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Correlation between interfacial microstructure and bonding strength of sintered nanosilver on ENIG and electroplated Ni/Au direct-bond-copper (DBC) substrates

Qianye Xu [a, b], Yunhui Mei [a, b, *], Xin Li [a, b], Guo-Quan Lu [a, c]

[a] Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education, Tianjin University, Tianjin, 300072, China
[b] School of Materials Science and Engineering, Tianjin University, Tianjin, 300072, China
[c] Department of Materials Science and Engineering, Virginia Tech, Blacksburg, 24061, USA

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ABSTRACT

We studied the diffusion bonding mechanism and interfacial reactions between sintered nanosilver and direct-bond-copper substrates with different surface finishes, i.e., electroless nickel immersion gold (ENIG) and electroplated nickel gold (Ni/Au). The correlation between the interfacial microstructure and bonding strength of sintered nanosilver joints was discussed. The shear test results indicated that the strength of the Ni/Au joints was approximately three times higher than that of the ENIG joints. Scanning electron microscopic (SEM) and transmission electron microscopic (TEM) images showed that the interface was bonded well in the Ni/Au joint. However, a delamination region appeared along the interface in the ENIG joint. Excess diffusion of Ag element into the immersion gold layer during sintering at high temperatures resulted in poor densification of the sintered nanosilver adjacent to the Au surface. As a consequence, a continuous Ag–Au layer and the delamination region formed between the sintered Ag layer and the Ag–Au layer and a weakened the ENIG joints. A modified sintering process involving a preheating stage at 150 °C for 5 min and a sudden increase to 275 °C held for 30 min effectively reduced the poor densification and increased the shearing strength of the ENIG joints.

1. Introduction

Nowadays, the trend of continuous high-density integration observed in the electronics industry requires not only smaller components to be assembled on the printed circuit boards (PCB), but also components and packaging materials more resistant to high temperatures. In recent years, due to the superior properties of sintered nanosilver joints, such as low sintering temperature [1], high melting point, high thermal and electrical conductivity [2,3], and high mechanical reliability [4–6], nanosilver paste has been increasingly used as a novel lead-free interconnection material in the microelectronics packaging industry, especially for high-temperature applications [7,8]. It is a promising alternative to the traditional interconnection materials, i.e., solder alloys and conductive epoxies.

Normally, prior to bonding semiconductor dies with substrates using nanosilver paste, the substrates need a surface finish to prevent oxidation and to enhance solderability. In the PCB manufacturing industry, common surface finishes in use today include electroplated nickel gold (Ni/Au) [9], electroless nickel immersion gold (ENIG), and organic solderability preservative (OSP) [10,11]. ENIG is widely used in telecom, automotive and industrial, due to its outstanding flatness and good surface solderability. There have been many reports on the mechanical properties and interfacial chemical reaction of the joints on ENIG surface finish with various kinds of solder alloys [12–18]. However, there are no reports on the interconnection between nanosilver paste and substrate with ENIG finish. And in our trial test, we unexpectedly found that the shearing strength of the sintered Ag joint with the Ni/Au finish was much higher than that of the joint with the ENIG finish, although both ENIG and Ni/Au finish are nickel-gold-based metallization.

Therefore, it is of great significance to clarify the interrelation between interfacial microstructures and bonding strength of the joint between sintered Ag and both ENIG and Ni/Au substrates,

* Corresponding author. Key Laboratory of Advanced Ceramics and Machining Technology of Ministry of Education, Tianjin University, Tianjin, 300072, China.
E-mail address: yunhui@tju.edu.cn (Y. Mei).

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separately. In this work, the interfacial microstructures and metallurgical reactions between the sintered Ag joints with both ENIG substrate and Ni/Au substrate was analyzed. A possible way to enhance the bonding quality of the joint between sintered Ag and ENIG substrate was also proposed.

2. Experimental

The nanosilver paste used in this study was prepared by mixing Ag nanoparticles with an organics containing dispersants, surfactants, binders, and thinners [19]. The Ag nanoparticles in the paste have an average particle size of 40 nm [20]. In the present work, 9×9 mm^2 chips with a 1 μm thick electroplated Ag layer and direct-bond-copper (DBC) substrates with two different surface finishes, i.e., ENIG and Ni/Au, were used. The sizes of the Ni/Au and ENIG substrates were 15×15 mm^2 and 20×20 mm^2, respectively. In the Ni/Au substrate, the thickness of the electroplated nickel (EP-Ni) and gold (EP-Au) layers were about 4 and 0.5 μm, respectively. In the ENIG substrate, the thickness of the electroless nickel (EN) and immersion gold (IG) layers were about 2 and 0.25 μm, respectively, and the EN layer contained approximately 15 at.% of phosphorus (P).

The nanosilver paste was stencil-printed to a thickness of 50 μm onto a substrate with the ENIG or Ni/Au surface finish for the die attachment. During assembly no pressure was applied to the chips after being placed onto the substrate. Then the samples were heated by a programmable digital hot-plate (Torrey Pines, HS40A) and a conventional sintering process with a temperature profile consisting of a ramp from room temperature to 275 °C at an average rate of 5 °C/min and a holding time of 30 min was adopted. After bonding, the shearing strength of the sintered joint was measured by a XTZTEC Condor150 tester. The shearing tests were performed at a height of 70 μm from the base of the component and a shear speed of 400 μm/s.

Cross-sectional samples were prepared for interfacial microstructural examination. The samples were first cut by a low-speed diamond saw. They were then mounted in epoxy resin, ground with silicon carbide cloths, and polished with three-micron, one-micron, and quarter-micron diamond in water base suspensions. Finally, the cross-sectional samples were soaked for 2 s in a solution containing equal amounts of 30% H_2O_2 and 20% NH_4OH and cleaned with deionized water. A scanning electron microscope (SEM, Hitachi-S4800) equipped with an energy dispersive X-ray (EDS) analyzer which determined the elemental lines and compositions at the interface of die attachment, was then used to reveal the interface microstructure of the joints.

Two samples, each of ENIG and Ni/Au joints, were also prepared for transmission electron microscopy (TEM) analysis by a Helios Nano Lab 600 (FEI) dual beam system consisting of a Field Emission Gun Scanning Electron Microscope and a Focused Ion Beam (FIB). The samples were analyzed by a JEOL JEM 2100f transmission electron microscope operating at 200 kV.

3. Results and discussions

3.1. Shearing test results

Fig. 1(a) shows the schematic illustration of the shearing test. Fig. 1(b) and (c) exhibit the photographs of the as-sheared samples on Ni/Au and ENIG substrate, respectively. Fig. 2 shows the SEM images of fracture surfaces on the DBC side. Five samples were tested to obtain the average shear strength of each joint. Considerable differences in shear strength and fracture morphology are found between the two types of sintered nanosilver joints, i.e., on Ni/Au and ENIG substrate. Fig. 1(b) shows that the chip cannot be sheared off on a Ni/Au substrate (the die-shearing strength on average was 23.9 MPa). And Fig. 2(a) shows that on a Ni/Au substrate, the fracture occurs in the layer of sintered Ag, and plastic flow is evidently shown in the inset of Fig. 2(a).

However, the die can be easily sheared off the ENIG substrate, as shown in Fig. 1(c), and the bonding strength of the sintered nanosilver joint with ENIG substrate was only 7.8 MPa on average, which is much lower than that with the Ni/Au substrate. Fig. 2(b) shows the fracture surface morphology of the sintered joint with the ENIG substrate. There is a dense and flat surface formed on the fracture site, as shown in Fig. 2(c). Parts of residual sintered nanosilver were adhered to the flat layer, as indicated by the arrows in Fig. 2(d). According to the EDS results, the basic elements of the flat layer are Ag and Au.

Above die-shearing results indicated that the sintered nanosilver can easily attach the Ni/Au substrate but can hardly form a reliable joint with ENIG substrate, although both ENIG finish and Ni/Au finish are nickel-gold-based metallization. Therefore, it is of great significance to explain the above findings for further application and promotion of nanosilver paste.

3.2. Ni/Au joint microstructure

Fig. 3 shows the SEM images of cross sections of a sintered nanosilver joint on Ni/Au DBC substrate. As shown in Fig. 3(a), the thickness of the uniform bondline is approximately 40 μm. A few small voids are scattered within the sintered nanosilver joint. Fig. 3(b) exhibits the interfacial layers of the joint, which consist of sintered Ag layer, EP-Ni layer, EP-Au layer, and copper layer. It is obvious that there is no significant defect, such as cracking, voids and apparent intermetallic compound (IMC) layer, at the interface between the EP-Au layer and the sintered Ag layer. Fig. 4 is the EDS line scan profile results of sintered Ag interface on Ni/Au substrate, which confirms the element inter-diffusion between the sintered Ag layer and Au layer. It is known that the EP-Au layer would dissolve into solder alloys during solder reflowing [21]. In our case, Ag atoms could diffuse into the interstitial position of the EP-Au layer in the sintering process of nanosilver paste, and then the Ag atoms could form an infinite solid solution with the Au atoms, resulting in reliable metallurgical bonding [22].

3.3. ENIG joint microstructure

Fig. 5 shows the cross-sectional images of the sintered nanosilver on the ENIG substrate. As shown in Fig. 5(a), significant delamination could be observed between the sintered Ag layer and the ENIG substrate. The delamination should lead to a decrease in shear strength. Fig. 5(b) and (c) show magnified images of the interfaces between the sintered Ag layer and the electroplated Ag on the Si-based chip, and between the sintered Ag layer and the ENIG substrate, respectively. It is interesting to note that the delamination region is only presented adjacent to the interface between the sintered Ag layer and the ENIG substrate. As shown in Fig. 5(d), a continuous layer about 1 μm thick (likely to be IMC) can also be observed adjacent to the EN layer.

Fig. 6 shows the EDS line scan results of sintered Ag interface on ENIG substrate. The EDS results confirm that the continuous layer observed in Fig. 5(d) is an Ag–Au layer. And it is also confirmed that the inter-diffusion between Ag and Au atoms occurs in the case of ENIG substrate as well as Ni/Au substrate, but the inter-diffusion speed of Au and Ag atoms should be much higher in the ENIG joint than that in the Ni/Au joint. In the ENIG joint, the Ag atoms almost diffuse across the whole IG layer, resulting in the formation of the Ag–Au layer, so the IG layer disappeared after sintering of nanosilver paste. It is worth noting that the absence position of all