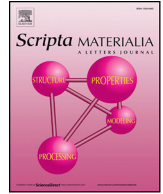
Scripta Materialia 146 (2018) 123–127

Contents lists available at ScienceDirect

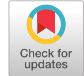
Scripta Materialia

journal homepage: www.elsevier.com/locate/scriptamat



Regular article

Bonding technology based on solid porous Ag for large area chips



Chuantong Chen [a,*], Seungjun Noh [a,b], Hao Zhang [a,b], Chanyang Choe [a,b], Jinting Jiu [a], Shijo Nagao [a], Katsuaki Suganuma [a]

[a] Institute of Scientific and Industrial Research, Osaka University, Mihogaoka 8-1, Ibaraki, Osaka 567-0047, Japan
[b] Division of Adaptive Systems, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka Suita, Osaka 565-0871, Japan

ARTICLE INFO

Article history:
Received 10 October 2017
Received in revised form 15 November 2017
Accepted 15 November 2017
Available online xxxx

Keywords:
Porous Ag structure
Large area bonding
Hillock growth
Bonding mechanism
Stress-induced migration
Power electronic module

ABSTRACT

A bonding technology is introduced by using surface polished porous Ag in die-attachment structure. Bonding strength did not change much as the chip size varied from 3 × 3 mm^2 to 15 × 15 mm^2. This confirms that the technology was not influenced by the chip size, and thus can be used in large area bonding. Bonding mechanism based on stress-induced migration was discussed with the three dimensional finite element analyses. Transmission electron microscopy (TEM) observation further confirmed that single crystal hillocks and Ag particles formed at the bonding interface, bridging the interface together.

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In the power electronic module, the silicon (Si) chip is attached by die attach materials usually solder materials to package substrate material. The package substrate is typically composed of copper (Cu) layers. Together with the trend of power electronic module achieving higher power and smaller volume, die attach materials going to be a larger current-carrying capacity as well as a better thermomechanical properties [1,2]. On the other hand, harsh environment are also required to increase usual temperature operating conditions beyond the limit of power semiconductor devices based on Si chip [3]. In this case, the application of silicon carbide (SiC) has been increasing to replace the Si chip in the electronic systems. One of the reasons is that SiC have a good performance at the high temperature up to 250 °C [4]. Traditional die attach materials such as Sn–Pb solder alloys exhibit a poor bonding reliability at high temperature operation [5,6].

In addition, large-area bonding technology (larger than 10 × 10 mm^2) have grown considerably to satisfy the applications for large chip size and the high performance requirements of power devices [7,8]. Alternative bonding techniques such as transient liquid phase soldering (TLP) [9–11] and Ag sintering technology [12–15] have been reported to achieve stable bonding at high temperature operations. TLP bonding technology has some advantages such as relatively short bonding time, tolerate some surface roughness, but which usually limited to material combinations with favorable phase diagram [16] and low bonding area ratio [17] especially for large area bonding. The advantages of the Ag sintering technology are mainly due to the low electrical resistivity (between 2.5–10 μΩcm) [18,19] of the sintered Ag joint, low elastic modulus and low temperature sintering-bonding process (≤250 °C) [20]. However, it was reported that shear strength for Ag sintering technology decreased with increased bonding area [21], which partly because the volatilization of solvent is blocked by the large area chip, making chip difficult to bond. The chip size effect on the bonding strength may be an obstacle in the application of Ag sintering technology for large area chips. Although these shortcomings of TLP and Ag sintering technology can be improved by some optimization processes, more advanced bonding technology also needs to be developed to meet the high temperature operation requirements and to satisfactorily accomplish large area bonding.

Recently, it was reported that Ag hillocks or Ag nanowires can grow on surface polished porous Ag structure because stress induced migration mechanism [22]. The porous Ag structure can be easily fabricated by sintering a hybrid Ag paste [22] and has the excellent material properties in thermal and electrical conductivity as well as high temperature stability. In addition, some studies also confirmed that the two interfaces can be bonding together by the growth of Ag hillocks [23–25] or nanowires [26,27] through a heating process in low temperature. Therefore, it was expected to use the porous Ag structure to achieve interface bonding with hillocks growth. From this viewpoint, this work examines a bonding technology based on solid porous Ag structure for power electronic modules. In order to ensure that the bonding technology can be used for large area, chip size effect on the bonding strength was investigated for the chip

* Corresponding author.
E-mail address: chenchuantong@sanken.osaka-u.ac.jp (C. Chen).

https://doi.org/10.1016/j.scriptamat.2017.11.035
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varying from 3 × 3 mm^2 to 15 × 15 mm^2. Bonding mechanism was discussed with the three dimensional finite element analyses (3D FEA) and transmission electron microscopy (TEM) observation.

In our experiment, Si dummy chips were prepared by cutting a four-inch Si wafer, with a 0.5 mm thickness, into 3 × 3 mm^2, 6 × 6 mm^2, 10 × 10 mm^2, and 15 × 15 mm^2 pieces. Cu substrates, size 20 mm × 20 mm × 1.5 mm dimensions, were also prepared. With a sputtering process, a Ti metallization layer with a thickness of 100 nm and an Ag layer with a thickness of 1 μm were serially deposited on the surface of Si chips and Cu substrates. The Ti layer will prevent the surface oxidation as well as the diffusion of Cu atoms from the Cu substrate [28]. The sputtered Ag layer can enhance the shear strength between sputtered Ag layer and porous Ag. The Ag paste was then printed on the surface of Cu substrate and Si chip with different sizes, respectively, and sintering was then performed at 250 °C for 1 h under atmospheric conditions. Ag paste was fabricated by mixing two kinds of Ag particles with ethylene glycol (EG, $HOCH_2$-CH_2OH) to improve its printability at a weight ratio of 5:5:1, respectively. One type of particles has a flake shape with an average lateral diameter of 8 μm. The other type is spherical particles which has an average diameter of 0.3 μm [7,29]. The thickness of Ag paste was 0.1 mm. After sintering, Ag paste exhibited a micro-porous structure with a rough surface due to the evaporation of EG organics. The porous Ag was mechanically ground with 1200, 1500, 2000 and 4000 grit SiC papers. After mechanical polishing, a dense Ag layer was formed with the thickness about 2 μm due to the large deformation occurred on the surface of porous Ag. The average surface roughness was measured as 15.3 nm by using atomic force microscope (AFM, Nanocute SII Nano Technology, Japan). The Si chips were then mounted onto the Cu substrate in such a way that both surface polished porous Ag surfaces face each other. The mounted structure was placed on a hotplate and heated at 250 °C for 1 h with a low applied pressure of 0.4 MPa. The die shear strength of the mounted structures was measured by die-shear tests (XD-7500, DAGE) at a shear rate of 50 μm/s. Five specimens were tested for each bonding conditions.

Fig. 1(a) shows the scanning electron microscopy (SEM, SU8020, HITACHI) image of cross-section of interface between two porous Ag structures. The cross-section of the bonded porous Ag interface was prepared by an ion-milling polishing system (IM4000, HITACHI). Fig. 1(b) shows its amplified view in the bridged location. The both surface polished porous Ag layer were bonded together and changed to one large Ag grain at the connection location. Fig. 1(c) shows the SEM image of a larger number of hillocks on the polished surface of non-bonded porous Ag sample. Fig. 1(d) shows the amplified view of some of hillocks. The average diameter of hillocks was about 100 nm. In addition, the chemical element of hillocks was confirmed as Ag by Energy Dispersive X-Ray analysis (EDX, SU8020, HITACHI).

Fig. 2 shows the shear strength of die-attachment structure with different bonding area. The average shear strength was about 25 MPa for the 15 × 15 mm^2 chip size. Error bar in Fig. 2 means the standard deviation of the tested five specimens for each chip size. The shear strength was comparable to that of traditional Sn–Pb solders (19–24 MPa) [30]. The value was also similar with that of Ag sintering technology for sintering Ag nanoparticles under low temperature sintering-bonding process [31,32]. In addition, it was found that the die shear strength did not change significantly with the increased bonding area. This result confirmed that the technology was not influenced by chip size and can thus be used for large area bonding. Because Ag has a high melting temperature (961 °C), the solid porous Ag can be applied in high temperature operation. Therefore, this technology developed in this work can be applied for large area bonding in high temperature operation for the power electronic systems of today.

In this work, the stress distribution for the surface polished porous Ag was analyzed with a 3D finite element simulation to understand the growth mechanism of hillocks. Fig. 3(a) shows the finite element model of surface polished porous Ag structure, which consisted of porous Ag and its polished surface layer. The model of porous Ag referenced the actual porous Ag structure obtained in the following procedures: firstly, the cross-sectional surface was gradually cut with intervals of 500 nm using the focused ion beam (FIB, FIB-2100, HITACHI) and then each cross-sectional image were captured by SEM observation. These cross-sectional images were then combined together to create a porous 3D model with a dimensions of 10 μm × 10 μm × 10 μm. Based on the integral-geometry morphological image analysis method [33–35], the porosity of porous Ag can be calculated as 33.4%.

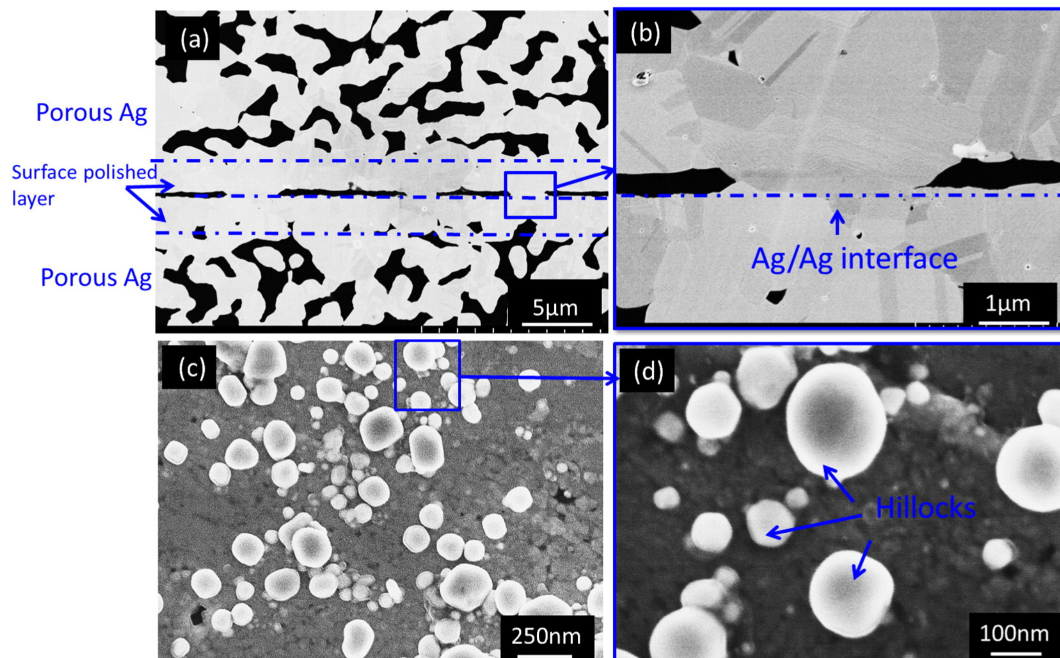

Fig. 1. SEM images of cross-section of bonding interface (a) and its amplified view in the bridged location (b), the surface hillocks growth after the heating process (c) and its local amplified view (d).

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