Evaluation of high temperature reliability of SiC die attached structure with sinter micron-size Ag particles paste on Ni-P/Pd/Au plated substrates

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***Abstract*— Next generation power modules empowered by wide bandgap semiconductors like SiC and GaN can operate for a higher power than Si-based semiconductors at a high temperature over 250℃. Ag sinter joining as a die attach material with a high melting point and good thermal conductive properties have obtained many attentions for the next generation power modules. This study investigated the bonding properties and the high temperature reliability of Ag sinter joining on ENEPIG (Electroless Ni plating (EN), Electroless palladium plating (EP) and immersion gold plating (IG)) metallized DBA substrates. The initial die shear strength for SiC (3x3 mm^2) power modules was 33.9 MPa at 250℃ sintering without assisted pressure in air conduction. The high temperature reliability of Ag sinter joint structure was evaluated at 250℃ aging for 1000 h. The Ag-Au interface bonding mechanism, fracture behaviors and microstructure evolution of sinter Ag-Au joint were systematically analyzed. In addition, the connected Ag particles change to coarse with pore size increase during the aging process. The Ag-Au inter-diffusion layer also increased with the aging time but not clearly delamination occurrence. The die shear strength was slightly increased from the initial to 36.5 MPa after aging 1000 h, which meaning the Ag-Au joint possessed a good high temperature reliability. This study should add the understanding of the reliability issues of Ag sinter joining on Au finished substrate for its applications at high temperature.**

Keywords— Ag-Au joint, Ag sinter joining, SiC power modules, high temperature reliability, ENEPIG metallization.

Ⅰ. INTRODUCTION

The excellent properties of wide bandgap (WBG) semiconductor materials bring new challenges for the packaging of WBG device. WBG semiconductors like GaN and SiC can handle heavy power density and are expected to generate massive heat, which will result in a severe operating temperature on the order of 250 °C [1, 2]. The massive heat generation leads to issues for thermal management and packaging of the whole device, causing a massive impact on device performance and long-term reliability problems, for instance thermal stress caused by different materials and high-temperature oxidation of packaging materials, will directly lead to the failure of WBG device. The quality of interconnection between different components directly affects the performance and reliability of WBG device because the failures usually happen in these vulnerable areas. The die attach material must possess an excellent thermal and electrical conductivity and is able to withstand a high junction temperature even over 250 °C. The topside interconnection must be suitable for severe CTE mismatch and high operating frequency.

To face the severe challenges caused by harsh operating conditions in WBG devices, there are some new die attach interconnection methods and materials have been developed for the die attach of WBG devices. Ag sinter joining might be the most suitable candidate for die attach. Ag paste, consisting of Ag particles and organic solvent, can be sintered below 250 ºC due to the high surface energy of small particles. After sintering, the Ag particles merger into a uniform porous structure due to Ag self-diffusion. This porous Ag structure possesses a high melting point above 900 ºC. In addition, Ag has excellent thermal and electrical conductivity and stable chemical properties. All these merits perfectly match the requirements of die attach technologies for WBG device, which needs to consistently operate at a harsh condition.

Recently, Ag paste just contains the micron-sized Ag flake particles shows a superior bonding performance even than that of the Ag hybrid paste [3]. Many researchers have observed in-situ nano-Ag particle generation in micron-sized Ag flake paste during sintering [4-6]. It can be attributed to the synergism effect of oxidization and reduction reaction of Ag, and release of micron strain in micron Ag flake particles [4]. The in-situ generated nanoparticles could accelerate sintering process due to their small size (within 10 nm) and free of the passive organic layer.

On the other hand, Au surface finish has been widely applied in electrodes, Si/SiC wafers and printed circuit boards (PCB) substrates. Electroless Ni plating (EN) with hypophosphate as the reducing agent, electroless pure palladium (or palladium phosphorus) plating (EP) with formate as the reducing agent, cyanide-type immersion gold plating (IG), usually called as ENEPIG, has received a lot attention because of its easy process, good solder ability, low consumption rate as well as good mechanical reliability properties. Ag sinter joining on Au finish surface is a very hot topic, but there are some difficulties to obtain a robust Ag-Au joint in a low temperature, low pressure sintering [7-9]. Furthermore, thermal aging reliability of Ag-Au joint is another issue, especially for the ENIG process where the Ni layer diffusion into the Au layer via Au grains boundaries, leads to die shear strength decrease after aging test.

In this study, high temperature reliability of SiC die attached structure was evaluated with sinter micron-sized Ag flake particles paste on ENEPIG (Ni-P/Pd/Au) plated

substrates at 250 ºC aging test for1000 h. The initial shear strength was investigated at the sintering temperature of 250 ºC without assisted pressure in air. The Ag-Au interface bonding mechanism and fracture behaviors were analyzed via Scanning Electron Microscope (SEM), and Energy dispersive X-ray spectroscopy (EDS). The changes of Ag-Au joint strength and microstructural evolution were also discussed after aging process.

Ⅱ. Experimental

A. *Micron-sized Ag flake paste preparation*

In this study, we used a kind of micron-sized Ag flake particles as Ag filler as shown in Fig. 1(a). The average size of the flake particles is about 2.5 μm (see Fig. 1(b)). The cost for this kinds of micron-sized Ag paste was just about one tenth of Ag nanoparticles because Ag nanoparticles fabrication process is very complicated， and which need many times washing process after fabricated than that micron-sized particles. A type of solvent (CELTOL-IA, Daicel Corporation) was used to make a Ag paste by add that into Ag particles as the weight ratio of the solvent at approximately 8 wt%. The TG–DTA curve of this kind of micron-sized Ag flake paste (MAFP) as shown in Fig.2 where the weight lost quickly from 50 to 130 °C, and very slowly from 130 to 260 °C, no obvious weight losses above 260 °C. In addition, the DTA curve presents a tiny exothermic peak at approximately 130 °C and a huge exothermic peak around 260 °C. At 130 °C, the exothermic peak may correspond to the evaporation of the solvent, and at 260 °C, which may be induced by the complex reaction of Ag and oxygen [10,11].

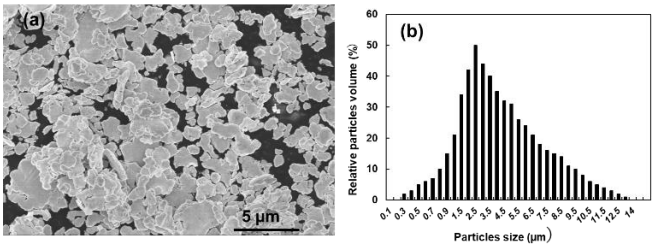

Fig. 1(a) The SEM image of micron-sized Ag flake particles, (b) the size distribution of Ag flake particles.

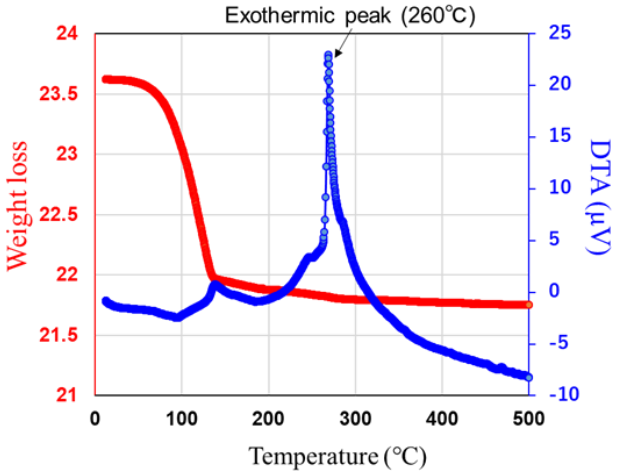

Fig. 2 TG-DTA curves of Ag paste in the static air atmosphere at a heating rate of 10 K/min.

B. *Au plating process*

Au plating is an exceptional finish for connectors where there is a demand for high reliability and durability. In this study, ENEPIG process was study which were prepared and coated on a direct bonding aluminum (DBA) substrate (see Fig. 3a and 3b). The thickness of electroless Ni plating was set as 7 μm, the thickness of Au was set at 0.15 μm. The thickness of Pd by electroless palladium phosphorus plating was 0.1μm. All of the Au plating process was provided by the company (C. Uyemura & Co., Ltd, Japan).

C. *Sintering process*

The SiC dummy chips (3 × 3 × 0.45 mm) were prepared and orderly sputtered with Ti (0.1 μm) and Ag (2 μm) on the side to bonding. Ag paste was screen printed onto the ENEPIG plated substrates (see Fig. 3c), and the dummy chips were then placed on substrates as shown in Fig. 3(d). All samples were sintered on a hotplate at 250 °C for 30 min in the air under a pressure-less condition as shown in Fig. 3(e). The thermal-stability of Ag-Au joint structures were evaluated by aging at 250 ºC up to 1000 h.

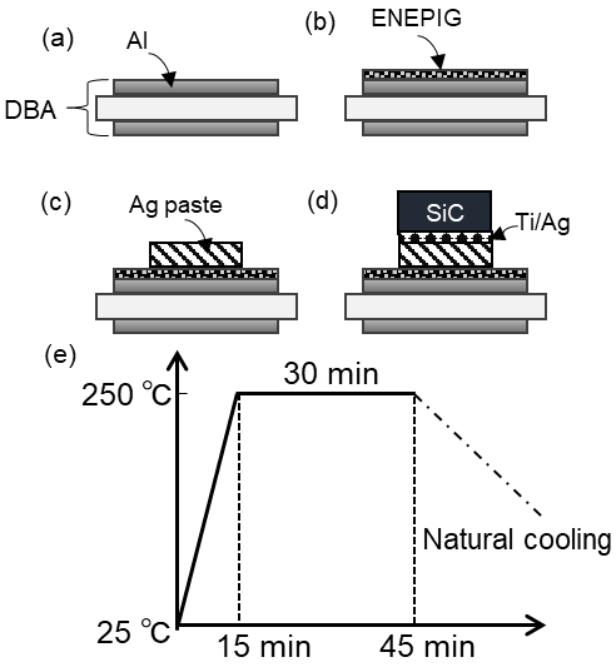

Fig.3(a) The prepared DBA substrate, (b) ENEPIG plating on the DBA, (c) printing Ag paste, (d) mounting the SiC chip on the paste and (e) the sintering profile.

D. *Characteristic Analysis*

The bonding strength of the Ag-Au joint structure was evaluated by a shear tester (Dage 4000, Japan) with the shear speed at 50 μm/s. The cross-section of the sintered Ag-Au joints were prepared by an ion milling polishing machine (IM 4000; Hitachi, Japan) and the morphologies and the atomic distribution of the cross-section were investigated by the scanning electron microscope (SEM, SU-8020; Hitachi, Japan). The bonding interface evolution between Au-Ag during the aging test was investigated by Energy dispersive X-ray spectroscopy (EDS).

III. RESULTS AND DISCUSSION

A. Sintered Ag morphology

Fig.4(a) and Fig. 4(b) show the SEM image of the surface and cross-section of sintered Ag paste at the sintering temperature of 250℃ for 30 min, respectively. The sintered Ag paste have a micron-sized porous network structure by Ag grains necking growth and the porosity was measured as 37%.

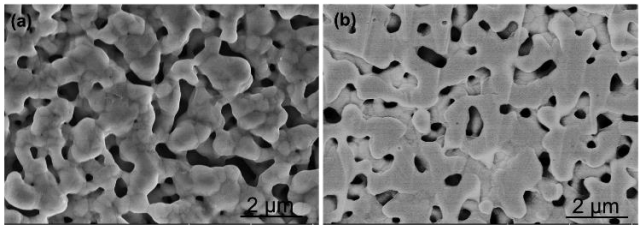

Fig. 4(a)The SEM morphology of the surface and (b) the cross-section sintered Ag flake paste

B. Die shear strength

Fig. 5 shows the average and standard deviation of the initial die shear strength of the sintered Ag-Au joints and aged at 250 ℃ for 1000 h. The initial shear strength was 33.9 MPa. The shear strength was larger than that Pb-5Sn solder and the other Pb-free solders [12]. The shear strength of the Ag sinter joining on ENEPIG was larger than that on ENIG reported by other groups [13, 14]. Recently, it is reported that the shear strength of Ag-Au joints was influenced by the grains size of the top Au layer, the larger Au grains size would lead to a stronger interface bonding [15]. Therefore, the good bonding for the study maybe attribute to the larger Au grains size. In addition, it was reported that the Ni could diffusion into Au lay during the sintering process for the ENIG substrate case, which lead to a weak interface bonding with sintered Ag layer due to the Ni oxide generation [9]. In this study, the Pd layer prohibited the Ni diffusion and thus assisted the Ag-Au interface bonding.

In addition, the die shear strength was slightly increased to 36.5 MPa after 1000 h, which means that the bonding structure have a good high temperature stability. In our previous studies, the high temperature aging reliability on ENIG was investigated, in which the die shear strength decreased with the aging time at 250℃ [16, 17]. The stability of Ag sinter joining on ENEPIG may be attributed to the Pb layer, which prohibit the diffusion of Ni into the Au layer during the aging process. The results indicated that we do not need to change the Au plating process to a Ag metallization process for the Ag sinter joining, for example, the printed circuit board (PCB) substrates which usually uses the Au finish.

C. Microstructure evolution of sinter Ag-Au joint

Fig. 6(a) and Fig. 6(b) show the initial cross section of Ag sinter joining on ENEPIG substrate and after aging for 1000 h at 250°C, respectively. The initial interface between sputtering Ag and sintered Ag at the SiC side was well bonded with a strong interface necking growth. On the other hand, voids appeared in the sputtered Ag layer after aging for 1000 h. The appearance of voids in the sputtered Ag layer was a de-wetting phenomena from Ti. The reason may be explained when coarsening is continuously triggered at 250 °C, Ag

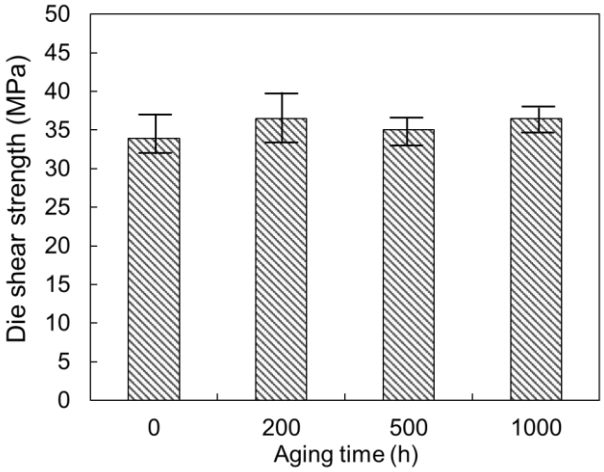

Fig. 5 the die shear strength of as-bonded Ag-Au and after aging for 1000 h.

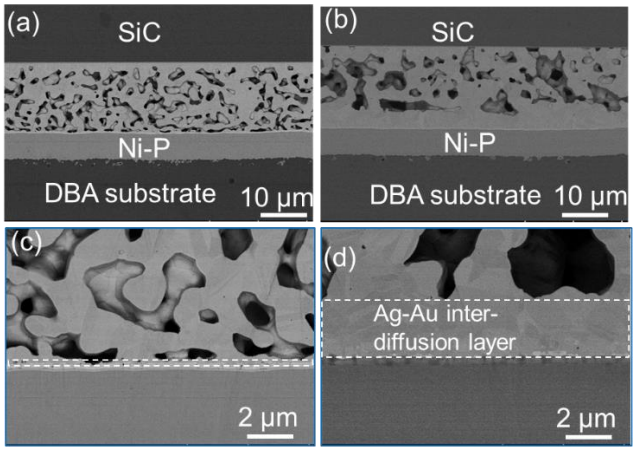

Fig. 6(a) the initial cross section of Ag sinter joining on ENEPIG substrate, (b) Ag-Au joint structure after aging at 250℃ for 1000 h, (c) the magnified view of Ag-Au bonding interface of initial structure and (d) after aging for 1000 h.

atoms in the Ag metallization layer were passively absorbed into the porous Ag to support the coarsening process due to stress migration.

The bonded interface between sintered Ag and ENEPIG substrate was magnified as shown in Fig. 6(c). The sintered Ag and Au layer was well connected with a thin Ag-Au inter-diffusion layer generation after sintering. The thickness of the Ag-Au inter-diffusion layer was influenced by the diffusion speed of sintered Ag to Au layer, which depends on the Au grains structure. For an Au layer with a fine grains, means that the grain boundary density was high, the Ag diffusion will quickly happened into Au layer via its grain boundary. In this study, the Ag-Au inter-diffusion layer was very thin, means that the Au grains boundary density was small. Considering that the good bonding strength of Ag-Au joints obtained in this study, the reason may be attributed to the small Au grains boundary density of Au layer, which lead to a thin Ag-Au inter-diffusion layer generation during the sintering. Fig. 6(d) shows the Ag-Au interface after aging at 250℃ for 1000 h. The magnified images reveal the bonding line between Ag and ENEPIG substrate still bonding well even after aging for 1000 h. The Ag-Au inter-diffusion layer increased to about 2 μm. It was seen that almost all the Au layer was diffused into the

Ag-Au inter-diffusion layer. Because the initial thickness of Au layer just was 0.15 μm, the 2 μm thickness of Ag-Au inter-diffusion layer was mainly contain Ag, which was gradually accumulated and was consumed from sintered porous Ag during the aging due to the thermal stress and inter-diffusion influence.

In addition, it was seen that with the increase of storage time, sintered Ag presents a coarsened structure, in which the Ag grain necks became larger and the pore inside also change to bigger. Ag grain coarsening has already been reported in many studies which was mainly induced by traditional Ostwald ripening. Recently, it was revealed that the coarsening structure is involved in the Ag-O reaction and form a large number of Ag nanoparticles around sintered Ag particles [18]. The mechanism of coarsening behaviors was revealed wherein oxygen plays an important role rather than the traditional Ag thermal self-diffusion.

Fig.7(a) shows the cross-section of initial Ag-Au joint and the elements mapping. It was clearly seen that the Au element was slightly diffusion into the sintered Ag layer. Fig.7(b) shows the cross-section of the Ag-Au joint and the elements mapping after aging 1000 h at 250°C. Further Au layer diffusion can be seen and the Au-Ag inter-diffusion layer mainly contain Ag element as analyzed above. In addition, the Ni layer almost did not diffuse into the Au layer due to the Pd layer protection and there are not clearly Oxygen elements generation before and after aging test.

D. Fracture mode

Fig. 8(a) and Fig. 8(b) show the fracture of the initial Ag-Au joint structure and after aging 1000 h at 250°C, respectively. The initial Ag-Au joint structure fractured at the interface between the Ag-Au diffusion layer and the sintered Ag porous layer, and changed after aging for 1000 h where the fracture occurred inside of the sintered Ag as seen in Fig. 8(b) and 8 (d). This means the strength of the Ag-Au bonding interface increased during the high temperature aging. Fig.9 (a) and Fig.9 (b) show the SEM image of the initial Au layer of ENEPIG substrate and the Au layer after aging 1000 h at 250°C, respectively. It was seen that the Au grains size changed to bigger after aging. This may be attributed to the recrystallization of Au grains at the aging process. Because the larger Au grains size will lead to stronger Ag-Au interface bonding, the increased Au grains size may lead to the fracture mode change after aging. In addition, because the die shear strength after aging was slightly increased, the fracture strength of the sintered Ag layer did not become to weaker than that initial state even the microstructure change to coarsening.

Ⅳ. Conclusion

This study investigated the bonding properties and the high temperature reliability of Ag sinter joining on ENEPIG metallized DBA substrates. The initial die shear strength for SiC power modules was 33.9 MPa at 250℃ sintering without assisted pressure in air conduction. The high temperature reliability of Ag sinter joint structure was evaluated at 250℃ aging for 1000 h. The die shear strength was slightly increased from the initial to 36.5 MPa after aging 1000 h, which meaning the Ag sinter joining on ENEPIG substrate possessed a good high temperature reliability.

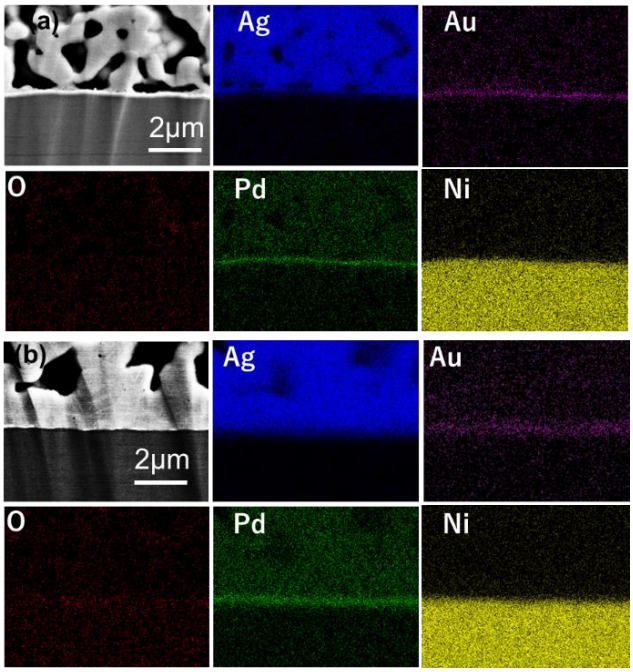

Fig. 7(a) the initial cross section of Ag sinter joining on ENEPIG substrate, (b) Ag-Au joint structure after aging at 250℃ for 1000 h, (c) the magnified view of Ag-Au bonding interface of initial structure and (d) after aging for 1000 h.

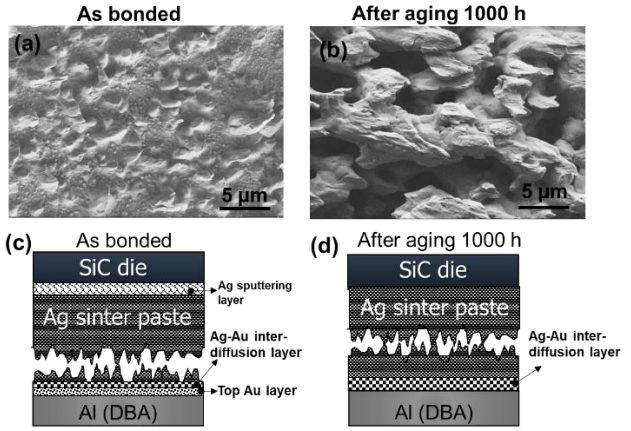

Fig. 8(a) the fracture surface of the initial Ag sinter joining on ENEPIG substrate, (b) the fracture surface of Ag-Au joint structure after aging at 250℃ for 1000 h, (c) the schematic diagram of fracture mode of (c) the initial structure and (d) after aging for 1000 h.

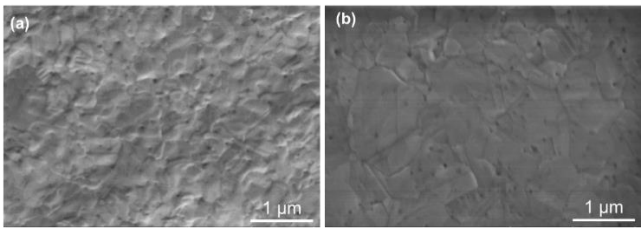

Fig. 9(a) the initial Au surface and (b) the Au surface after aging at 250℃ for 1000 h.

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