Enhanced reliability for power modules via a new Ag/Si sinter joining strategy

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***Abstract*—In this work, with an appropriate adding amount of 20 vol% Si, the novel Ag-Si sintering demonstrated enhanced reliability during thermal shock cycling, specifically including the improved bonding strength stability as well as good microstructure maintenance. The high reliability can be attributed to the reduced CTE value of composited Ag-Si sintering inhibition of thermomechanical stress generation, allowing for the ultra-stable joining structure without coarsening, delamination and deformation. Additionally, the well-adhered interface between sintered Ag and Si additive was also verified by examining the microstructure, ensuring the reliable bonding characteristics of the Ag/Si sintered joint.**

Keywords—die-attach, Ag sintering, CTE mismatch, thermo-mechanical stress

I. Introduction

Owing to the high conversion efficiency and switching frequency, the WBG materials (SiC, GaN, Ga_2O_3) permit power modules to be smaller, faster and more efficient than the counterpart Si-based devices by supplying higher power in a reduced semiconductor area. The merits of WBG semiconductors also create a harsh operation environment at temperature as high as 600 °C [1-2]. A major requirement for further development of WBG devices is to make packaging materials compatible with the harsh working environment. Recently, Ag particles sintering is a novel bonding technique that provides a service temperature up to the melting point of Ag (960℃) in theoretical and high electrical ($63*10^6$ S/m) and thermal (429 W/mK) conductivities, because of which, it is highly advantageous than the currently solders. However, a major challenge lies in the mismatch of coefficient of thermal expansion (CTE) between sintered Ag (18.9×10^{-6}/K) and SiC chip (4.1×10^{-6}/K)/ DBC substrate (3.2×10^{-6}/K) [3-5]. Such CTE mismatch would induce strong thermo-mechanical stress as the module is operated under temperature swings from repetitive switch on and off, which would subsequently be relieved by defection growth and material bending and the following joining failure.

Herein, a novel composite paste is proposed wherein silicon microparticles were added into Ag sintering matrix because of such superior properties as low density and CTE value. Si has intrinsic low CTE value of 2.6×10^{-6}/K quite close to those of SiC chip and DBC substrate. Thereby, an Ag/Si composite paste is expected to possess a more compatible CTE value with module components and thus mitigated thermo-mechanical properties as compared to pure sintered Ag.

II. Method

A. Fabrication of composited Ag/Si sinter paste

The micro-Ag flakes and bulk Si particles were adopted as the raw materials to prepare the composite joining materials. To systematically analyze the effect of Si additives on the bonding properties, the Ag/Si pastes with different Si volume ratios were prepared, that is, Ag100%-Si0%, Ag92%-Si8%and Ag80%-Si20% (hereafter denoted as, Ag100%, Ag-Si8% and Ag-Si20%). These particles were initially mixed using magnetic stirring and ultrasonication in ethanol. The mixtures were then dispersed in CELTOL-IA (CxHyOz, x>10, Diacel Corporation) to obtain three types of sinter pastes of Ag100%, Ag-Si8% and Ag-Si20%, respectively. The SiC/DBC die-attached structure was then established using the as-prepared pastes through a pressure-less sintering process at 250 °C.

B. Thermal shock test and evaluations

A harsh thermal shock test was conducted at the temperature range from -50 °C to 250 °C for 500 cycles. the variation in bonding strength was measured by shear tester (DAGE 4000 bonds tester, UK) at 50 µm/s. The microstructure evolution during thermal cycling was then visualized using SEM (SU-8020, Hitachi). The interface between sintered Ag and Si particles within the sintered joining layer was examined using TEM (TEM, JEM-ARM200F, JEOL).

III. Results and Discussions

In a composite sinter joining system, the interface between sintered silver (Ag) and silicon (Si) additive is a critical factor that determines the bonding quality. If the interface is weak, it can easily lead to crack initiation and degradation on bonding strength. Therefore, ensuring a robust Ag/Si bonding requires special attention to the interface between sintered Ag and Si. Thereby, the Ag/Si interface was pre-checked, and a thermal reliability evaluation was subsequently conducted. This evaluation involved assessing the die shear strength and observing the evolution of microstructure.

A. Analysis of Ag/Si interface of composite sinter network

Fig.1a shows the cross-section of initially formed Ag-Si20% sinter structure. It can be observed the uniform porous Ag structure was integrated with some Si bulk particle. The local enlarged view at the interface between sintered Ag and Si was presented in Fig. 1b. Si additive was found to tightly adhered to sintered Ag structure without apparent voids or gap detected. A further TEM observation was conducted by thinning the sintered Ag-Si20% joint structure through Focus ion beam milling. It is clearly seen the well-connected interface formed between the porous Ag and Si as shown in Fig. 1c. was indeed connected at certain area. The high-resolution TEM in Fig. 1d shows that no gap can be found even in the nanoscale observation. This result demonstrate an integrated Ag-Si sintering structure was obtained which is promising to provide reliable bonding quality.

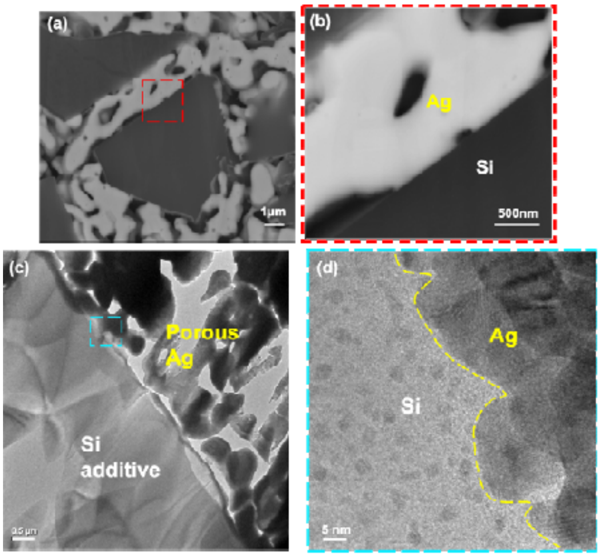

Fig. 1. (a) The cross-sectional images of Ag-Si20% sintering structure at the initial state. (b) The local enlarged view at the interface between Ag and Si (c), (d) TEM observation at the Ag/Si interface and its local enlarged view.

B. Evaluation on thermal properties

Considering the critical role of die-attach materials on thermal management, the change in thermal conductivity of the composited sintering structure were investigated as well. Fig. 2 shows that the thermal conductivity decreased gradually with the increase in Si amount due to the inherent low thermal conductivity of Si of 148 W/K·m. Although the thermal conductivity of Ag-Si20% dropped significantly to approximately 80 W/K·m that is almost half that of Ag100% sintered structure. This thermal property is still much better than the poor thermal conductivity of current Sn-based solders below 50 W/K·m. On the other hand, adding silicon at a volume ratio of 20% can significantly enhance the cost-effectiveness of Ag sinter joining. With the merits of both reduced cost and acceptable thermal conductivity, it is believed that the Ag/Si composited sintering holds promise as a reliable die-attachment used for high-temperature application.

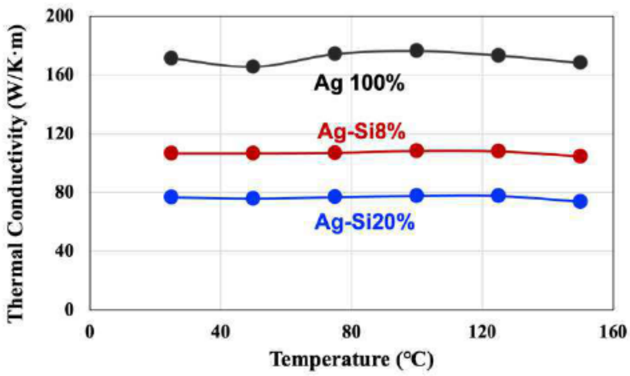

Fig.2. Thermal conductivity of Ag100%, Ag-Si8%, Ag-Si20% sintered structure with temperature.

C. Evaluation on bonding properties

Fig. 3a shows the die-attached module structure joined by three types of sinter pastes, Ag100%, Ag-Si8% and Ag-Si20%. The as-bonded module structures were then subjected to a harsh thermal shock cycling. Fig. 3b presents the corresponding die shear results. It can be seen that the initial bonding performance decreased with the increase in the amount of Si additives, where the Ag100% exhibited the highest shear strength of 60.1 MPa and Ag-Si20% exhibited the lowest bonding strength of 33.9 MPa. This is attributed to the inevitable decrease due to the integration of a heterogenous element into Ag homogeneous system. Of noted, different variation trend of shear strength occurred between joining structures during thermal cycling. With increasing number of thermal cycles, A similar rapid decline trend was found in the Ag100% and Ag-Si8% joint structures. However, a more gently decline trend appears in the Ag-Si20% joint. The specific difference was presented via retained ratio in bonding strength after 500 thermal cycles as shown in Fig. 3c. The strength retention rate of Ag-Si20% joint is 71.9%, which is obviously superior to the other joint structures. This result indicate that the addition of 8 vol% Si hardly affect the changes of bonding strength of sintered Ag, while the addition of 20 vol% Si can slow down the decline trend in shear strength. The detailed mechanism should be investigated through further microstructural analysis.

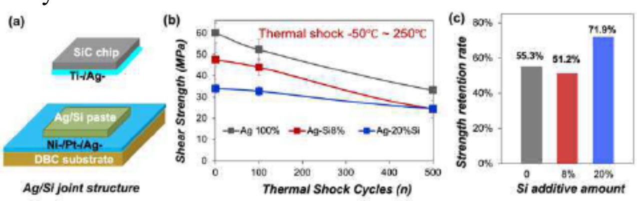

Fig.3. (a) The schematic for die-attachment via Ag-Si sinter joining. (b) Die-shear strength of joints by three types of Ag sintered pastes during thermal cycles. (c) Retention rate of shear strength after 500 thermal cycles.

D. Anlysis on microstruture evolution

The microstructural changes of the overall cross-section of three die-attached structures during thermal shock cycling are displayed in Fig. 4. All initial structures presented a porous network typical of press-less Ag sintering as shown in Fig. 4a. Meanwhile, some randomly distributed Si particles can be clearly seen in the Ag-Si8% and Ag-Si20% joining layers as shown in Fig. 4c and 4e. After 500 thermal cycles, distinct differences appeared in the defect growth among the three joining layers. Figure 4b shows that many cracks grow in the vertical direction with their size even spanning the whole joining layer. Additionally, the long cracks at horizontal direction that easily cause interface delamination were also found. The severe degradation of the microstructure of Ag-Si8% joint was similar to that of Ag100% joint, with both large vertical and horizontal cracks occurred, as shown in Fig. 4d. However, Fig. 4f shows that these serious degradation was significantly mitigated in the Ag-Si20% joint where only a few short vertical cracks was detected. This result indicates that 8 vol% Si particles are not sufficient to inhibit the deterioration of the microstructure, while 20 vol% Si has a significant effect on the maintenance of the microstructure. The improvement in microstructure deterioration of Ag-Si20% joint indicated the alleviated thermo-mechanical stress within the module structure. The severe microstructure evolution in Ag100% and Ag-Si8% joints was consistent well with their rapid decrease in shear strength.

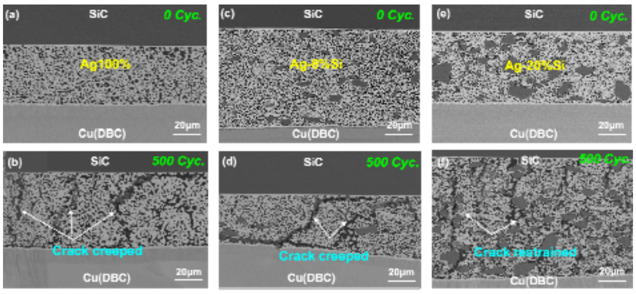

Fig. 4 The cross-sectional images of three die-attached structures before and after 500 thermal shock cycles. (a, b) Ag100% joint; (c, d) Ag-Si8% joint (e, f) Ag-Si20% joint.

The enlarged microstructure views at bonding interface were provided for a better understanding of the effect of Si additive on microstructure evolution. Since Ag100% and Ag-Si8% showed similar changes after thermal cycling, Ag100% was used as a representative for comparison with Ag-Si20% joint. Fig. 5a and b show the bonding structure at the interfaces of Ag100% sinter layer with SiC chip and DBC substrate after 500 thermal cycles, respectively. It can be clearly seen that large cracks of micron size appear at both the upper and lower interfaces, which should be the primary cause of bonding degradation and fracture of the Ag100% joint structure. In contrast, in the Ag-Si 20% joint, the upper bonding interface was well preserved and neither cracks nor delamination were observed. The crack size at the bottom interface is also reduced as displayed in Fig. 5d, further confirming the weakened structural damage caused by thermo-mechanical stress in the Ag-Si20% joint.

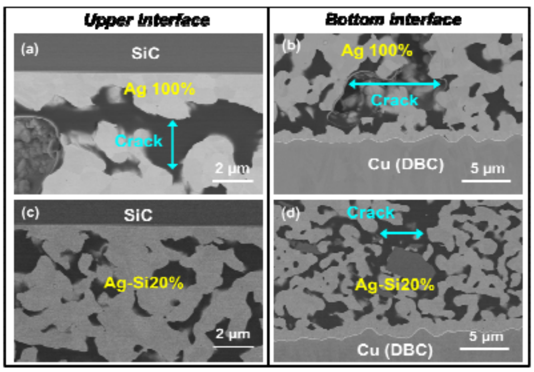

Fig. 5 The cross-sectional images at bonding interfaces with chip and substrate after 500 thermal cycles. (a, b) Ag 100% joint; (c, d) Ag-Si20% joint.

IV. Summary

In summary, the Ag100% and Ag-Si8% joint showed decreased bonding strength accompanied by degraded microstructure, while a significant improvement in reliability was achieved for the Ag-Si20% joint structure during the harsh thermal cycling. Based on a comprehensive investigation of strength evaluation and microstructural stability, it can be concluded that, an appropriate amount of Si additive play a critical role in alleviating the thermal stress derived from CTE mismatch. It is believed that the Ag/Si composite sintering with well-connected interfaces is a promising die-attach solution superior to sintered Ag for future high-power electronics applications.

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