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Lv, Guoping ; Yan, Haidong; Yan, Haidong; Yang, Daoguo; Wu, Xinke ; Sheng, Kuang; Liu, Chaohui ; Zhang, Yakun ; Zhang, Guoqi

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Bonding Process of Copper Foam-Silver Composite and Performance Characterization of the Joint

Guoping Lv
School of Mechanical and Electrical Engineering, Guilin University of Electronic Technology
Guangxi Key Lab of Manufacturing System and Advanced Manufacturing Technology
Guilin, China
l953759778@163.com

Haidong Yan*
ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University
College of Electrical Engineering, Zhejiang University
Hangzhou, China
haidong_yan@zju.edu.cn

Siliang He*
School of Mechanical and Electrical Engineering, Guilin University of Electronic Technology
Guangxi Key Lab of Manufacturing System and Advanced Manufacturing Technology
Guilin, China
siliang_he@guet.edu.cn

Daoguo Yang
School of Mechanical and Electrical Engineering, Guilin University of Electronic Technology
Guangxi Key Lab of Manufacturing System and Advanced Manufacturing Technology
Guilin, China
daoguo_yang@163.com

Xinke Wu
ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University
College of Electrical Engineering, Zhejiang University
Hangzhou, China
wuxinke@zju.edu.cn

Kuang Sheng
ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University
College of Electrical Engineering, Zhejiang University
Hangzhou, China
shengk@zju.edu.cn

Chaohui Liu
Powertrain Department, National New Energy VehicleTechnology Innovation Center (NEVC)
Beijing, China
liuchaohui@nevc.com.cn

Yakun Zhang
Powertrain Department, National New Energy VehicleTechnology Innovation Center (NEVC)
Beijing, China
Zhangyakun@nevc.com.cn

Guoqi Zhang
Delft Institute of Microsystems and Nanoelectronics (DIMES), Delft University of Technology
Delft, Netherlands
g.q.zhang@tudelft.nl

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***Abstract*—As a key heat-dissipating and electrical interconnecting component in high-temperature power modules, die-attach and substrate-attach layers play an important role in effectively reducing the thermal resistance and improving the long-term reliability. Traditional substrate-attach materials limit the high-temperature applications of packaging modules due to their high thermal resistance and high-temperature reliability. To solve the above deficiency, a copper foam-silver composite was proposed in this paper, which was prepared by mixing copper foam solid skeleton with micron silver paste. According to the results of thermogravimetric analysis (TGA) of silver paste, the preheating process was determined and sintered at 270℃ and 10MPa. The influence of different preparation technology on the quality of sintered joint was investigated. The morphology characteristics and distribution of sintered silver in the copper foam were observed by scanning electron microscope (SEM). The results show that the sintered silver of group C samples can be uniformly filled into the solid skeleton of copper foam, and the densification degree is high, without cracks, delamination, and holes. The shear strength can reach 55MPa.**

Keywords—large-area bonding, copper foam-Ag composite film, preparation process

I. INTRODUCTION

With the development of power semiconductor devices, wide bandgap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) are gradually replacing silicon-based devices. SiC devices can handle larger current and voltage, which means that the power density will also be greatly improved[1]. However, a large increase in power density will cause the module to generate more heat. To ensure long-term reliable operation of the module, the heat must be removed in time. The heat generated by the chip is transferred to the heat sink via direct bonding copper (DBC), baseplate, and two layers of thermal interface material (TIM). Two layers of TIM account for the largest proportion of the thermal resistance of the junction case, so it is particularly important to improve its thermal performance and reliability[2].

At present, low temperature jointing technology (LTJT) has been fully developed for die bonding layer between chip and substrate, and sintered silver is one of the representatives. The thermal conductivity of the bonding interface obtained by the sintered silver technology reaches 240 W/m·K, much higher than the 50-70 W/m·K of the traditional solder, the melting point of the sintered silver layer reaches 700°C, and the reliability is also improved compared with the solder[3]. However, the development of large-area substrate connection materials with substrate and heat sink is relatively slow. Common commercial large-area TIM includes thermal greases and solders. Greases have excellent fluidity and a certain viscosity, so they can well fill the tiny voids on the surface. However, the thermal conductivity of these TIM (traditional greases are around 10W/m·K) is too low compared with other materials in the power module[4]. Solders have good thermal conductivity (50-70 W/m·K) and very low thermal resistance (5 mm^2·K/W) compared to the aforementioned TIM, but lead-free solders at high temperatures (>150°C) have reliability problems in applications[5-6]. There is an urgent need for a TIM with good heat dissipation at high temperatures.

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Small-area sintered silver has been successfully used as die connection material in power modules[7-8]. However, the die attachments are usually less than 50 microns, which is difficult to ensure the consistency of Ag sintering interface for the severe thermal warpage cases with large-area or ultrathin packaging structures, e.g., thin substrate or large-area heatsink[9]. In order to compensate for the severe thermal warpage issue, the usual solution is to increase the thickness of Ag sintering attachments, e.g., 100μm or even more. Nevertheless, the increment of Ag sintering attachments could lead to deteriorative mechanical properties of sintered Ag due to its inherent mechanical brittleness[10].

To solve the above problems, we introduced a Cu foam material. Cu foam is a material with a rigid skeleton and many continuous or discontinuous voids inside, as shown in Fig. 1. Copper has similar thermal conductivity to silver, copper foam has a large specific surface area and can fully contact the silver paste. Meanwhile, the relatively loose structure has better ductility, which can make up for the defect of poor plasticity of sintered silver[11]. However, the porous structure means that the contact between the silver slurry and the copper skeleton is difficult, and the poor connection will lead to larger defects in the joint. Therefore, the effects of different preparation methods on the microstructure and mechanical properties of the joint were analyzed.

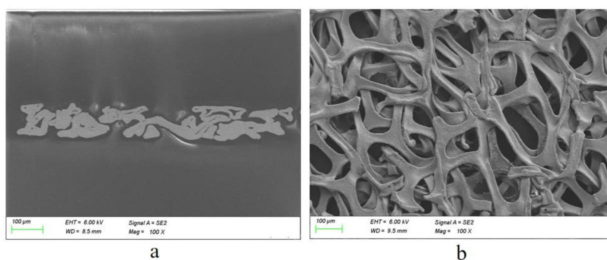

Fig. 1. The structure of copper foam

II. EXPERIMENAL

A. Thermal Characteristics of the Silver Paste

The processing profile of pressure-assisted sintering depends on the thermal properties of the paste itself. Therefore, in order to obtain the appropriate sintering profile, the commercial silver paste used in this experiment was subjected to thermogravimetric analysis (TGA). The rapid sintering technology was adopted in this experiment. The silver paste was heated at a rate of 15℃/min in a nitrogen atmosphere from 30℃ to 300℃. The result is shown in Fig.2.

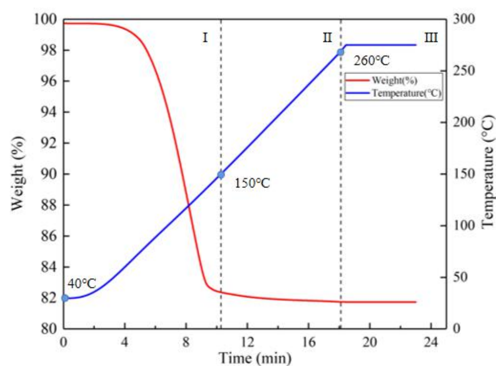

Fig. 2. The profile of sintering process

According to Fig. 2, silver paste sintering can be roughly divided into three stages. In the first stage, organic solvents evaporate rapidly with the temperature rise, and most solvents have evaporated at about 150℃. When the temperature rises from 150℃ to 260℃, almost all the solvent has been burned out. When the temperature exceeds 275℃, the weight of the silver paste does not change. At this time, silver paste has become dense and a silver neck is formed between silver particles. Therefore, it is reasonable to assume that organic solvents can be completely burnt out when the temperature reaches 275℃ and remains there for some time. TGA results can guide the design of the heating profile to remove most organic solvents.

B. Sintering temperature profile

The silver paste contains a variety of organic additives, including dispersants, which disperse silver particles to prevent agglomeration[12]. In the sintering process, the organic matter will be removed slowly. When the dispersant begins to evaporate, the silver particles will gather rapidly. At this time, the surface energy of the accumulated silver particles will be reduced, resulting in the reduction of the sintering driving force and poor joint quality. Therefore, it is necessary to avoid staying for a long time at the low-temperature stage. Rapid sintering technology can avoid agglomeration to a certain extent and improve sintering quality. The commonly used pressure-assisted silver sintering process is to pre-dry the silver paste for some time at a temperature not higher than the beginning of evaporation of dispersant and then pressure sintering. This method can remove the organic solvent in the silver paste to the greatest extent and improve sintering quality.

Copper foam has a rigid skeleton, and there are many interlaced and irregular cavities inside. The silver paste will change from paste to powder during heating and it is difficult to fill into the cavities. Therefore, in the sintering process, the pressure should not be applied after the completion of drying like sintered silver, but at the beginning of heating sintering, so as to squeeze the silver paste into the cavity better. According to the above analysis and TGA results, the sintering profile was determined, as shown in Fig. 3. In order to have sufficient time for the solvent to evaporate completely, the porosity is smaller and the degree of densification is higher after sintering. It is kept for 5 minutes at 150℃ and 275℃ respectively.

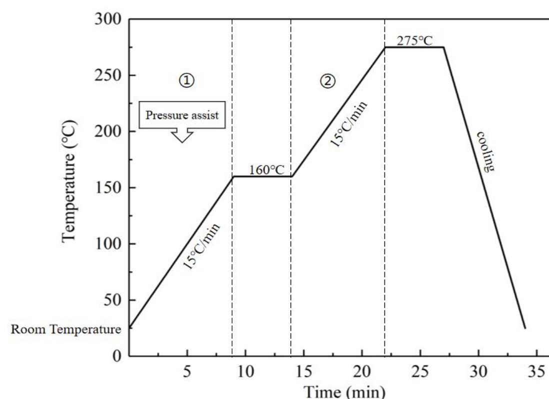

Fig. 3. TGA image of silver paste

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C. Preparation of Lap-Shear samples

The top and bottom copper substrates used in this paper are 5 mm × 5 mm × 1.5 mm and 15 mm × 15 mm × 1.5 mm respectively. The 8 um silver film is plated on the copper substrate to prevent the diffusion of copper and better connect with the silver paste. Copper foam is commercially purchased. The minimum hole diameter is 20 um and the thickness is 80 um. Before use, acid pickling is carried out to remove the oxide film. First, 20 um thick silver paste is printed on the bottom substrate, as shown in Fig. 4(a). Secondly, the copper foam is covered with silver paste, as shown in Fig. 4(b). Finally, 120 um thick silver paste is printed, as shown in Fig. 4(c). Put the prepared sample into the hot-press for sintering, as shown in Fig. 4(d). The hot-press is divided into the upper head and the main heating plate at the bottom. Although the sintering temperature mainly comes from the bottom heating plate, the upper head can rise to the same temperature as the bottom plate while pressurizing, to ensure that the sintering temperature is closer to the set temperature and improve the sintering quality.

To obtain better sintering quality of the joints, we tried to optimize the process by changing the timing of the applied pressure as well as the pre-drying conditions. The variables are shown in Table 1. The sintering profile shown in Fig. 3 was used for all samples in group A. Group B samples were changed from the first stage of pressure applied to the second stage of pressure application in Fig. 3. Group C was subjected to two additional steps after that shown in Fig. 4(c): firstly, pre-drying at low temperature (70°C) for 10 min, and then performing the operation in Fig. 4(c) once more. In addition, we made group D silver sintered samples according to the conditions of group A as a comparison. The specimen cross-sections were polished and then the surface was observed by SEM. The shear strength was tested using a shear tester.

D. Transient thermal characterization

The top Transient thermal testing method was used to characterize the thermal performance of the bonding layer. A continuous heating current is applied to the chip until the system is turned off after reaching a steady state. Switch to test current immediately after turning off heating current to measure voltage. This approach is specified in the Joint Electron Device Engineering Council (JEDEC) standard. Using this method, the accuracy of temperature measurement can reach 0.01°C, and thousands of data points can be obtained.

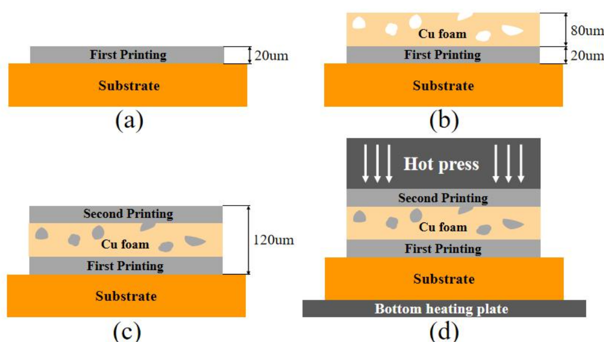

Fig. 4. Schematic diagram of sample preparation process

TABLE I
SAMPLE PREPARATION CONDITIONS

Variables	Group A	Group B	Group C	Group D
Pre-drying (70°C)	Not	Yes	Not	Not
Pressure stage	I	I	II	I
Joint material	Composite material	Composite material	Composite material	Silver paste

The power device we selected for transient thermal characterization is the silicon carbide Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET). The temperature of the body diode is used as the junction temperature of the chip. The die is connected to DBC by copper foam- silver composite and silver paste respectively. For better connection effect, DBC is plated with a 5um thin silver layer. At the gate, the source and their respective pads are wire-bonded, and the drain directly adopts terminals. The fabricated assembly is shown in Fig. 5. Thermal grease is used at the bottom of the DBC to ensure good contact with the heat sink.

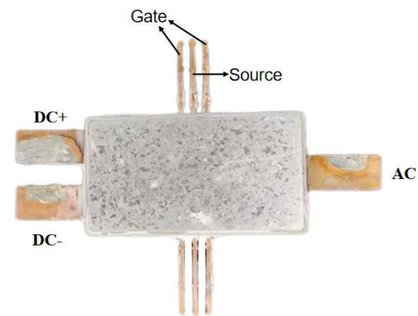

Fig. 5. Power module package structure for thermal resistance testing

III. Results And Discussion

A. Filling quality of silver paste in copper foam

Put the samples obtained by different preparation methods into the hot-press respectively, and ensure the same position to eliminate the influence of uneven pressure, and then sintering according to their respective process profile. Insert and grind the sintered sample, and observe the cross-section characteristic by SEM. The results are shown in Fig.6. According to Fig. 6, the microstructure of sintered silver in composite joints can be roughly divided into I, II, and III types, as shown in Fig. 6(a). The type I structure indicates that sintered silver can fill the cavity in the copper foam, the densification degree is high, no obvious holes, and the sintered quality is good. Type II structure mostly appears in small cavities, which means that although it is filled with sintered silver, it is not full filled, the degree of densification is low, the porosity is high, and the sintering quality in general. Type III also appears in smaller cavities. This type indicates that sintered silver is not filled into the cavity of copper foam, and the sintered quality is very poor. So, this type is the biggest defect in the joint. Therefore, type I structure is beneficial to the improvement of joint performance. However, types II and III are the opposite.

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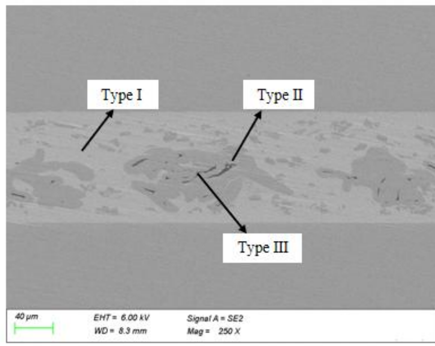
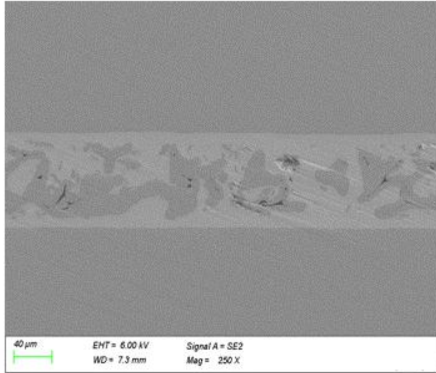
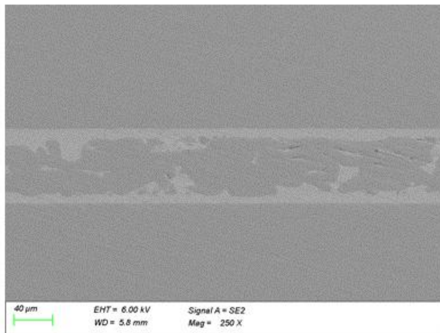


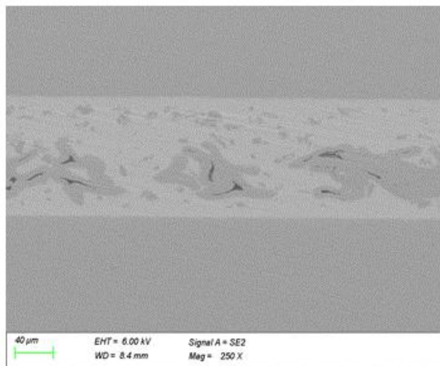
(a)



(b)



(c)



(d)

Fig. 6. SEM images of copper - silver foam joint prepared by different methods. (a) Schematic diagram of defects; (b) Group A; (c) Group B; (d) Group C.

It can be seen from Fig. 6 that the larger cavities of group A samples have been filled with type I, and the smaller pores contain all three types, among which type III are more distributed. Most of the samples in group B are type I, and type II exists in some small holes, but type III does not appear. Type I and type III appeared in group C. Compared with group A, type III appeared more and had larger cavities. According to the above analysis, the sintering quality of group B is the best, group A is the second, and group C is the worst.

B. Shear strength of joint

The effect of different preparation technology on the shear strength of copper foam-silver composite joints were investigated. Five samples for each sintering condition were selected to evaluate the sintering parameters, as shown in Fig. 7. The average shear strength of group A is 40.53MPa, group B is 52.3MPa, group C is 29.487MPa, and in group D, the sintered silver joint is 37.68MPa. According to the conclusion in Fig. 6, group B mostly consisted of type I, a small part of type II, and no type III. According to the results discussed in section A, type I shows a high sintering quality with high shear strength. In group C, except for type I, the rest are type III, and almost all the pores are type III, i.e. not filled with sintered silver, so the sintering quality is theoretically the worst. Compared with group C, the small holes in group A have both type II and type III, and the number of type III is lower than that of group C. Therefore, the connection quality of group A is better than that of group C. It can be seen from Fig. 7 that the shear strength of group A is 11MPa higher than that of group C. The above two points can prove that more type III will greatly weaken the mechanical properties of composite joints. At the same time, type II will also weaken the performance of the joint, so it needs to be avoided as type III.

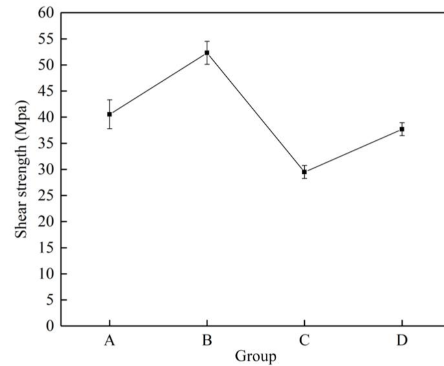


Fig. 7. Average shear stress for each group of samples

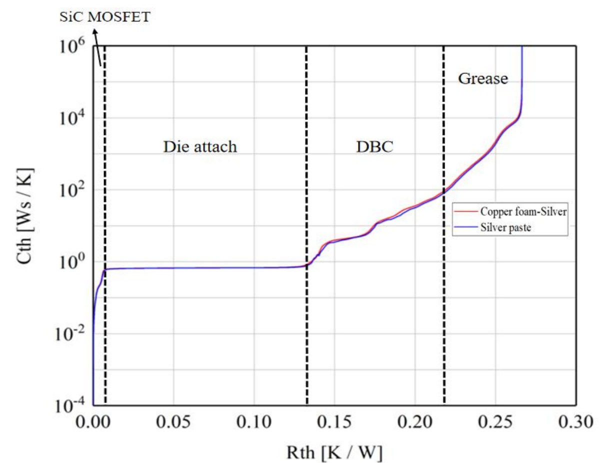


Fig. 8. Structure function profiles of composite sintered joint and sintered silver joint

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C. Determination of thermal resistance

The structural functions of the two specimens are shown in Fig. 8. The profile includes four parts, which are the thermal resistance contributions from the die, die-attach layer, DBC and grease. It can be seen from Fig. 8 that the thermal resistance of the chip and DBC of the two assemblies are almost the same, which are 0.008K/W and 0.076K/W respectively. This is certain because the materials used are the same. However, the thermal resistance difference of the die-attach layer is also very small, which is 0.132K/W. This is because the thermal conductivity of copper and silver are very similar (401W/m·K for copper and 429W/m·K for silver). Moreover, the copper skeleton is not a porous structure like sintered silver, which has a better heat conduction effect and can make up for the small disparity between copper and silver. However, the thermal resistance of composite joint is not better than sintered silver, because of the connection problem between copper and sintered silver. The connection between copper and sintered silver is worse than that between silver and sintered silver, which leads to larger pores between the copper and sintered silver structure and prevents further reduction of thermal resistance.

IV. CONCLUSION

In this paper, a feasible preparation process is explored by comparing the composite joints prepared through different approaches. The quality of the composite joint was evaluated and the shear strength of the specimen was tested. Finally, the thermal resistance of the composite was preliminarily characterized. The results show that the sintered silver structure in the composite joint can be roughly divided into three types, of which type I will improve the connection quality, while the other two have the opposite effect, and type III is the worst. The average shear strength of four groups of specimens was obtained through the shear test, of which group C was the highest, group B was the worst, and there was little difference between group A and group D. This result proves the above microstructure analysis. The thermal resistance of the composite bonding layer is almost the same as that of sintered silver. This paper only makes a general analysis, and the specific detailed experiments need to be supplemented.

ACKNOWLEDGMENT

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