[Short Note]

Bonding Abilities of Pressure-assisted Sintered Copper for Die-Bonding of Large Chips

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Abstract

This paper describes sintering properties and bonding abilities of mechanical pressure-assisted sintered copper (pressure-sintered Cu) in N_2 atmosphere for power devices with large chips. The pressure-sintered Cu showed equal or improved sintering and bonding properties compared with pressureless-sintered Cu and pressure-sintered silver (Ag). The bonding abilities of pressure-sintered Cu on two different Ag plating (Ti/Ni/Ag, Ti/Ni/Au/Ag) were also investigated. The Cu pressure-sintered at 2 MPa and 300°C for 5 min was successfully bonded to $10 \times 10 \text{ mm}^2$ chips with Ti/Ni/Ag. Thus, pressure-sintered Cu has a potential as a reliable die-bonding material for power devices with large chips.

Keywords: Copper Sinter Die-bonding Paste, Mechanical Pressure-assisted Bonding Process, Bonding Ability, Large Chip, Molecular Dynamics Simulation

1. Introduction

Concerns over power device techniques have risen in terms of efficient usage on electrical power. Efficient power devices with silicon carbide (SiC) chips, which can operate over 175°C, have been reported recently.[1] Die-bonding materials with high thermal conductivity and tolerance of thermal stresses compared with conventional solders are required because the wide temperature swings during the operation of SiC chips deteriorate the bonding reliability of solders.[2] Ag sinter pastes with high thermal conductivity and improved bonding reliability have been widely studied as an alternative die-bonding material of solders,[3] however the cost of Ag is high. To overcome the cost problem, our group has suggested an inexpensive Cu sinter die-bonding paste (Cu paste), which sinters in H_2 atmosphere on a pressureless bonding process.[4] We have especially reported the bonding abilities and reliability of pressureless-sintered Cu towards small dies. For wide application of Cu pastes on high-power devices, die-bonding abilities of Cu pastes on large chips should be understood. In this research, we investigated the sintering properties and bonding abilities of the Cu paste pressure-sintered in N_2 atmosphere for large chips.

2. Experimental

A. Evaluation of Sintering Properties and Bonding Abilities

Dodecanoic acid adsorbed Cu sub-micron particles within a range of 100 to 500 nm diameter (see Fig. 1) were used to fabricate a Cu paste. Thermodynamic behavior of the Cu particles in N_2 atmosphere was analyzed using thermogravimetry differential thermal analysis (TG-DTA). The Cu paste was prepared by mixing the Cu particles with terpineol at a weight ratio of 88:12, respectively. Silicon (Si) chips with Ti/Ni/Ag sputter-deposited plating, SiC chips with Ti/Ni/Au/Ag sputter-deposited plating,

Fig. 1 SEM image of the Cu particles.

and DBC substrates (Cu/Al₂O₃/Cu) were used. The Cu paste was first printed on the bare Cu surfaces of DBC substrates using a stencil printing machine. The printed Cu paste was dried at 90°C for 30 min in N₂ atmosphere. The chips were then mounted on the dried Cu paste. The samples were subsequently mechanical pressure-assisted sintered in N₂ atmosphere at various bonding pressures, temperatures, and time using a press machine. Die shear strengths were determined by die shear tests of ten specimens for each bonding condition at room temperature using a shear tester. The shear velocity and shear height were set to 100 μ m/s and 200 μ m. The pressure-sintered Cu layer bonded on the metal plating of chips was analyzed using scanning electron microscopy and dispersive X-ray spectroscopy (SEM/EDX). The porosity of the pressure-sintered Cu layers was determined by calculation of the fractions of solid Cu and voids in cross-section SEM images. The adhesion state of pressure-sintered Cu to chips was also analyzed using scanning acoustic microscopy (SAM). The three-point bending tests to determine mechanical properties of pressure-sintered Cu for five specimens on each sintering condition were conducted in air at room temperature using a bending machine.

B. Molecular Dynamics Simulations

Molecular dynamics (MD) simulations were performed using the LAMMPS package [5] to calculate the interaction energy (ΔE) between metals (Cu/Ag, Cu/Ag-Au alloy) as index values of adhesive strengths. The ΔE is calculated using (1),

$$\Delta E = (E_{\text{Cu}} + E_{\text{Metal}})_{\text{separated state}} - E_{\text{connected state}} \quad (1)$$

where $E_{\text{connected state}}$ and $E_{\text{separated state}}$ are the potential energy of the material-connected state and that of the material-separated state, respectively. The embedded-atom method of Zhou *et al.* was applied to describe the interaction between atoms.[6] The equilibration calculations were performed at 300°C and 1 atmosphere with the isothermal-isobaric ensemble.

3. Results and Discussion

A. Sintering Properties

Figure 2 shows the TG-DTA curve of Cu particles. The exothermic peak and the precipitous weight-loss curve around 270°C were observed. This result implies dodecanoic acid desorbs from the surface of Cu particles and then the Cu particles start to sinter at the temperature. Table 1 displays the mechanical properties of pressure-sintered Cu. For comparison, the data of pressure-sintered Ag in our previous study [4] is also listed. The bending stress

Fig. 2 TG-DTA of the Cu particles.

Table 1 Mechanical properties of sintered metals.

Material	Pressure-sintered Cu	Pressure-sintered Ag[4]
Sintering condition	300°C, 2 MPa, 10 min	300°C, 10 MPa, 10 min
Porosity	15%	13%
Young's modulus	22 GPa	29 GPa
Bending stress	230 MPa	170 MPa

Table 2 Shear strengths of sintered Cu.

Material	Pressure-sintered Cu			Pressureless-sintered Cu[4]
Sintering condition	in N ₂ 260°C 12 MPa 5 min	in N ₂ 260°C 20 MPa 5 min	in N ₂ 300°C 12 MPa 5 min	in H ₂ 300°C 0 MPa (Pressureless) 60 min
Shear strength	62 MPa	70 MPa	97 MPa	40 MPa
Porosity	12%	11%	6%	22%
Residual carbon	3.0%	2.4%	1.7%	<0.1%

of pressure-sintered Cu was higher than that of pressure-sintered Ag even though the Cu was pressure-sintered at the low pressure of 2 MPa.

B. Bonding Abilities

Table 2 lists the shear strengths of pressure-sintered Cu bonded on Ti/Ni/Ag plating, including our previous data of Cu pressureless-sintered in H₂ atmosphere.[4] For the pressure-sintered Cu, it was found that the shear strengths increased and that the porosity and the residual carbon decreased with increasing bonding pressures and temperatures. The pressure-sintered Cu obtained under various pressure bonding conditions showed higher shear strengths compared with pressureless-sintered Cu.

We here discuss the bonding abilities of pressure-sintered Cu on two different Ag plating. The shear strengths

of Cu sinter-bonded at 12 MPa and 300°C for 5 min on Ti/Ni/Ag and Ti/Ni/Au/Ag were found to be 70 MPa and 52 MPa, respectively. Figure 3(a) and (b) show the EDX mapping between the pressure-sintered Cu and the Ti/Ni/Ag or the Ti/Ni/Au/Ag. It was confirmed that the Au atoms diffused into the Ag layer in the Ti/Ni/Au/Ag. The Ag-Au random alloy layer seems to be formed by the Au diffusion into the Ag layer because Ag and Au form a complete solid solution. Figure 4(a) and (b) show the ΔE between Cu layer and Ag layer or Ag-Au random alloy layer on the MD simulations. The ΔE of Cu/Ag was higher than that of Cu/Ag-Au. Note that the simulation results qualitatively reproduce the trend of experimental shear strengths. Hence, Au diffusing into Ag layer seemingly exacerbates the bonding ability of pressure-sintered Cu on Ti/Ni/Au/Ag.

Fig. 3 SEM images and EDX mapping of the Cu sinter-bonded at 12 MPa and 260°C for 5 min: (a) On Ti/Ni/Ag and (b) On Ti/Ni/Au/Ag.

Fig. 4 MD simulated ΔE of Cu layer: (a) On Ag layer and (b) On Ag-Au random alloy layer.

Fig. 5 Die-bonding results of the Cu sinter-bonded at 2 MPa and 300°C for 5 min on the $10 \times 10 \text{ mm}^2$ chip: (a) Photograph of the bonding sample; (b) SAM image; (c) Cross-sectional SEM image.

We finally show the example of results towards the pressure-sintered Cu bonded to the $10 \times 10 \text{ mm}^2$ chip with Ti/Ni/Ag (see Fig. 5(a) (b) (c)). The pressure-sintered Cu was successfully bonded on the whole area of the chip without large voids or delamination.

4. Conclusion

The pressure-sintered Cu in N_2 atmosphere showed the equal or improved sintering properties and bonding abilities compared with pressure-sintered Ag and pressureless-sintered Cu. The pressure-sintered Cu can attach to large chips and has a potential as a reliable die-bonding material for power devices with large chips.

References

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