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Proceedings of NMJ 2012
Dec. 2-5, 2012, Beijing, China

NEiJ-05

Ag Nanoparticles and their Application in Low-Temperature Bonding of Cu

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Keywords: Ag Nanoparticles, Sintering, Melting theories, Surface premelting, MD simulation.

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1. Introduction

The main objective of the current work is to develop a low cost bonding method that can be used in electronic industry[1]. This will be achieved by fabricating a dense Ag nanoparticles (NPs) paste and use it to bond thin Cu wires to Cu substrate at temperatures below 523 K [2]. Unlike conventional soldering techniques, these bonds should also withstand temperatures that are higher than the bonding temperature [3]. On the other hand, thermal properties of Ag NPs such as melting, and surface premelting will be studied by using a molecular dynamic (MD) code [4]. These properties are expected to have a strong effect on the joint strength.
Materials properties such as melting points, mechanical properties, and electrical properties change at nanoscale. The bulk material properties and the theoretical models found in literature may not be valid for nanomaterials. Melting of a NP starts at the surface by forming a thin liquid layer, which expands to the core and complete full transition of the structure from solid to liquid. This initial stage of melting is called surface premelting which initiates in order to reduce the total interfacial energy of the material. The diversity of the analytical models found in literature for determining melting point (T_m) of NPs and the different results that can be obtained by them, makes it difficult to decide which model can correctly predict T_m. Also, the kinetics of surface premelting of Ag NPs is still not well understood and at what ranges of temperatures it occurs.

2. Experiments

The Ag NP paste was simply fabricated by increasing the concentration of the Ag NP sol from 0.001 vol.% to 0.1 vol.% by centrifugation. A centrifugal force of 1700 × g was applied for 30 min on 15-mL centrifuge tubes (length 118.54 mm, outer diameter 15.62 mm) filled with 0.001 vol.% sol. As a result of the centrifugal force, the Ag NPs condensed at tubes, the bottom of the centrifuge leaving only water on top. The water was extracted from the centrifuge tubes using a pipette, leaving 0.15 mL 0.1% Ag NP sol (Ag NP paste) at the bottom. The carrier of the Ag NP paste was just water. This paste was used for all experiments in this work. After depositing the Ag NPs onto the Cu foil, the Cu wire was mounted on the Ag NP paste and clamped by a 2-inch screw clamp. The pressure exerted on the sample was 5 MPa, which was determined by dividing the applied force by the area of the ceramic piece. The applied force was measured using a load cell. A torque wrench was used to tighten the screw and thus to exert the same force on all samples. The clamped sample was then heated at the bonding temperature for 30 min. The Ag atoms in the NPs were arranged as an FCC truncated Marks decahedra (Dh) that defines planes (111) and (100) as surface facets. We have made use of a linear scaling parallel MD code to investigate melting and surface premelting behaviours of the NPs. The code was based on Voter-Chen version of the embedded atom method (EAM) potential.

3. Results and Discussion

TEM images of the interfaces of a joint bonded at 523 K are shown in Fig. 1 between 50-μm Cu wire and Ag NPs. Close contact at the lattice level between Ag and Cu is shown in Fig. 1. High-resolution TEM images show that both Cu wire and Cu foil are nanocrystalline. This may have enhanced the diffusion process with the Ag NPs. The dark areas on both sides of the interface were caused by the nonuniform thickness of the TEM sample.

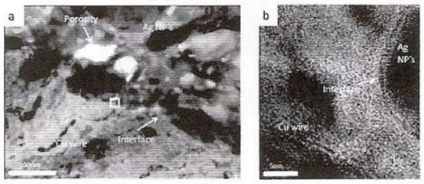

Fig. 1. TEM images of Cu wire–Ag interface (a) at low resolution and (b) at high resolution.

T_m and T_{sm} obtained by our simulation are compared to the theoretical models at Fig. 4.6. T_m obtained by our simulation approach the bulk melting temperature (1235 K) as the NP size reach 20 nm. They also show good agreement with the liquid drop model and Shi's model for NPs smaller than 8 nm and with Hanszen's model for larger particles. T_{sm} occurred at lower temperature than T_m for 8 nm NPs and larger. The difference between T_m and T_{sm} increased as the NPs size increased and T_m for larger particles approach the melting point of bulk. Fig. 2 also shows that surface premelting did not occur for NPs smaller than 8 nm.

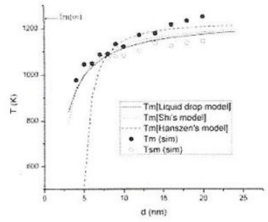

Fig. 2. Melting and surface permelting dependence on the size of Ag NPs determined by our simulation and by the other theoretical models.

4. Conclusions

Cu wire and Cu foil were successfully bonded together by soild state sintering of Ag NPs paste at low temperatures down to 433 K. The microstructure analysis of the cross sectional area of the joint confirmed the metallic bond between the Ag NPs and the Cu. Bonds that are formed by sintering of Ag NPs are proved to withstand higher temperatures than the bonding temperatures. Melting and surface premelting temperatures of different sizes of Ag NPs were determined by MD simulation. Melting points of NPs approached the bulk melting temperature (1235 K) as the size of the NP increased to 20 nm. T_{sm} was determined at the temperature at which a liquid layer of 2 nm thickness is formed. TAg NPs that are smaller than 8 nm did not pass through the surface premelting stage. This confirms the previous theory that estimated the critical radius for Ag as 3.62 nm.

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