Reliability of Double Side Silver Sintered Devices with various Substrate Metallization

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Abstract

Silver sintering technology is one of the most promising high performance lead-free die-attach technologies. The work presented focuses on the thermo-mechanical and electrical performance evaluation of double side sintered modules. Die and clip attachments are processed with pressure assisted Argomax® silver sintering technology developed by Alpha Assembly Solutions. Power cycling tests following automotive requirements (200A, 5s ON and 10s OFF, until failure) and thermal cycling tests (liquid to liquid, -55°C/+165°C, 3 minutes dwell time for 1000 cycles) were applied to the devices. Thermal impedance measurements along with optical observations (metallographic and CSAM analysis) showed a significant increase of the 650V/200A IGBT device reliability when compared with best in class solder technology.

Introduction

The continual evolution of electric and hybrid automotive vehicles have increased the requirement for high power component reliability in smaller packages. Lead-free technologies are widely investigated in academic research [2, 3 and 4] and private consortium; such as the DA5 composed by Infineon, Bosch, NXP, ST Microelectronics and Freescale, as thermal, electrical and mechanical efficiency of standard solder based interconnection is approaching its limit [1] Several technologies have emerged over the past decade to achieve high temperature power modules (175°C and beyond junction temperatures) with high reliability. Some examples of such technology include gold base, high cost solders such as AuGe and AuSn, self-gripping assemblies using Van der Waals forces as the gecko, electrically conductive adhesives (ECAs), transient liquid phase bonding, SnSb alloys, high lead solder, SAC systems and silver sintering.

The commercialization of new technology has proven to be a complex process. Silver sintering has attracted a lot of interest over the last decade and has shown the ability to fulfill the electronics device reliability requirements. Argomax® silver sintering paste and film technologies are developed by Alpha Assembly Solutions and allow a fast (< 2 min), low-pressure (5-10 MPa) process for a wide range of applications including power modules, power discretes, thyristors, high power LEDs, and power RF devices.

Additionally, wire-bondless technology allows further miniaturization and significant reduction in parasitic inductance related losses. This design also improves the thermal management of power modules as heat dissipation is possible from both sides of the die [5, 6]. An internal simulation study has shown IGBT junction temperature decreases approximately 33% when
using silver sintering as die-attach material in place of conventional solders (Fig. 1). This assumes nominal bond lines of 20 μm for sintering, 150 μm for soldering, and same die configurations and power applied (2kW). Specific process conditions were investigated to confirm the results obtained during simulation.

![Figure 1: Junction Temperature in °C (Y Axis) for a 2kW power applied to 90um Si chip, using Argomax® sinter material and solder at different bond line thicknesses (BLT). Thermal conductivity in [W/(m.K)] (X Axis)](image)

In this paper, we propose to evaluate the impact of double side sintering (die and clip attach) on the thermo-mechanical performances of 650V/200A IGBTs on Si₃N₄ AMB substrates with three different metallization: raw copper, spot silver and full electroless silver, when exposed to thermal shock and power cycling. Thermal impedance measurements throughout the power and thermal cycling tests were used to characterize the thermomechanical behavior of the sintered modules. Metallographic and CSAM (Scanning acoustic microscopy) analysis were used to correlate those failures to a defect inside the assembly.

### Experimental approach

A 650V/200A 8.80 x 8.80 x 0.090 mm IGBT from Renesas Electronics America (REA) was assembled on a Si₃N₄ AMB substrate from Rogers (Curamik® Performance) with 3 types of metallization: raw copper, spot silver and full electroless silver (Fig. 2). Argomax® 8020 film technology was used for the die-attach process on electroless silver and spot silver finish substrates; whereas, Argomax® 8050 film technology that is specifically developed for copper finishes was used for attachment on the raw copper substrates. Copper clips were attached to the die and substrates using Argomax® film technology as well. This design replaced the wire bonding as the top connection to create the electrical interface for the power cycling and thermal impedance measurement using the Mentor Graphics MicReD 1500A tester. A four steps process was used to manufacture seven sintered modules for each substrate metallization. Three were used for power cycling tests, three more for thermal shock tests and the remaining one for baseline metallographic analysis. One of the modules used in power and thermal cycling tests were analyzed optically for any failure occurring in the assembly. CSAM analysis was completed on all sintered modules to detect delamination throughout the tests.

### Assembly process:

1. **Die placement step (Fig. 2)**
   - i. Laminate the dies with the Die Transfer Film (DTF) process using die-bonder equipment capable to apply heat and pressure via the bond-head.
   - ii. Place the die on the bonding position at room temperature
   - iii. Transfer to the sintering press
2. **Die sintering step:** Sintering of the assembly with the following parameters
   - 10 MPa, 2 minutes at 250°C
3. Laminate the clip using Argomax® 8020 film
4. Sinter the clip onto the assembly (die + substrate) (Fig. 3)
The MicReD Industrial 1500A Power Tester from Mentor Graphics measures the variation in $V_{CE}$ (voltage between collector and emitter of the IGBT) during each relaxation period (cooling period) and calculates the variation in the thermal resistance to help indicate if the die- or clip-attach interfaces of the assembly are failing. The devices were continually subjected to 200A for 5s and then to a 10s relaxation period. The double side sintered modules were placed on the cooling sink with a thermal grease (G751 from ShinEtsu Group) filled with silver particles to improve the thermal path. A torque wrench and consistent application of thermal grease was used to ensure the same pressure was placed on all modules to the cooler sink. The cooling liquid was kept at 30$^\circ$C at all-time throughout the tests. When carrying 200A, the max junction temperature was $130^\circ$C with little variation in function of the finish observed. Junction temperature reached $125.5^\circ$C for the raw copper substrates. 3 soldered pieces with wire bonding used as electrical connection for top face were also cycled under same conditions to create a baseline for comparison.

The power cycling tests were conducted until the sintered modules failed. Thermal impedance was conducted throughout the experiment as thermo-mechanical failures in power modules are typically due to cracks between attachment interfaces. Coefficient of Thermal Expansion (CTE) mismatches between the different layers of a power module contributes to the expansion and shrinkage phenomena created during thermal variations (table 1); especially between the substrates materials and the dies (Silicon) as well as the die-attach layer. Thermal dissipation performance in a power modules becomes compromised when the ratio of cracking becomes too high in the module layers. Therefore, thermal impedance measurements, taken throughout power cycling, are used to find failure in power modules. The measurements were conducted continuously throughout the power cycling tests with the same equipment. An increase of 15% of the thermal resistance or max delta $T^\circ$C or on the $V_{CE}$ (voltage between collector and emitter) of the module was defined as
the failure criteria. Optical analysis using Scanning Acoustic Microscopy (CSAM) and metallographic analysis were conducted after initial processing the parts (time t=0) and at the end of the power cycling tests to correlate any failure to the sintered modules.

<table>
<thead>
<tr>
<th>Table 1: CTE mismatches between power module materials</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>CTE (10⁻⁶°C)</td>
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</table>

The sintered modules were submitted to -55/+165°C (liquid-to-liquid, three minutes dwell time) thermal shock testing for 1000 cycles. Profiles were continually adjusted to ensure temperature measured on the boards is in line with test specifications. Thermal impedance was measured prior to the test and at the end of 1000 cycles. If the thermal impedance presented an increase of 15% the modules were considered to have failed. CSAM and metallographic analysis were used to identify delamination and crack that lead to failure in the sintered module assembly.

![Thermal cycling profile](image)

Figure 5: Thermal cycle profile - Liquid-to-liquid, -55°C/+165°C and 3 minutes dwell time

3. Tests results and analysis

3.1. Thermal shock test analysis

Nine sintered modules were submitted to liquid-to-liquid thermal cycling (three for each substrate metallization). The tests were conducted for 1000 cycles between -55°C and +165°C with three minutes dwell time (Fig. 5). Liquid-to-liquid equipment was used to ensure fast transition between the extreme temperatures. The thermal impedance variations for all tested sintered modules were below the failure criteria: 15% increase from the initial measurements (Table 2). This illustrates the encouraging properties of sintered modules compare to soldered modules. Indeed, previous internal tests have shown that similar soldered modules with Innolot (SnAgCu+Sb+Bi alloy) 150 µm preform cannot withstand more than 200 thermal cycles without a drastic increase of the thermal impedance. The CSAM analysis confirmed the behavior of the sintered modules compared to the soldered modules. No delamination was observed on the sintered modules compare to those observed on the soldered modules (Fig. 6 and 7).

Metallographic analysis was conducted on two sintered modules for each substrate metallization: one at t = 0 cycle and one at t = 1000 cycles. The cross-sections were taken on one edge and in the middle of each module. The sintered silver layer exhibits an average density of 90% for all three substrate metallization types. The sintered modules present well-formed bonds between the die and sintered silver layer as well as between the substrates and sintered silver layer (Fig. 8). As depicted in the microscope pictures below (Fig. 9), no
defect was found on all of the sintered modules. The absence of defect was expected due to the intermediate test results for thermal shock. The sintered layers and interfaces with the die and substrates did not exhibit any structural modifications throughout thermal cycling test.

Table 2: Average thermal impedance variation throughout thermal cycling for the three types of substrates metallization - Three modules were tested for each substrates configuration

<table>
<thead>
<tr>
<th>Module type</th>
<th>Thermal Impedance (°C/W) @ t = 0 cycle</th>
<th>Thermal Impedance (°C/W) @ t = 1000 cycles</th>
<th>Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag AMB</td>
<td>0.350</td>
<td>0.355</td>
<td>+1.40%</td>
</tr>
<tr>
<td>Spot Ag AMB</td>
<td>0.338</td>
<td>0.343</td>
<td>+1.46%</td>
</tr>
<tr>
<td>Bare Cu AMB</td>
<td>0.326</td>
<td>0.322</td>
<td>-1.22%</td>
</tr>
</tbody>
</table>

![Figure 6: CSAM pictures for sintered modules @ t = 0 and t = 1000 thermal cycles (-55/165°C)](image)

Figure 6: CSAM pictures for sintered modules @ t = 0 and t = 1000 thermal cycles (-55/165°C)

![Figure 7: Delamination on the soldered modules (Innolot (SnAgCu+Sb+Bi alloy) soldered interface thickness 150um, die size 8.80 x 8.80 x 0.090 mm) observed during the CSAM analysis after 200 and 400 thermal shocks. At 200 cycles, the thermal impedance already reached the increasing of 15% failure criteria, at 400 cycles the assembly is severe delaminated. Internal study.](image)
3.2. Power cycling test analysis

Nine sintered modules, three for each substrate metallization, were subjected to power cycling using the MicReD Industrial 1500A Power Tester from Mentor Graphics. It was agreed that the test were to end when the failure criteria of 15% increase of the thermal impedance, max delta T°C or Vce was reached for each module. After 65k cycles (200A, 5s ON and 10s OFF, Delta T= 100°C), none of the nine sintered modules presented an increase of 15% of the thermal impedance (Table 3). Nevertheless, the power cycling tests were
stopped to proceed with the CSAM and metallographic analysis. Analysis of the aged sintered modules did not present any defect (delamination or cracks) inside the assemblies (Fig. 10,11 and 12). The low thermal impedance of the silver layer creates a better thermal path inside the assembly and reduces the overall thermomechanical stress. The improved thermal performance of the sintered module permits a reduction of the maximum junction temperature to 130°C subjected to 200A current. For solder, the junction temperature reaches 172.6°C due to the high thermal impedance of the solder layer (SnAgCu). Soldered power modules failed at 45.6K cycles due to cracking on the die attach that caused the wire bond to lift off.

Table 3: Average thermal impedance variation throughout power cycling for the three types of substrates metallization - Three modules were tested for each substrates metallization

<table>
<thead>
<tr>
<th>Module type</th>
<th>Thermal Impedance (°C/W) @ t = 0 cycle</th>
<th>Thermal Impedance (°C/W) @ t = 65000 cycles</th>
<th>Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag AMB</td>
<td>0.345</td>
<td>0.320</td>
<td>- 7.25</td>
</tr>
<tr>
<td>Spot Ag AMB</td>
<td>0.338</td>
<td>0.330</td>
<td>- 2.37</td>
</tr>
<tr>
<td>Bare Cu AMB</td>
<td>0.326</td>
<td>0.295</td>
<td>- 9.51</td>
</tr>
</tbody>
</table>

Figure 10: CSAM pictures @ t = 0 and 65000 power cycles for sintered modules, clips were detached from the top for analysis.

Figure 11: SEM analysis of the sintered modules @ t = 0 Power Cycle
Summary

The findings on double sided sintered power module for automotive applications in presented in this work. Silver sintering was chosen because of its promising properties for die and clip attach applications for power electronic modules and other devices. Silver sintering has demonstrated superior thermo-mechanical performance compared to conventional solder. The double side sintered module increased the performance of the assembly due to the high thermal conductivity of the silver layer and subsequent heat path (top and bottom side of the die) created to extract the heat from the semiconductor. The sintered modules did not exhibit any defect after thermal cycling (1000 cycles, liquid to liquid, 3 minutes dwell and -55°C/+165°C) and power cycling (65000 cycles, 200A, 5s ON and 10s OFF). The CSAM and metallographic analysis confirmed the thermal impedance measurements done throughout the cycling tests. The failure criteria was not met for all tested sintered modules; whereas, soldered samples failed at 45k cycles. The work presented confirmed the significant improvement that sintered silver technology offers for the thermomechanical performance of power module. The lower thermal impedance and junction temperature of the sintered assembly when compared to that of solder offers the possibility to operate semiconductors at a higher current level without reaching the 200°C Silicon barrier where its performance will be reduced.

This work is part of a consortium between Alpha (electronic interconnection materials supplier), Rogers Germany GmbH (former Curamik - electronics’ substrate manufacturer), Renesas Electronic America (semiconductor manufacturer) and Mentor Graphics (electronic design automation company).

The authors would like to thank Dr. Aoki from Keio University, Akihiro Mochizuki, Yoshio Murakami and Goro Yoshinari from Alpha Japan for their valuable help on the Finite Element Modelisation work.

References