Pressure-Assisted Low-Temperature Sintering of Silver Paste as an Alternative Die-Attach Solution to Solder Reflow

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Abstract— Pressure-assisted low-temperature sintering of silver paste as an alternative die-attach solution to solder reflow was presented in this paper. A quasi-hydrostatic pressure was achieved to lower the sintering temperature. Also the choice of silver paste and the processing parameters such as temperature and pressure have been investigated. Characterization of the silver attached samples shows a significant improvement in electrical conductivity, thermal conductivity, and mechanical strength of the joint. Given that silver deforms with little accumulation of inelastic strains, we also expect the joint to be more resistant to fatigue failure than a solder attached junction.

I. INTRODUCTION

Power semiconductor devices in individual packages or multi-chip power modules are attached to substrates that serve as electrical connection and heat dissipation path. The selection and processing of this die-attach layer are also crucial to the mechanical strength of the joint and package reliability due to thermo-mechanical stresses arising from mismatched coefficients of thermal expansion on both sides of the layer. Thus far, die-attach is accomplished via solder-reflow process at temperatures below 300°C depending on the composition of solder used. The characteristics of a good die-attachment ought to have: high thermal conductance and low coefficient of thermal expansion (CTE) to minimize thermo-mechanical stresses; high electrical conductance to handle large current; high temperature stability; and high mechanical strength and resistance to fatigue failure. But, solders of the Pb-Sn binary system or lead-free systems belong to a class of relatively poor metal with low electrical and thermal conductivity. Also, because of their low yield strength and accumulation of high inelastic strains during deformation, they are susceptible to fatigue failure under cyclic loading. Furthermore, the use of lead-containing solders raises a serious environmental and public health concern. Consequently, to improve the performance and reliability of the integrated power electronics modules being developed at the Center for Power Electronics Systems, we set to explore alternative die-attach materials and processes that can provide significantly improved performance and reliability metrics over current solder-reflow practice.

Metal-powder pastes, e.g. silver, silver-palladium, or copper pastes, are widely used in the fabrication of hybrid and cofired microelectronic packages. These metals have high electrical and thermal conductivity and do not have much of fatigue problem as in solder. Unfortunately, these metal pastes normally have to be processed or sintered at high temperatures to be useful as conductors. There have been some studies [1-5] reported on the use of pressure to lower the sintering temperature of silver powder compacts for attaching power semiconductor devices. H. Schwarzbauer et al developed a diffusion welding joint technique [1-3] for improved power device performance. S. Klaka and R. Sitting proposed to reduce the thermo-mechanical stress by this technique [4]. U. Scheuermann et al has disclosed the use of pressure to lower the sintering temperature of silver powder compacts for attaching power semiconductor devices in building power electronics modules and reported significant improvements in performance and reliability achieved in these power modules over the solder attached modules [5]. In this paper, we report our study on the pressure-assisted low-temperature sintering of silver pastes as a feasible alternative die-attach process to solder reflow.

II. EXPERIMENTAL PROCEDURES

The pressure-assisted low-temperature sintering process consists of four major steps: (1) substrate metalization with a silver film by electroplating or vapor deposition; (2) silver paste selection and printing; (3) pre-heat; and (4) pressure-assisted sintering in a quasi-hydrostatic press. For the substrate metalization process, a thin silver layer was electroplated on the substrate. If copper is the terminal surface of the substrate, then a thin layer of nickel is plated before silver deposition in order to improve adhesion between silver and the substrate. The use of lead-containing solders raises a serious environmental and public health concern. Consequently, to improve the performance and reliability of the integrated power electronics modules being developed at the Center for Power Electronics Systems, we...
using Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometer (EDS). The chosen silver paste was stencil-printed on the substrate to a thickness of 40 to 100 microns, and trapped air pockets within the films were subsequently removed by a vacuum pump.

The printed silver layers were pre-heated at temperatures below 300°C for a few hours to remove much of the organic components, solvents and binders, in the paste. The pre-heat conditions were determined by studying the paste binder burnout process using Thermal Gravitational Analysis (TGA) and examining the heat-treated microstructure using Scanning Electron Microscopy (SEM). Finally, the pre-heated silver was pressurized and sintered at temperatures similar to that for solder-reflow, at around 240°C. To avoid cracking the silicon devices due to stress-concentration spots at the device edges, a silicone-filled fixture was designed and fabricated for carrying out pressure-assisted sintering. Quasi-hydrostatic pressure was achieved through pressing on the silver-attached devices that are tightly sealed by the silicone in the fixture as shown in Figure 1. The pressure-assisted low-temperature sintering conditions (pressure, temperature, and time) were determined by examining the shrinkage profile and sintered microstructure using Scanning Electron Microscopy (SEM). By measuring the silver layer’s thickness before and after temperature and pressure treatment, the shrinkage profile can be obtained.

To investigate the properties of pressure-assisted low-temperature sintered silver layers, the ratio of porosity (relative density), mechanical strength, electrical and thermal conductivity of the layers were measured and compared with those of the solder reflowed layers. Since it is difficult to determine the relative density of sintered films, we prepared silver bulk samples using a die and plunger to half inch in diameter and 1.5 to 2 mm thick and then sintered at low temperature under pressure. The densities of the sintered bulk samples were determined by Archimedes method. Of samples that were attached to substrates through the sintered silver films, the mechanical strength of the joints was measured using an Instron 5566 Universal Testing Machine. In order to measure the resistivity of the sintered silver joints, silver prints formed like the resistor pattern shown in Fig. 2 were prepared by screen-printing and sintered under pressure, and their resistances were measured with a digital multimeter.

III. RESULTS AND DISCUSSION

A. CHARACTERIZATION OF SILVER PASTES

Shown in Fig. 3 is the SEM and EDS results of the silver paste acquired from Heraeus indicating that the C1075 paste contains nearly pure silver particles, while the C8772 has about 20% lead. Since the use of lead raises a concern to health and environment and it did not seem to help in any way with the sintering process, we recommend the pure silver paste over the lead-filled silver paste.

B. PRE-HEAT CONDITION

Fig. 4 shows the weight loss curve of the C1075 paste as it is heated in a TGA from room temperature. It is evident that upon heating, volatile solvents and decomposed binders were progressively driven out of the paste. Fig. 5 is a SEM micrograph of the silver paste after a binder burnout heat treatment at 300°C for 10 minutes. Although necking was developed between the silver particles, there was no cracking observed.

The cross-sectional area of the resistor line in the pattern was measured using a Dek-Tak3 profilometer. The average of three measurements was used to determine the cross-sectional area. The resistivity of the silver trace is calculated by:

$$\rho = \frac{R \cdot A_{\text{average}}}{L}$$

where \(\rho\) is resistivity; \(R\) is the resistance; \(A_{\text{average}}\) is the average cross-sectional area; and \(L\) is the total length of the line. The resistivity values of four types of silver samples were determined; they were: 80°C heated; 280°C pre-heated; sintered at 240°C under 40 MPa for 5 minutes; and sintered at 880°C without pressure.

The thermal conductivity of the sintered bulk silver samples mentioned above was determined by measuring its thermal diffusivity, specific heat, and density. The thermal diffusivity was obtained by Parker’s flash-light method [6]. Specific heat of the sample was measured by a differential scanning calorimeter using sapphire as the standard.
significant densification. The necking is a result of silver self-diffusion along the particle surface driven by the reduction of surface free energy [4]. We believe that necking may hinder the deformation process under pressure, thus we selected a preheat treatment at 270°C for 3 hours for binder burnout prior to sintering.

Figure 3 shows the thickness shrinkage profiles of silver films after sintered at temperatures ranging from room temperature to 250°C for minutes under a pressure of 40MPa. It is evident that at high enough temperatures, greater than 170°C, the application of pressure significantly increases the densification of the silver films. This is also clearly illustrated by the SEM micrographs in Figure 7: (a) showing the microstructure of silver sintered at 250°C without any pressure; (b) silver sintered at 250°C with an applied pressure of 10 MPa; and (c) silver sintered at 800°C without pressure. We believe that the pressure helps the densification process by (1) eliminating some fraction of pores through compression/deformation and (2) increasing the contact area between the silver particles therefore speeding up the free surface area reduction.

C. PRESSURE-ASSISTED SINTERING CONDITION

Figure 6 shows the thickness shrinkage profiles of silver films sintered at temperatures ranging from room temperature to 250°C for minutes under a pressure of 40MPa.

```plaintext
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>250</th>
<th>170</th>
<th>100</th>
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</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>0</td>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>Shrinkage Ratio</td>
<td>70</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>
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We believe that the pressure helps the densification process by (1) eliminating some fraction of pores through compression/deformation and (2) increasing the contact area between the silver particles therefore speeding up the free surface area reduction.
D. PROPERTIES OF SINTERED SILVER LAYER

The relative density of the pressure-assisted low-temperature sintered bulk silver sample was found to be about 80% by Archimedes method and confirmed from the SEM micrograph of its porous microstructure. Table 1 lists the properties of pressure-assisted low-temperature sintered silver films and joints along with those from eutectic solder (Sn63+Pb37) and some properties on pure silver. Our results on the sintered films/joints- electrical and thermal conductivity and adhesion strength - are clearly better than those for soldered joints. It is also clear that the porous films have lower electrical and thermal conductivity than those of pure silver.

However, we believe that the porous microstructure can provide the compliancy necessary to relieve the thermo-mechanical stresses generated from mismatched coefficients of thermal expansion in the joined structure, and thus leading to better reliability. Research is underway to establish a good understanding on the processing, microstructure, and property relationships in order to optimize the performance and reliability of the low-temperature sintered silver joints.

IV. CONCLUSIONS

An alternative die-attach process to solder reflow, here termed pressure-assisted low-temperature sintering was demonstrated in this study. Measurements on the electrical and thermal conductivity of a silver paste sintered at a temperature as low as 240°C under a quasi-static pressure of 40 MPa were found to be significantly better that those in an eutectic solder layer. The shear strength of the sintered silver joint is also found to be much stronger than that of a soldered joint. The low-temperature sintered silver has a density of about 80% resulting in lower electrical and thermal conductivity than those for pure silver. However, the porous microstructure may be necessary for relieving the thermo-mechanical stresses due to mismatched coefficients of thermal expansion, thus improving the joint reliability under thermal or power cycling.

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Table 1. Summary of properties measured on sintered silver and soldered joints

<table>
<thead>
<tr>
<th></th>
<th>Sintered silver joint (250°C, no pressure)</th>
<th>Solder joint (Sn63Pb37)</th>
<th>Pure Silver</th>
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<tbody>
<tr>
<td><strong>Joining temperature</strong></td>
<td>240°C</td>
<td>210°C</td>
<td></td>
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<tr>
<td><strong>Pressure</strong></td>
<td>40MPa</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td><strong>Metal Metalization</strong></td>
<td>Ag</td>
<td>Cu/Ag/Ni</td>
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</tr>
<tr>
<td><strong>Joint Shear Strength</strong></td>
<td>50</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Electrical resistivity (ohm-cm)</strong></td>
<td>2.4E-6</td>
<td>1.4 E-5 to 5E-5</td>
<td>1.5E-06</td>
</tr>
<tr>
<td><strong>Thermal Conductivity</strong></td>
<td>80</td>
<td>43</td>
<td>*428</td>
</tr>
</tbody>
</table>

Data * from reference webmat.com
References