Bonding Performance of Pressure Copper Sintering Paste on Different Metalized Substrate/Die

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Abstract

In this work, a pressure copper (Cu) sintering paste, which has been promoted to high-power application with high thermal and electrical conductivity, was developed. The sintering of the pressure Cu-paste in a nitrogen atmosphere on different metal surfaces (Cu, silver (Ag), and gold (Au)) was investigated. The pre-dry (temperature and time) and sintering parameters (temperature, pressure, and time) were adjusted to achieve strong joints. Compared to the Ag and Au surfaces of the substrate or dummy die, the highest shear strength over 65MPa was achieved on a Cu surface with the advanced Cu sintering paste. This property breaks the regular procedure of requiring Ag or Au plating for dies or substrates for Ag sintering paste. The sintering conditions for the pressure Cu paste are 250–280°C, 12–25MPa, and 3–10 minutes under a nitrogen atmosphere. After 1,000 cycles of thermo cycling testing (TCT) at -65°C–150°C, the pressure Cu sintered joints showed stable performance without delamination. Furthermore, this Cu sintering paste can be applied by both printing and dispensing, which are widely used in the electronic industry.

Keywords: pressure, copper, Cu, sintering paste, shear strength, different surface

Introduction

The third generation semiconductor materials, which are represented by silicon carbide (SiC) and gallium nitride (GaN), have wide band-gap widths and high thermal conductivities. They are capable of stability in high-temperature environments, when exposed to high frequency, and have broad application prospects in the fields of electric vehicles, wind power generation, and aerospace [1, 2]. However, it is difficult for lead-free solder, leaded solder, and conductive adhesive interconnect materials, which are commonly utilized in electronic packaging, to meet the harsh requirements of packaging material applications in third-generation semiconductor materials. This is due to their high welding temperature, limited service temperature, poor thermal conductivity, and poor high-temperature reliability [3, 4].

Therefore, sintering material such as Ag sinter paste for die-attachments, which demonstrates high reliability at high service temperatures, is increasingly applied to power electronics packaging [6]. However, Ag migration occurs for fine pitch, and considering the high cost of Ag, researchers are working on new materials to overcome the weaknesses of Ag sintering while maintaining its high thermal conductivity and high electrical conductivity [7].

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Since it has a lower cost than Ag, Cu is a promising raw material for die-bonding paste. In addition, a recent study showed that sintered Cu achieved superior thermal cycling reliability due to its mechanical and fatigue properties, which are superior when compared to sintered Ag [5].

In this paper, a novel pressure Cu sintering paste was researched. It was designed both for printing and dispensing applications. A comparatively high shear strength can be achieved after sintering, particularly on Cu-to-Cu surfaces. Luckily, with this sintering paste, electromigration in fine pitch is not a concern. Additionally, it can save the expense of surface coating for consumers.

Experiment

Materials

The pressure Cu sintering paste was prepared by mixing Cu particles with binders. The Cu particles are commercially available with diameters in the range of 100–1,500nm. A chemical was added to prevent the Cu paste from oxidizing while being stored and sintered.

The pressure Cu sintering paste can be packed in jars for printing (Figure 1) and in syringes for dispensing (Figure 2), depending on the applications.

Figure 1. Jar package of pressure Cu sintering paste.

The Cu dummy dies with 5mm × 5mm, 0.6mm thickness, combined with 23.5mm × 23.5mm Cu substrate, were utilized to prepare samples for shear strength and reliability. Additionally, 5mm × 5mm Ag and Au dummy dies with a 0.6mm thickness combined with 23.5mm × 23.5mm Ag and Au substrates were employed with the Cu surface to evaluate the shear strength. Figure 3 shows the printing performance of the pressure Cu sintering paste. Figure 4 displays the samples of dispensing.

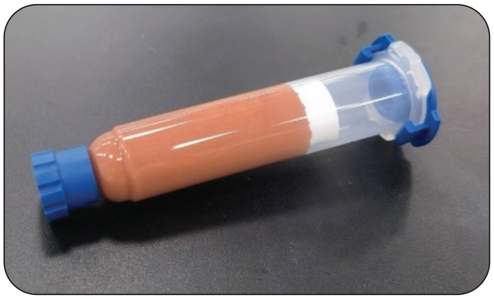

Figure 2. Syringe package of pressure Cu sintering paste.

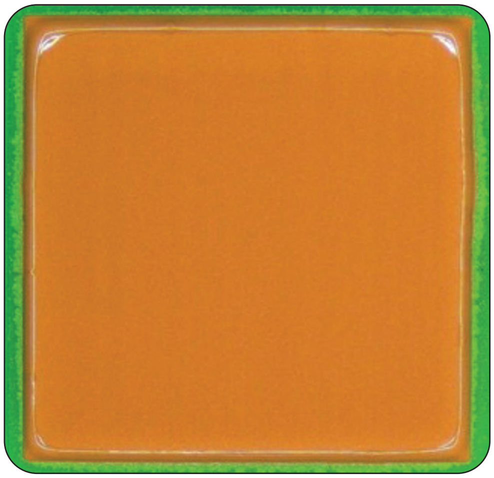

Figure 3. Printing of pressure Cu sintering paste.

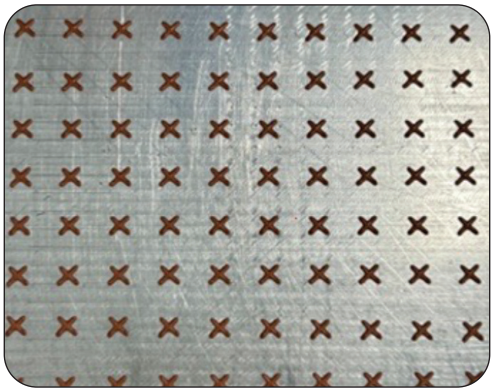

Figure 4. Dispensing of pressure Cu sintering paste.

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Experiment Procedures

Prior to sintering, the Cu sintering paste was manually printed using a 4mil stencil before being pre-dried. Both the pre-drying and sintering procedures were carried out in a nitrogen atmosphere, with the oxygen concentration maintained at less than 100ppm. A nitrogen oven was utilized for pre-drying. The oven temperature was set to 40°C in a nitrogen atmosphere, and the specimens were placed into the oven. The temperature was raised to 70°C and maintained for 20 minutes, then cooled for 1 hour. The pre-dry profile is showed in Figure 5. After pre-dry, a die bonding procedure was carried out under 8kg of pressure for 5 seconds. The temperature of the nozzle utilized to pick dies was set to 120°C, and the substrate was not heated. Finally, the pressure Cu paste sintering parameters were adjusted to 250–280°C and 12–25MPa. The sintering time was set to 3-10 minutes.

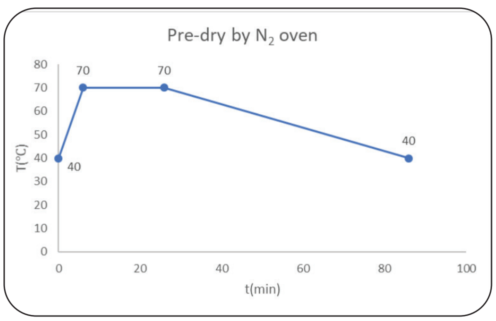

Figure 5. Oven pre-dry profile of the pressure Cu sintering paste.

Characterization and Measurement

The bonding strength of the sintered Cu joints was evaluated by implementing XYZ Condor Sigma with the shear speed at 500um/s. The confocal scanning acoustic microscopy (C-SAM) of the TCT specimens was tested by Nordson P300. The TCT was tested by WEISS TECHNIC WKS 3-480/70/15.

Results and Discussion

The pressure Cu sintering paste has an excellent sintering capacity, particularly on Cu-Cu surfaces, according to the testing results. When high-temperature, high-pressure, and extended sintering times are used as sintering conditions, other surfaces like Ag-Ag, Ag-Cu, and Au-Au also function well. The die shear strength still has good values for Cu-Cu sintering, even with the sintering conditions set to 250°C, 15MPa, and 3 minutes.

TCT was used for reliability testing. The pressure Cu sintered joints demonstrated sustained performance free from delamination over 1,000 cycles of TCT (-65°C–150°C).

Proper pre-dry parameters setting can help in sintering of the Cu pressure sinter paste. From this study, the pre-dry conditions of 70°C/20 minutes are benefited to ensure both die bond process and high shear strength.

Shear Strength with Different Surfaces

The sintering test was carried out at 270°C with a pressure of 25MPa and a duration of 7.5 minutes. A 5mm × 5mm dummy die was utilized. The shear strength of various surfaces is shown in Figure 6, which represents the average value of the test specimens. We can see from Figure 6 that the Cu-Cu surface has the highest shear strength, reaching up to 69MPa. Au-Au comes second at 49MPa, and Ag-Ag is the lowest at 43MPa. However, the shear strength of the sintered Cu paste on these surfaces is excellent and can satisfy most customer requirements.

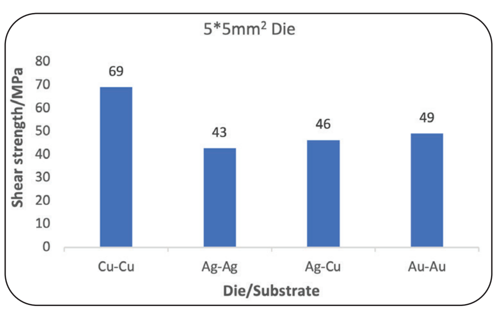

Figure 6. Shear strength of pressure Cu sintering paste on various metal surfaces (270°C, 25MPa, 7.5 minutes).

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Die shear strength, which sintered at a lower pressure, was also checked. We observed the strength variations of Ag-Ag and Ag-Cu surfaces and found that the average shear strength can still achieve 40MPa when the pressure is 20MPa. The details are as follows, displayed in Figure 7.

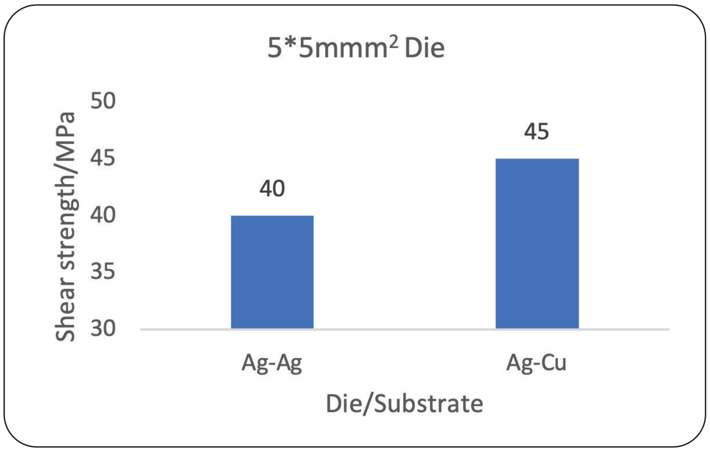

Figure 7. Shear strength of pressure Cu sintering paste on various metal surface (270°C, 20MPa, 7.5 minutes).

The shear strength of the copper-nickel (Cu-Ni) surfaces was also investigated: it can reach 40MPa when the sintering parameters were set at 270°C, 25MPa, and 7.5 minutes.

In the case of the Cu-Cu joint, the sinter bonding material and the die/substrate were both Cu. Therefore, there were expectations of strong bonding and superior adhesion for this Cu-Cu combination joint. The lattice constant of Cu is 0.3615nm. Conversely, the Ag and Au die/substrate have a different lattice geometry (Ag lattice constant: 0.4086nm, Au lattice constant: 0.4079nm), which makes them less compatible with Cu sintering paste [6]. So, the shear strength on Cu surface is higher than that on Ag or Au surfaces.

Shear Strength Variations with Different Sintering Parameters on Cu-Cu Surface

Since the shear strength of the pressure Cu paste on a Cu-Cu surface is the higher compared to other surfaces in the sintering conditions of 270°C, 25MPa, and 7.5 minutes as listed in Figure 6, lower sintering conditions were investigated for Cu-Cu to see the bonding performance.

Table 1 shows the sintering performance at different sintering parameters. The temperature was reduced from 270°C to 260°C or 250°C, the pressure dropped from 25MPa to 20MPa or even 15MPa, and the sintering time was shortened from 7.5 minutes to 5 minutes or 3 minutes. The shear strength exhibited a very mild declining trend from 69MPa to 61MPa with the reduction of the three parameters temperature, pressure and sintering time as demonstrated in Figure 8. This result indicates that strong bonding can achieve with lower sintering conditions such as 250°C ,15MPa, and 3 minutes for Cu-Cu.

Table 1. Shear strength at different sintering parameters of Cu-Cu surface.

Cu-Cu	Shear Strength at Different Sintering Parameters			
	Temperature (°C)	Pressure (MPa)	Time (min)	Shear Strength (MPa)
1	270	25	7.5	69
2	260	20	5	68
3	260	15	3	65
4	250	15	3	61

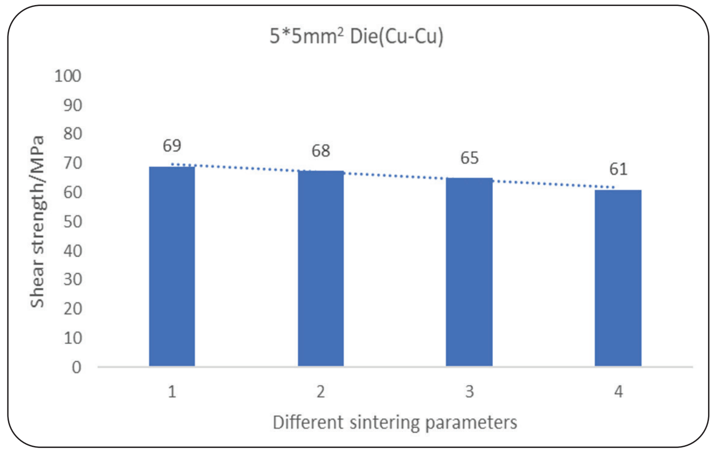

Figure 8. Shear strength of pressure Cu sintering paste on Cu-Cu surface at different sintering parameters.

Reliability Testing

TCT (-65°C–150°C): TCT testing with -65°C to 150°C condition was done to check the reliability of the sintered joints. Samples for TCT with three group surfaces of Cu-Cu, Ag-Ag and Ag-Cu were prepared as listed in Table II, III and IV. For each specified temperature cycles with 0, 500, or 1,000, the shear strength was conducted at room temperature. For Cu-Cu, with the cycles increased from zero to 500 and 1,000, the shear strength remained above 60MPa constantly. Meanwhile for the other two groups of Ag-Ag and Ag-Cu, the shear strength is also stable with more than 40MPa after 500 cycles or even 1,000 cycles treatment. The pressure Cu sintering paste exhibits high reliability on TCT with various metal surfaces of Cu, Ag and Au.

Table 2. Shear strength of strength of 1,000 cycles TCT (-65°C–150°C) on Cu-Cu surface.

Cu-Cu (5mm x 5mm Die)			
TCT cycles	0	500	1,000
Shear strength (MPa)	61	66	65

Sintering parameters: 250°C, 15MPa, 3 minutes.

Table 3. Shear strength of 1,000 cycles TCT (-65°C–150°C) on Ag-Ag surface.

Ag-Ag (5mm × 5mm Die)			
TCT cycles	0	500	1,000
Shear strength (MPa)	44	42	40

Sintering parameters: 275°C, 20MPa, 7.5 minutes.

Table 4. Shear strength of 1,000 cycles (-65°C–150°C) on Ag-Cu surface.

Ag-Cu (5mm × 5mm Die)			
TCT cycles	0	500	1,000
Shear strength (MPa)	46	40	46

Sintering parameters: 270°C, 25MPa, 7.5 minutes.

C-SAM Testing of the TCT Specimens: After 500 and 1,000 cycles of TCT (-65°C–150°C), the sintered layers of the Cu sintered joints for Cu-Cu, Ag-Ag, and Ag-Cu were investigated by C-SAM testing to check the bonding of the die with the substrate. With both 500 cycles and 1,000 cycles treatment, the sintered layers for the three combinations were all very dense, and no delamination was observed. The C-SAM images suggested the high reliability of the Cu sintered joints with different metal surfaces Cu,Ag and Au. The specific situation inside the sintered layer is shown in Figure 9, Figure 10, and Figure 11.

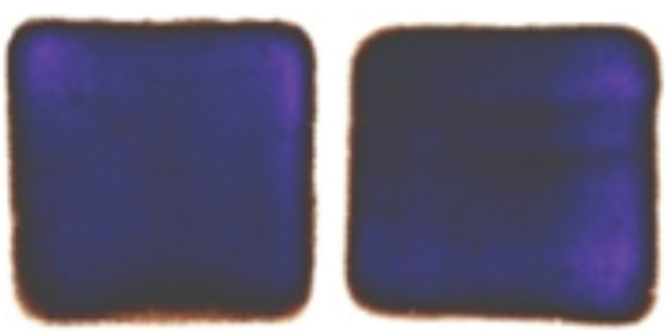

Figure 9. C-SAM pictures after TCT (-65°C–150°C) on Cu-Cu surface (1) 500 cycles, (2) 1,000 cycles.

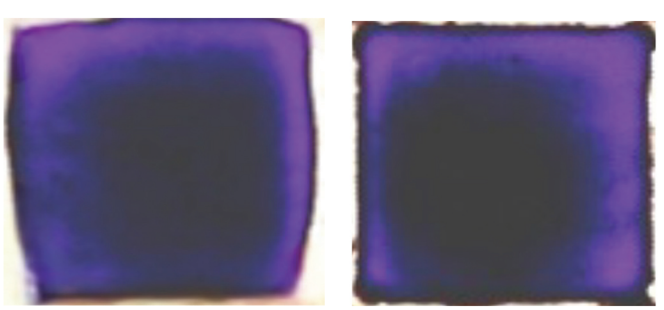

Figure 10. C-SAM pictures after TCT (-65°C–150°C) on Ag-Ag surface (1) 500 cycles, (2) 1,000 cycles.

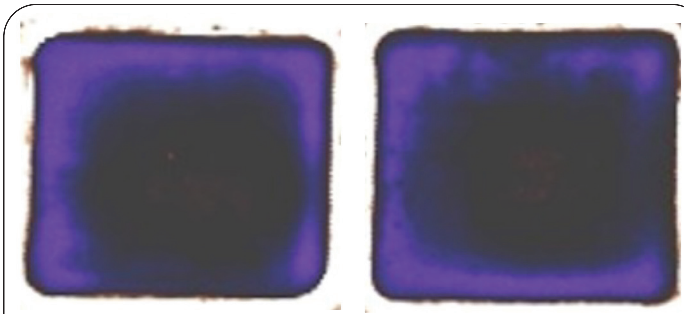

Figure 11. C-SAM pictures after TCT (-65°C–150°C) on Ag-Cu surface (1) 500 cycles, (2) 1,000 cycles.

Effect of Pre-Dry Degree on Sintering

The Cu sintering paste should be pre-dried before sintering for pressure Cu paste, and the degree of the pre-dry would affect the sintering shear strength and reliability. In this research, the pre-dry parameters (temperature and time) were adjusted to ensure the success of die bond and the strong bonding with high shear strength. The sintering with conditions of 270°C/20MPa/7.5 minutes was conducted following different pre-dry conditions.

Table 5 displays the pre-dry parameters, which were examined to find the appropriate conditions. With the pre-dry parameters of 65°C/20 minutes, the die can be attached well and got 50MPa shear strength. When the temperature was increased to 70°C and the same time of 20 minutes was kept, the shear strength drastically achieved 69MPa. Since the temperature increase of the pre-dry improved the bonding performance obviously with higher shear strength, the pre-dry time was also prolonged to 25 minutes to compare the joint strength. Unexpectedly, the paste was too dry to proceed die bond with the pre-dry conditions of 70°C/25 minutes.

Table 5. Parameters of pre-dry adjustment.

Temperature (°C)	Maintain Time (min)	Effect	Cu-Cu Shear Strength (MPa)
65	20	Insufficient	50
70	20	Good	69
70	25	Too dry, die bond failed	-

The shear failure modes were inspected for the sintered joints with pre-dry conditions of both 60°C/20 minutes and 70°C/20 minutes. As shown in Figure 12, with pre-dry parameters of 60°C/20 minutes, almost all the paste remained on the die side after shear. In other words, the bonding of the paste with the substrate was poor. In addition, some volatilization channels were found in the sintering layer, which was caused by excessive chemicals that remained after the pre-dry stage. Meanwhile, a little bit of wet paste was found on both die and substrate after shear. This indicates that the chemicals, which did not volatilize adequately during the pre-dry, hindered the sintering of the Cu particles. By contrast, for the group of the pre-dry at 70°C/20 minutes conditions, the paste sintered well with strong bonding to the substrate. And no volatilization channels were found for the sintered joint, which relates to the sufficient evaporation of the chemicals in the pre-dry stage (Figure 12).

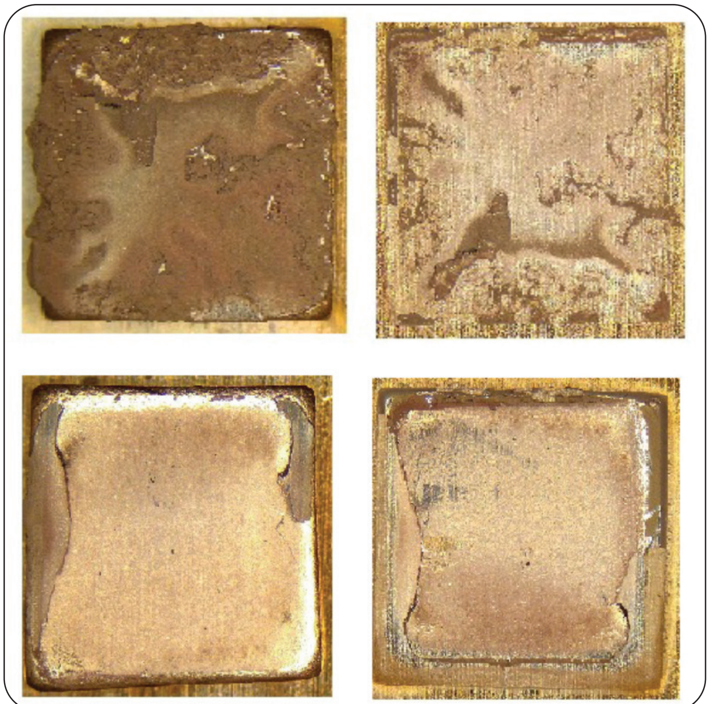

Figure 12. Fracture interfaces of pressure Cu sintered joints (Cu-Cu) with pre-dry conditions of 65°C/20 minutes (upper two) and 70°C/20 minutes (lower two). Left for die and right for substrate.

Conclusion

A pressure Cu sintering paste was developed for high-power applications. The Cu paste was sintered on various metal surfaces, including Cu, Ag, and Au. The Cu surface provides the highest shear strength of approximately 69MPa for 5mm × 5mm dummy die in 270°C, 25MPa, and 7.5 minutes conditions. Additionally, the material can be utilized in certain applications where dies cannot sustain high pressure when sintering. Even with a low sintering pressure of 12MPa and a short sintering time of 5 minutes, the shear strength still achieved over 65MPa. Customers can avoid Ag or Au plating for die or AMB (Active Metal Brazing) with the pressure Cu sintering paste's excellent bonding ability on a bare Cu surface. To guarantee a strong bond, the paste should be pre-dried as much as possible to remove the solvent that hinders the sintering of Cu particles. Starting from the sintered Cu joint, a TCT (-65°C–150°C) was performed to verify the reliability. After a 1,000-cycle treatment, the shear strength on the three different metal surfaces remained stable. With high thermal and electrical conductivity and high reliability, this pressure Cu sintering paste is promising for the next generation of high-power die-attach applications such as electric vehicles (EVs) and high-speed trains.

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