3. Composition of the silver pastes

In addition to silver (regardless of the size of the silver particles, nano or micro), the silver pastes contain several organic components which ensure three functions:

- binder: it gives its consistency to the paste, allowing for easy dispense (screen printing, syringe...);
- dispersant: this component covers the silver particles and prevents them from touching each other (hence blocking any un-wanted sintering);
- thinner: to adjust the viscosity of the paste.

Additives can also be added to improve the sintering kinetics. All these organic components must be removed from the paste before the actual sintering. This occurs during a “drying” step.

3. Practical implementation of a nano-particle based sintering process

Research studies at CPES (Center for Power Electronic Systems), at Virginia Tech (USA), have resulted in the commercial availability of a paste based on silver nanoparticles (Bai, 2005). The composition and manufacturing process of this paste is described in details in the scientific literature (the composition is also fully described in the patent application (Lu *et al.*, 2007)). This is why we chose it for the present study. The brand name is Nanotach, manufactured by NBE Tech.

Based on this material and the existing literature, our work (Masson, 2011) consisted in developing a bonding process to achieve well-controlled and repeatable die attaches. Several process parameters were varied, as described in table 1: thickness of the paste deposit, type of substrate, sintering pressure. The other parameters (mainly the temperature profile) were directly taken from a publication from CPES (Wang *et al.*, 2007).

Preliminary tests showed that some minimum pressure was required to achieve adhesion of the dies on the substrate. This is in contradiction with the information from the manufacturer: the datasheet of the paste mentions that for dies smaller than $3 \times 3 \text{ mm}^2$, no pressure is normally required. However, in all cases described in table 1, the pressure applied is much lower than the pressure required for most micro-particles-based pastes (around 40 MPa).

3.1. Modus Operandi

Our test vehicle is made of a ceramic substrate (such as a DBC), on which a SiC die is attached using silver sintering

The chosen dies are SiC dummy chips (the devices discarded at the end of the production line). They were manufactured by SiCED, and have a size of $2,7 \times 2,7 \text{ mm}^2$. 4 different substrates types were used:

Table 1. Bonding parameters

Series	Deposit thickness	Substrate	Pressure
A, 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
J	50 μm	raw DBC	0.7 MPa
N	50+50 μm	polished DBC	6 MPa
O	50+50 μm	raw DBC	6 MPa
T	50+50 μm	Au-finished Si_3N_4	6 MPa

- DBC (Direct Bonded Copper), without any plating (bare copper)
- the same DBC, but with polished copper tracks (to reduce their natural surface roughness from a few micrometers down to a few tens of nanometers)
- Si_3N_4 AMB (Active Metal Braze) substrates, with a Ni/Au finish over the copper layers
- DBC substrates with a Ni/Au finish over the copper layer

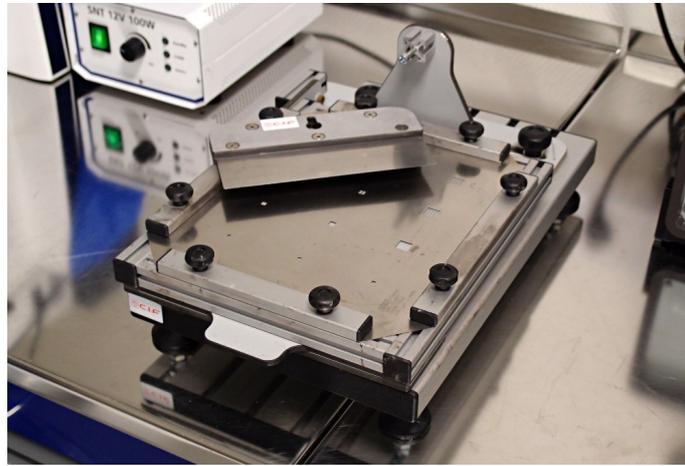
The various combinations we tested are listed in table 1. For each series, the paste was applied on the substrate by stencil-printing (Figure 3a), using a 50 or 100 μm -thick metal stencil. The die was then placed on top of the paste deposit, and the test vehicle was placed on the heating platen of a press that was specifically developed for the present work (Figure 3b).

The temperature profile was chosen according to the literature (Wang *et al.*, 2007). It is depicted in Figure 5. Note that for the “50+50 μm ” configuration (N, O and T series in table 1), this temperature profile is preceded by a drying profile (maximum temperature 180°C). This will be detailed hereafter.

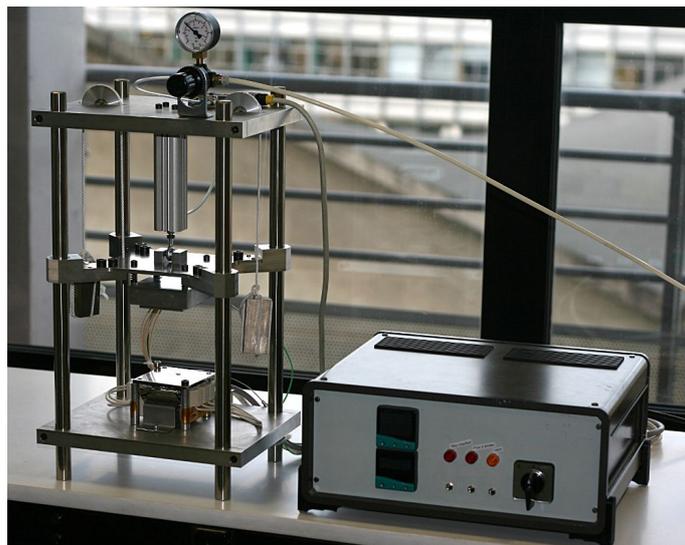
All the process takes place in air, without any protective atmosphere. The bonding pressure indicated in table 1 is applied continuously from the beginning of the temperature profile until cooling down to room temperature.

The assessment of the assemblies is performed for each series using two methods:

- 5 test vehicles (at least) were submitted to a shear test (Figure 4), and the force required to separate the die from the substrate was measured. The objective is not only to achieve a high shear strength, but also to achieve reproducible results, i.e. to have the shear strength of all the test vehicles of a series as close as possible to each other.
- 1 test vehicle was cross-sectioned and polished for microscope observation. The objective is to measure the thickness of the silver layer, and to evaluate the joint quality (presence of voids, cracks...)



(a)



(b)

Figure 3. The equipment used to apply the paste (a) and to generate the thermal profile (b)

3.2. Results and discussion

The measured shear strength values for all test vehicles and all series are summarized in Figure 6. It can be seen that the results vary dramatically depending on

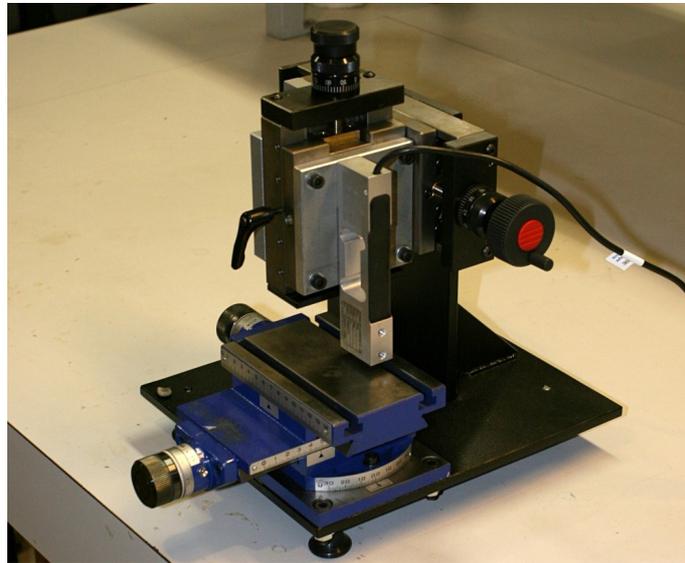


Figure 4. The equipment used to measure the die shear strength

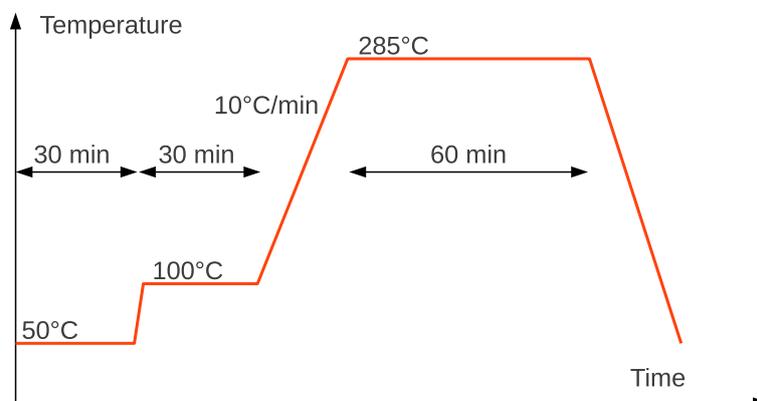


Figure 5. The temperature profile used for the silver sintering

the bonding parameters. As previously mentioned, we are looking for a high shear strength (i.e. a set of measurement that is as high as possible in Figure 6), but also for reproducible results (i.e. a compact symbol in Figure 6).

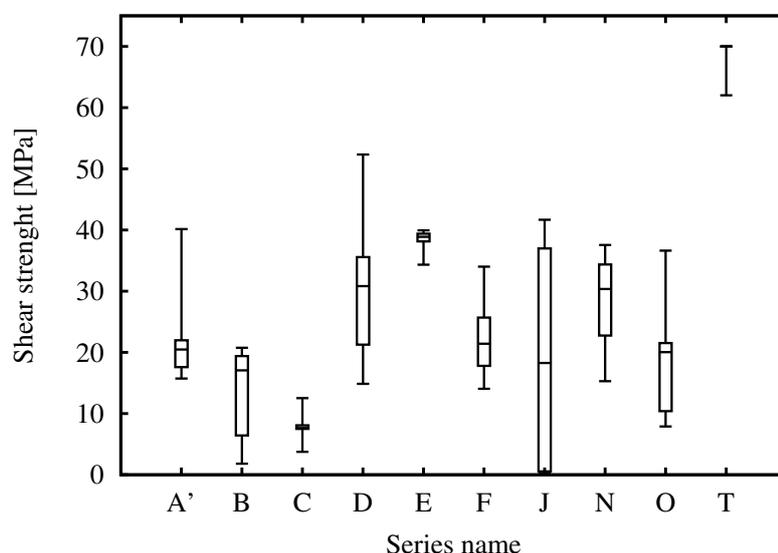


Figure 6. Results of the shear tests plotted using a “box and whiskers” chart, for each series of table 1. The ends of the “whiskers” correspond to the extreme values (min and max), the limits of the boxes to the first and third quartile of the distribution, and the separation in the box to the median. In other words, all the measured values fit within the limits of the whiskers, and half of them fit within the box.

Using these criteria, two series stand out: E (very reproducible) and T (very good shear strength). Note that for most of the test vehicles of the T series, we were not able to separate the dies from the substrates, because the shear strength exceeded the capability of our test system. Therefore, we cannot conclude regarding the reproducibility of the T series.

The cross-section pictures of three series (A, E and T) are visible in Figure 7. Between series A and E, only the surface roughness of the substrate is different (raw DBC in one case, polished DBC in the other). In both cases, the silver layer is very thin (about 10 μm for an initial fresh paste deposit thickness of 50 μm). As the surface roughness of the raw DBC is of the same order (Figure 7a), the silver layer is not thick enough to fill the voids. For a polished DBC, the surface roughness is much lower (a few tens of nanometers), the silver joint has a much more homogeneous thickness, which explains the very good consistency of the shear test results for series E.

It is important to note that these results were obtained on bare copper (without any surface protection against oxidation such as a Ni/Au plating), and that the process took place entirely in air, in presence of oxygen. The copper layers did oxidize, but without

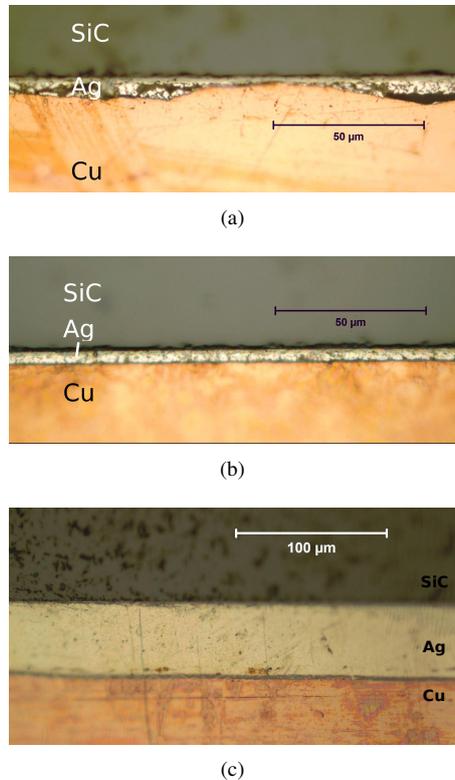


Figure 7. Cross sections of samples from series A' (a), E (b) and T (c). Note: the scale of picture (c) is roughly twice as big as that of the other pictures.

preventing the bonding to occur. This might be due to the silver paste protecting the substrate from oxidation, or to the silver paste adhering to copper oxide.

However, as discussed previously, the silver joint obtained is fairly thin. A 50 μm deposit of paste should result in a solid silver joint of approximately 25 μm (the paste has about 50% vol. content of silver). However, a large part of the fresh paste is “squeezed” out when the pressure is applied on the dies. The resulting silver joint is not thick enough to overcome the surface roughness of a standard DBC. As it is not desirable to polish the substrates before assembly, we tried several solutions to achieve a thicker silver joint:

- to use a thicker stencil (100 μm versus 50, F series), to achieve a thicker silver deposit;
- to reduce the pressure applied on the die to limit the paste creep (J series);

– to proceed to a 2-step deposit: a first 50 μm deposit, followed by a drying step, to make the deposit stronger and avoid the “squeezing” effect, then a second 50 μm deposit of fresh paste and then bonding of the die). According to the paste manufacturer, this is the preferred method for large-area die bonding (surface area larger than $3\times 3\text{ mm}^2$) (N, O, T series).

It appears in Figure 6 that the results of series F do not differ noticeably from those of the reference series (A). Indeed, the thicker fresh paste deposit only resulted in more paste being squeezed out from under the dies, producing a solid silver joint no thicker than for series A. Reducing the pressure (series J) produced a large dispersion, with a very poor bonding strength for two of the test vehicles.

The two-step method (series N, O and T) produced more interesting results. For series N and O (two-step deposit on raw and polished DBC respectively), there is no improvement over the reference series (A). For a substrate with a Ni/Au plating, however (series T), there is a dramatic increase, with an average shear strength exceeding the capability of our shear tester (70 MPa, corresponding to 510 N for a $2,7\times 2,7\text{ mm}^2$ die).

The difference between series N, O and T is related to oxidation issues: during the drying step, there is little protection against oxygen (no die and no pressure applied on the deposit). The substrates from series N and O do not have any plating (bare copper), while the substrates from series T have a Ni/Au plating are protected against oxidation. As mentioned previously, it seems that oxidation is not a problem during sintering, in spite of a higher temperature (285°C vs 180°C during drying) because it is assumed that the die and the pressure provide a tighter sealing against oxygen. The cross section in Figure 7c shows a much thicker silver joint (note that the scale of this picture is larger than that of the two pictures above). With the 2-step technique, the surface roughness of the substrate is no longer an issue.

4. Considerations on substrate metallizations

As opposed to the more classical soldering processes used in power electronics (vacuum soldering or controlled-atmosphere soldering), the sintering process described here takes place in air. Oxygen is used to consume some of the organic materials of the silver paste (Knoerr, Schletz, 2010). As a consequence, the copper metallizations of the substrates must be protected against oxidation: even if a satisfying bonding can be achieved on bare copper (see for example the results for series E in Figure 6), the oxidation of the copper layers is not acceptable, as it forbids any further operation, such as wirebonding of the dies.

Several metal finishes were evaluated. In particular, we studied electroless Ni/Au finishes from various manufacturers, as well as some silver finishes. For the test vehicles assembled with the silver paste from NBE tech, we observed large differences between the various Ni/Au finishes. As an example, in Figure 6, series C and D were assembled on substrates with the same finish specification (a few micrometers

of nickel, covered with 50 nm of gold), but from different manufacturers. Yet the results are very different, with the strongest result in series C weaker than the weakest in series D.

Currently, we cannot offer any explanation for these differences. More investigations are required to be able to define exactly the surface finish offering the best results for silver sintering.

5. Conclusions

Silver sintering is an attractive alternative to soldering, as this technology allows in theory a very high operating temperature capability (higher than 300°C). Nevertheless, it must be noted that its performances still need to be evaluated. In particular, ageing tests are required to ensure the good initial bonding strength observed in this article are retained over the operating life of the assembly. Electrical and thermal performance evaluations are also required before and after ageing tests.

The present study showed some of the main parameters to achieve a good die attach. A moderated (6 MPa) pressure must be applied on the dies. When a thicker joint is required, a two-step deposit method (deposit/drying/deposit/sintering) must be preferred.

The shear strength achieved with such two-step procedure is satisfying (over 70 MPa). However, the process is very slow (more than 4 hours including cooling down to room temperature). The objective of the present study was to achieve good and reproducible bonds. The next step is to optimize the process duration to make it compatible with industrial requirements.

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