Study of die attach technologies for high temperature power electronics: Silver sintering and gold–germanium alloy

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A B S T R A C T

Silver sintering joints and AuGe soldering are promising technologies for high temperature (>200 °C ambient) power electronics packaging. This paper presents the implementation of two silver-sintering processes with the one hand micrometer-scale silver particles, and on the other hand nano-meter-scale particles. Two substrates technologies have been investigated: A12O3 DBC and Si3N4 AMB. After the process optimization, tests vehicles have been assembled using both sintering processes, as well as a more classical high-temperature die attach technology: AuGe soldering. Multiple analyses have been performed, such as thermal resistance measurement, shear tests and micro-sections to follow the evolution of the joint during thermal cycling and high-temperature storage ageing.

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1. Introduction

Conventional power electronic packaging uses solder alloys to attach the dies to the substrates. This includes lead-free SACs (Sn, Ag, Cu, with a melting temperature slightly higher than 200 °C), HMP (High Melting Point, around 300 °C, with a high lead content) and gold-based alloys (AuSn, AuGe, AuSi, up to 362 °C) [1]. An alternative to solder is the sintering of silver particles, as the joining process is performed at a moderate temperature (<300 °C), but the resulting joint (pure silver) has a melting point of 961 °C. Silver sintering pastes offer very high thermal, mechanical and electrical performances for the die-attach purpose [2,3]. Various experimental parameters have an influence on the kinetics of the sintering process: temperature (duration of the process decreases when the temperature increases), pressure (sintering kinetics increase with pressure) and particles size (sintering time is reduced when the particles size decreases) [4,5].

2. Silver sintering process and preliminary shear test analysis

The Test Vehicles (TV) are composed by 3 × 3 mm² size silicone chips and a metalized substrate. Two types of substrate were used: Si3N4 Denka AMB substrate with an electroless nickel–immersion gold finish (see Table 1) (measured surface roughness: 650 nm) and Curamik A12O3 DBC substrate with the same metallization (measured surface roughness: 700 nm). The paste was applied using 50 μm-thick stencils and then three chips were sintered at the same time on each substrate.

For the nanosilver paste, the sintering process is realized in 2 steps. For the first step called pre-drying, a 50 μm-thick deposit of paste has been screen-printed on the substrate, and let to dry for 1 h at 180 °C. Several silver sintering profiles were studied to obtain the best die shear strength reproducibility. In the second step, additional paste is applied on top of the previous deposit, the die is placed on top, and the stack is introduced in a press for sintering (see Fig. 1).

With the micro-silver sintering paste, the test vehicles were assembled using an industrial press including 2 hotplates (20 × 20 cm² sizes) that can reach a maximum force of 30 kN. A specific software is associated to the press to control the pressure applied on the substrates. The sintering process is realized in only one step (see Fig. 2) [6].

In addition to the sintered test vehicles, AuGe solder die-attach assemblies have been fabricated. AuGe alloy preform was used with applied pressure on the die for better bonding. The reflow process was made with 4 zones oven (300/300/330/450 °C + H2; speed: 6.5 cm/min). Four types of test vehicles were assembled for thermal ageing (see Fig. 3).

2.1. Preliminary die shear results on non-aged test vehicles

The die-shear tests are made with a DAGE 4000 machine and the results have shown a better reproducibility of the process on Denka substrate (see Fig. 4: Denka Si3N4) and higher shear strength on Curamik substrate (see Fig. 4: A12O3 DBC).

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Although both substrates are supposed to have similar metallization (4 µm electroless nickel thick) and immersion (flash) gold (50 nm for Denka and 90 nm for Curamik) and have very close surface roughness’s (650 and 700 nm), a large difference is observed on the shear strength of nanosilver bonded samples. This may indicate an influence of the NiAu finish depending on the substrates provider. Such difference cannot be observed with the micro-silver samples. With the AMB Si₃N₄ substrate, a better shear strength is achieved with the micro-silver paste process. Opposite results can be observed with the Curamik DBC. For both processes, the pressure applied on the dice is similar (5 and 5.5 MPa) but the process is much longer for the “nano” process (1 h sintering (see Fig. 1), 4 h total, including drying and cooling down) than for the “micro” (3 min sintering, 30 min total, see Fig. 2). The highest die-shear strength value did not exceed 70 MPa with the “microsilver” and “AuGe solder alloy” compared to more than 100 MPa with the nanosilver. Note that in both cases, these strengths are much higher than required by the MIL-STD-883 standard.

3. Ageing tests

As shown in the previous section, both micro- and nanoparticle based silver sintering technologies offer very high shear strength capability. The next step was to assess their reliability both in thermal cycling conditions and in high temperature storage.

3.1. High-temperature storages

A large number of TV (68 TVs) were assembled using 204 mechanical Si chips (3 per substrate), using the three technologies under investigation (nano and micro-particles silver sintering and AuGe soldering). Then, they have been submitted to a series of high-temperature steps, ranging from 200 to 300 °C, with 20 °C increments (see Fig. 5).
For one half of the test vehicles, the step duration was 24 h, for the other half, the duration was 240 h.

### 3.2. Thermal cycling tests

To follow the evolution of the die-attach joint, test vehicles were assembled, with three functional SiC diodes on each substrate. The dice were wire-bonded (see Fig. 3). 75 TVs were assembled, and fully characterized (measurement of the thermal resistance, acoustic microscopy and X-ray inspection) before cycling. Two cycling profiles were used: thermal shocks from \( T_{176}^0 \) to \( T_{176}^{+180} \) at \( 40^\circ C/min \) and Rapid Temperature Variation (RTV) from \( T_{176}^{-55} \) to \( T_{176}^{+245} \) at \( 10^\circ C/min \). Periodically, samples were removed from the environmental chambers, fully-characterized using the same nondestructive protocol, followed by the shear-test of the dice. Two types of TV using nanosilver paste were assembled with different sintering processes.

### Table 2

<table>
<thead>
<tr>
<th>Die shear test (MPa)</th>
<th>µAg–Si₃N₄</th>
<th>nAg–Si₃N₄/Proc. 4°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cycle</td>
<td>Die1</td>
<td>Die2</td>
</tr>
<tr>
<td>2500 cycles-Shock°</td>
<td>59</td>
<td>58 µs°</td>
</tr>
<tr>
<td>900 cycles-RTV°</td>
<td>µs°</td>
<td>11 9 µs°</td>
</tr>
<tr>
<td></td>
<td>8 µs°</td>
<td>16 µs°</td>
</tr>
<tr>
<td>AuGe–Si₃N₄/Proc. 3°</td>
<td>Die1</td>
<td>Die2</td>
</tr>
<tr>
<td>0 cycle</td>
<td>&gt;100</td>
<td>&gt;100 µs°</td>
</tr>
<tr>
<td>2500 cycles-Shock°</td>
<td>&gt;100</td>
<td>&gt;100 µs°</td>
</tr>
<tr>
<td>900 cycles-RTV°</td>
<td>µs°</td>
<td>&gt;100 100 µs°</td>
</tr>
<tr>
<td></td>
<td>79 µs°</td>
<td>81 µs°</td>
</tr>
</tbody>
</table>

µs°: chosen die for microsection; F°: Failure; Shock°: “–55 °C to +180 °C”; RTV: Rapid Temperature Variation “–55 °C to +245 °C”. Proc. 1–4: different process (Fig. 3).

### 4. Die shear results after thermal storage ageing test

As we can see on the Fig. 5, the short duration of the micro-silver sintering process does not give the highest die shear. But after a step of 24 hr or 240 h thermal storage at 200 °C, the die shear value rise (see Fig. 6). It can be explained that the sintering process continue with the thermal ageing test. This phenomenon is only shown with the nanosilver assembly after 240 h thermal storage.
with a small increase of the die shear strength because of the long duration of the process.

According to [7–9], the failure evolution of the sintered silver joints is caused by micro-cracks increasingly important making the joint strength unstable. Delamination is more observed for the test vehicle assembled by nanosintering silver joint (see Fig. 7).

5. Die shear results after thermal cycling ageing test

Before thermal cycling test, the test vehicles assembled with gold–germanium and nanosilver paste have an excellent shear strength (>100 MPa) (see Table 2).

All die shear strengths are much higher than required by the MIL-STD-883 standard. Before thermal ageing test and die shear test, the die has not been pulled from the substrate. Microsection was made and we observed cracks inside the AuGe solder alloy and the nickel layer (see Fig. 8). After thermal cycling test, it was observed that solder alloy joint has the best bonding than silver sintered joint.

5.1. Thermal impedance measurement

The thermal impedance is a good ageing indicator, as it will increase when a delamination or a crack develops under a die. We have performed a classical thermal impedance characterization procedure based on the measurement of a Thermal Sensitive Parameter (TSP) which is the on state voltage drop through a SiC diode obtained with the same calibration current.

In this study, all the samples are aged in the climatic chamber and one TV is definitely removed for analysis. As we can see in Fig. 9, each TV was analyzed before (Dies 1, 2 and 3 @T0) then after (Dies 1, 2 and 3 after ageing @Tn) thermal ageing test. The thermal resistance of the assembly rises up after the thermal cycling test.

5.2. Scanning acoustic microscope

The acoustic analysis provides useful information in the joint evolution after thermal ageing. Compared to the thermal impedance characterization, which gives a single parameter per die, the SAM offers a much more detailed information, as the propagation of the crack inside the joint. As it is shown in Figs. 10 and 11, important delamination is observed after 900 cycles of RTV test and increase of the void for the AuGe solder alloy. After 2500 thermal shocks cycles, dice are not attached anymore with the nanosilver sintered joint and delamination started from the edge of the micro-silver joint. And no evolution of the AuGe solder alloy is observed.

6. Conclusions and future work

In this paper, the performance of silver-sintered die-attach (both in its micro- and nanoparticle version) to a more classical Au–Ge high temperature solder have been compared. It was shown that before ageing, the die-attach strength is excellent. The thermal performance is also as good as that of AuGe (our test method cannot discriminate between them), and the silver die attaches show
very little voids (less than for AuGe). After RTV cycling test, important delamination is observed for the silver sintered joint and increase of the void for the AuGe solder alloy. And after thermal shock cycling, no attach of the die is observed with the nanosilver sintered joint and no evolution of the solder alloy joint.

References