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Micro-cantilever Bending Test of Sintered Cu nanoparticles for Power Electronic Devices

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Abstract

The application of microporous sintered copper (Cu) as a bonding material to replace conventional die-attach materials in power electronic devices has attracted considerable interest. Many previous studies have focused on the effect of processing parameters (temperature, time, pressure) on the microstructure evolution of sintered Cu. However, there are only a few studies with regard to the mechanical properties of sintered Cu. As the die-attach layer undergoes thermal and mechanical stress during its application, it is essential to investigate the micro-scale mechanical properties of sintered Cu. Fracture toughness is a measure of the resistance of a material to crack propagation under predominantly linear-elastic conditions, which is an essential parameter for predicting fracture failure. As cracks and defects are difficult to avoid during fabrication and application processing for sintered Cu, which will definitely cause a significant effect on micro-mechanical properties. Thus, it is essential to reveal the effect of microstructure on fracture toughess of sintered Cu nanoparticles.

1. Introduction

The emerging field of sintered nanoparticles as an alternative bonding material for wide band-gap power electronics is driven by the limitation of solder materials due to low melting temperatures. As the reliability of solder marterials drops rapidly under the high operating temperature of power electronics, sintered Ag nanoparticles sintering is therefore gaining traction for large-area die or heat sink attach in various analog applications[1]. While sintered Ag nanoparticles (AgNPs) have been shown to have good electrical and thermal properties than solder, the high-cost and the weak durability towards ion migration are still needed to be addressed. In recent years, an emerging low-cost alternative is the sintering of copper nanoparticles (CuNPs)[2]. Sintered CuNPs have been shown to have low electrical resistivity, high thermal conductivity, and strong durability towards ion migration, which make them a suitable replacement for conventional AgNPs materials in high power electronics.

Many studies have been published on the mechanical properties of AgNPs [3-5], for example, Fan et al [3] performed tensile tests of sintered AgNPs under different strain rates. They found the tensile strength of sintered AgNPs samples declines under the low strain rate and higher temperature. The Anand model of AgNP can well represent the mechanical properties of sintered Nano-silver. Jeyun et al [4] compared the sintering mechanism of Ag flake particles with sphere particles. The spherical particles exhibited the necking process followed by conventional diffusion. The flake particles, however, generated AgNPs during the heating process, and these AgNPs accelerated the sintering process. The shear strength of the sintered joints using flake paste measured 45 MPa, obviously superior to 30 MPa achieved with the sphere paste. Moreover, Su et al [5] reported a novel computational framework was proposed to generate the random micro-porous structures and simulate their effects on mechanical properties and fracture behaviour based on the one-cut gaussian random field model and the thermo-elasto-plastic phase-field model. However, there are only a few studies related to CuNPs, especially their mechanical properties.

Because the die-attach layers are fabricated by stacking multiple layers and the bonding process of CuNPs is usually a pressure-assisted process, the pressure is suspected to cause anisotropy in the microstructure of sintered CuNPs. According to a previous study [2], the crack tends to initiate inside the sintered CuNPs due to CTE mismatch among different materials. The orientation of crack propagation depends on the local microstructure, which can be affected by the anisotropy of the microstructure. It is hard to characterize the anisotropy of microstructure-based observation from scanning electron microscopy (SEM) as the porous and the particles are both in tens and hundreds nanometer scale, which makes the statistics and analysis difficult. However, the microscale mechanical test such as microcantilever bending tests can be a very precise technique to reveal the mechanical properties under microscale[6]. Meanwhile, it is hard to get the mechanical properties at the die-attach level using the conventional mechanical test setup due to the sample size limitation. And the mechanical properties of samples under the macroscale will definitely present differences compared with the samples under the microscale due to the size effect. Therefore, it is more reasonable to investigate the mechanical properties at the microscale to ensure the reliable estimation of mechanical failure.

Fracture toughness (K_{IC}) is an important parameter for assessing fracture failure, which describes the ability of a material containing a pre-existing crack to resist crack propagation. Chen et al [7] studied the fracture toughness of sintered AgNPs using micro-cantilever bending tests. They found that fracture toughness decreased as the width of the specimen decreased from 20μm to 5μm. In this study, our objective is to reveal the effect of anisotropy of microstructure on the fracture toughness of sintered

CuNPs. The result helps to understand the crack propagation mechanism of the CuNPs-based die--attach layer during the application.

2. Sample Preparation and Testing set-up

In this study, a sandwich-shaped die-attach structure was fabricated based on pressure-assisted sintering technology. The Cu paste is sintered at 250℃ (25MPa) for 10 minutes under a reducing atmosphere (5% H_2/N_2). Then, the sandwich sample was cut using wire cutting to get the cross-section. Afterwards, the sample was polished by using SiC grinding paper down to 4000 grit and followed by ion milling to get a flat surface. Finally, focused ion beam (FIB) machining was used to prepare the microcantilevers. Fig. 1 shows the diagram of microcantilevers for the in-situ bending test. It is shown that two types of microcantilevers are fabricated. The first type (type A) refers to the microcantilever vertical to the Si chip, which means the crack surface is parallel to the Si chip. The second type (type B) refers to the microcantilever parallel to the Si chip, which means the crack surface is vertical to the Si chip.

The FEI Quanta 200 FEG ESEM scanning electron microscope was utilized to conduct the bending experiments[8]. The experiments were performed in a high vacuum environment and a Kleindiek micromanipulator setup was used. The Kleindiek force measurement sensor (FMS) was used to measure the force, which provides a voltage signal from a bending piezo-electric beam that was applied to the cantilever. The FMS was calibrated against a copper spring with a known spring constant, with an uncertainty of about 10%, and the accuracy of the calibration procedure itself was determined to be in the order of ±5%. Displacements were measured through post-processing of images taken in the SEM at a frequency of 1 Hz during testing. A schematic of the experimental setup is shown in Fig. 2

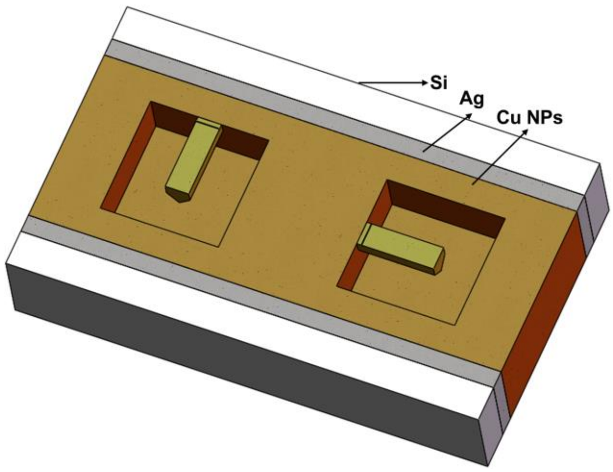

Fig. 1. Diagram of microcantilevers for the in-situ bending test.

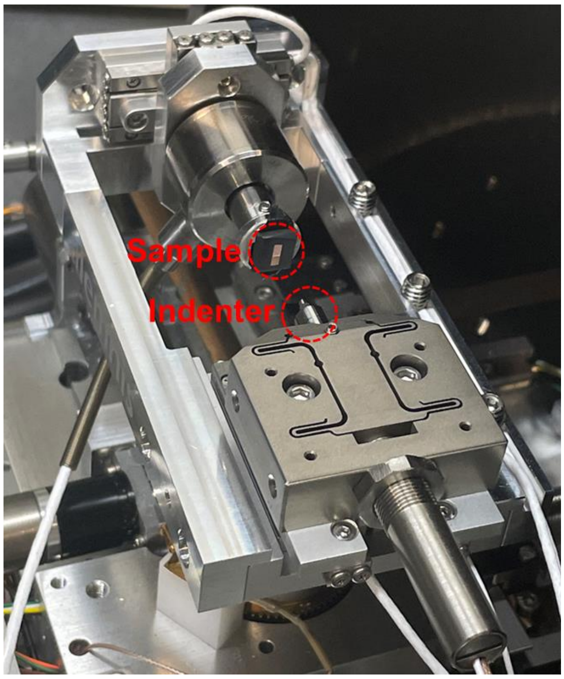

Fig. 2. Experimental setup.

3. Results and Discussion

The stress intensity factor is a function of applied stresses, crack size, and component geometry. According to the Griffith and Irwin fracture criterion, failure or fracture of the component is inevitable when the stress intensity factor exceeds the fracture toughness of the specimen. Therefore, the fracture toughness is calculated when the load reaches its maximum value. For microscale specimens, K_{IC} is calculated according to the following equations[6]:

$$K_{IC} = \frac{Fl}{wh^{3/2}} f\left(\frac{a}{h}\right) \quad (1)$$

$$f\left(\frac{a}{h}\right) = 1.46 + 24.36\frac{a}{h} - 47.21\left(\frac{a}{h}\right)^2 + 75.18\left(\frac{a}{h}\right)^3 \quad (2)$$

where the beam length l, the beam height h, the crack length a and the beam width w are the dimensions of the beam, and the maximum load is denoted with F.

Fig. 3 shows the load-displacement curves obtained from the bending test for the different specimens. The angle in the figure represents the angle between the long axis and the Si chip. Therefore, 90° refers to the type A sample and 0° refers to the type B sample. Results show that the microcantilever situated vertically to the Si chip presents significantly higher strength than that of a microcantilever located parallel to the Si chip. Fig. 4 presents the fracture toughness of sintered CuNPs for microcantilevers with different orientations. The fracture toughness was calculated from Eq. (1) and the maximum load, F_{max}, was taken from the load-displacement curves. The K_{IC} was 2.06 MPa $m^{1/2}$ for the type A sample and 1.27 MPa $m^{1/2}$ for the type B sample. The big difference between type A and type B samples proves the presence of microstructure anisotropy. Thus, the ability to resist crack propagation of the sintered CuNPs presents anisotropy, which is due to the microstructure anisotropy. This finding provides a valuable reference for the failure analysis and prediction of the CuNPs-based die-attach layers.

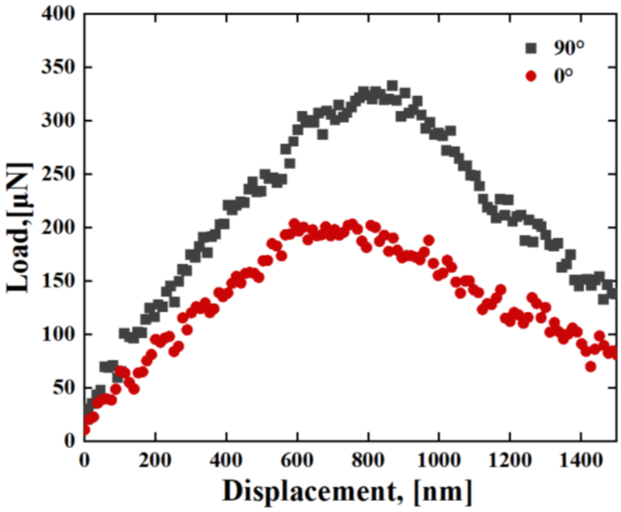

Fig. 3. Load-displacement curves obtained from the bending test for the microcantilevers with different orientations.

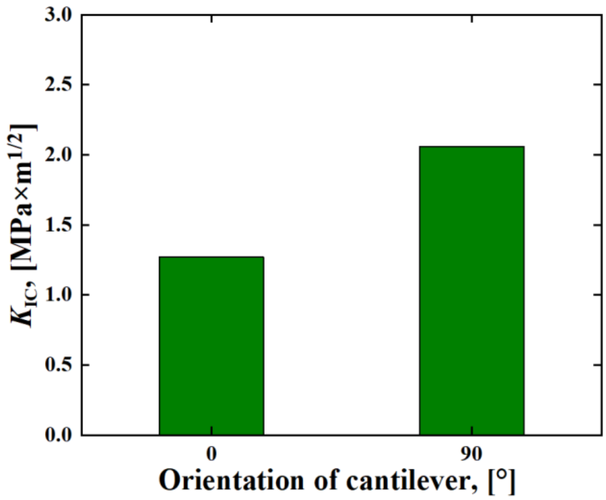

Fig. 4. Fracture toughness of sintered CuNPs for microcantilevers with different orientations.

Fig. 5a shows the SEM image of the microcantilever before the bending test. A pre-crack is fabricated close to the fixed end. Fig. 6(a) shows an SEM image of the microcantilever specimen after the bending test. The microcantilever beam fractured from the location of the pre-crack. The porous dominate the crack propagation path, which provides a rapid expansion path. The next step is to investigate the mechanism behind the anisotropy of fracture tougheness. It is critical to consider the anisotropy of fracture toughness when studying the crack initiation and propagation issue for sintered CuNPs.

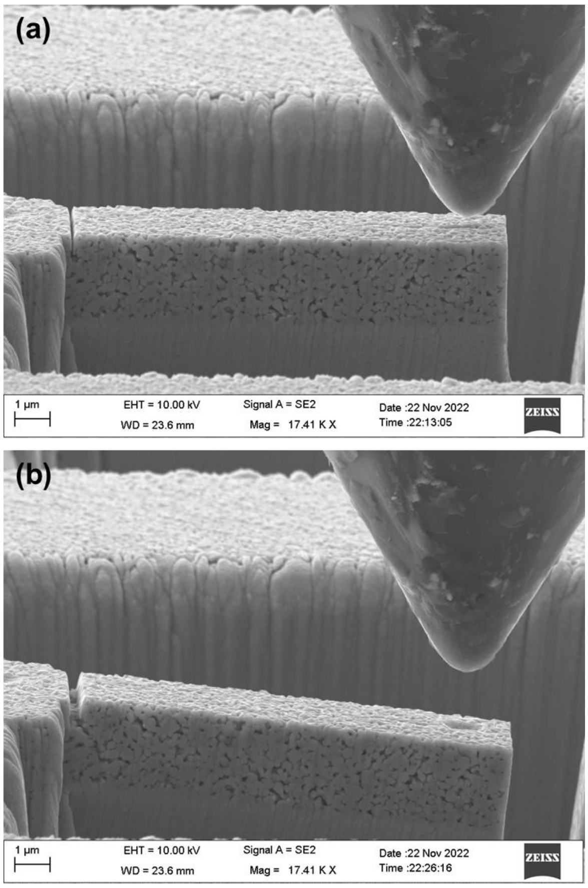

Fig. 5. SEM images of the microcantilevers, (a) before the bending test; (b) after the bending test.

4. Conclusions

In this paper, the effect of microstructure anisotropy on the fracture toughness of sintered CuNPs was studied by using microcantilever bending tests. Results show that the ability to resist crack propagation is better when the crack surface is parallel to the Si chip compared with the crack surface being vertical to the Si chip. This finding provides a novel understanding of the mechanical analysis of pressure-assisted sintered CuNPs.

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