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Ultrafast formation of unidirectional and reliable Cu_3Sn-based intermetallic joints assisted by electric current

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ABSTRACT

High-temperature-stable Cu_3Sn-based joints were selectively fabricated using electric current-assisted bonding process within an extremely short time (~200 ms) and under a low pressure of 0.08 MPa in a Cu/Sn/Cu interconnection system at ambient temperature. The experimental results showed that the imposed electric current density (~10^4 A/cm^2) resulted in sharply increased local temperature as well as accelerated growth of Cu_3Sn intermetallic compounds (IMCs). Under the effects of electron wind force-induced electromigration and joule heat-induced temperature, the transient formation of Cu_3Sn-based joints can thus be obtained across the interfaces. Furthermore, highly unidirectional ⟨1 0 0⟩ growth of Cu_3Sn IMCs was achieved along the direction of electron flow. By calculating the planar atomic densities of projected images on different planes, the particular growth direction was confirmed to represent the low-scattering path for the traveling electron flow. The oriented Cu_3Sn-based joints exhibited more reliable shear properties than the Sn-based joints.

1. Introduction

With two-dimensional, very large-scale integration circuits (ICs) approaching the limit of Moore's Law, three-dimensional (3D) ICs based on chip stacking are undergoing extensive research and development [1]. For 3D chip stacking technology, high-temperature-stable circuit interconnections are highly desirable for withstanding the multiple melting risk of solder joints in previously bonded chips during subsequent chip stacking processes [2,3]. Recently, this technical requirement has been satisfied by forming high–melting point intermetallic compound (IMC) joints through solder reflowing or transient liquid phase (TLP) bonding processes at relatively low temperatures (~300 °C) [4–6]. The Cu-Sn IMCs such as Cu_3Sn and Cu_6Sn_5 are widely used interconnection materials in 3D ICs and have better properties than Sn-based solders in terms of melting temperature, hardness, yield strength and Young's modulus [7–9]. Specifically, Cu_3Sn, with good thermal stability up to 600 °C, is a more promising candidate because of its higher fracture toughness, elastic modulus, and lower electrical resistivity compared to Cu_6Sn_5 [4,7,8,10]. However, the long bonding time (>100 min) of the transient liquid phase process for forming Cu_3Sn joints not only hinders wide application in electronic packaging but also seriously affects the reliability of the packaging system [11–13].

Conversely, as the diameter of solder joints on stacked chips downsizes from 100 μm to 1 μm in the future, each solder joint may contain only a few grains [1,14,15]. The orientation of IMCs thus plays a critical role in the performance of joints, e.g., mechanical strength [16,17], electrical conductivity [18], and electromigration resistance [19–21]. However, maintaining control over the textured microstructure of IMCs is nontrivial under traditional reflowing conditions or TLP bonding processes.

Recently, several studies applying electric current to the metallic liquid-solid reaction systems have indicated rapid formation of unidirectional IMC joints. The applied electric current can enhance mass transport through electron wind-induced electromigration (EM), point defect generation, and defect mobility [22,23]. Under the effect of EM, dissolution and diffusion of the base metals such as Cu, Ni, and Au can be significantly enhanced in the molten solder interlayer [24,25]. Once the concentration of solutes in the molten solder increases to a certain level, the base metal solute atoms in the molten solder precipitate as IMCs, which combines with the accelerated growth rate of the interfacial IMC layer. In the Cu/molten Sn/Cu reaction system, the thickness of Cu_6Sn_5 at the anode

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interface can be increased to 110 μm under current stressing (~10^2 A/cm^2) for 1 h at relatively low operating temperatures (~250 °C) [26]. When the operating temperature is above 415 °C, the thermodynamic stable Cu_3Sn compounds are primarily formed [27]. Liu et al. [18] used the liquid-phase electroepitaxy method to obtain highly oriented Cu_6Sn_5 and Cu_3Sn at different temperatures. After a long heating period at 500 °C, the epitaxial-grown Cu_3Sn can grow in particular directions with respect to the electron flow.

The present work investigates the ultrafast fabrication of IMC joints using an electric current-assisted bonding process at ambient temperature. By carefully controlling the current densities (~10^4 A/cm^2), the expected temperatures corresponding to different IMC microstructures are achieved within a very short duration (~ms). This study is focused on the thermal-electric interaction at the solid Cu/liquid Sn solder interface, which is crucial for the transient formation and unidirectional growth of IMC joints. The methodology and understanding developed in this work are also applicable to the similar metallic interconnection systems with low-melting point solder interlayers.

2. Materials and methods

As shown in the inserted schematic of Fig. 1a, a sandwiched Cu/Sn/Cu structure was used in this experiment. After carefully polishing the polycrystalline Cu slices (2.5 × 2.5 × 0.5 mm^3), one piece of 30-μm-thick pure Sn foil was sandwiched as a solder interlayer. Then, the sandwiched structure was bonded by an electric current-assisted bonding process at ambient temperature. The electric current was supplied by a micro-resistance spot welding resistance system (Unitek Equipment HF25). As shown in Fig. 1a, DC pulsed currents of 810, 875 and 950 A were carefully controlled and applied to the Cu/Sn/Cu samples (the dotted arrows marked by "e^-" indicate the electron flow direction). The electrons entered the sandwiched sample from the cathode electrode on the upper side, passing through the Sn interlayer (2.5 × 2.5 mm^2 in area), and exited through the anode electrode on the bottom side (anode). Thus, the average current densities in the Sn interlayer were 1.3, 1.4, and 1.5 × 10^4 A/cm^2. The pressure applied on the sandwiched sample via the upper electrode was 0.08 MPa, and the total bonding times were fixed as 100 ms and 200 ms. As shown in the waveform of the bonding current in Fig. 1a, the applied current density increased to the given value in 10 ms, held constant for 80–180 ms, and then decreased to zero in 10 ms. After the bonding process, the samples were air cooled to room temperature.

To clearly observe the microstructure evolution of Cu-Sn IMCs, the cross-sectional Cu/Sn/Cu joint after 100 ms were deeply etched with 5 g $FeCl_3$ + 15 mL vol% HCl +85 mL deionized water to remove the excess Sn solder. The microstructures of the samples were characterized by scanning electron microscopy (SEM, FEI Quanta 200 FEG), X-ray diffraction (XRD, Bruker D8 Advance), and transmission electron microscopy (TEM, FEI Tecnai G2 F30, 300 KV, and JEOL JEM-2100, 200 KV). The TEM specimens were prepared by a dual beam focused-ion-beam (FIB, FEI Helios Nanolab 600i). Electron backscatter diffraction (EBSD) was used to analyze the statistical distributions of the IMC grain orientations. In addition, the corresponding overlap joints were designed to measure the shear strength using an Instron-5948 Micro-Tester with a loading rate of 100 μm/s.

3. Results and discussion

3.1. Appropriate bonding temperatures induced by the joule heating effect

To obtain the appropriate bonding temperature, an FLIR A615 infrared thermal imaging camera was used to measure the bulk temperatures of samples during the bonding process. Because the dimension of the Cu substrates was much larger than that of the Sn interlayer, the camera emissivity was set equal to the Cu emissivity value of 0.65. The temperature data were acquired at a rate of 200 fps (frames per second). Fig. 1b shows that the bonding temperatures increased above the Sn melting point (232 °C) within 50 ms, and the peak temperatures were dominated by the current densities. When the current flowed through the conductive Cu/Sn/Cu joint, sufficient joule heat was generated at the Cu/Sn and electrode/Cu interfaces due to their larger contact resistances. For the current density of 1.3 × 10^4 A/cm^2, the peak temperature reached 290 °C. For the higher current density from 1.4 to 1.5 × 10^4 A/cm^2, the peak temperatures of 420 °C and 510 °C, respectively, were between the melting temperatures of Cu_6Sn_5 (415 °C) and Cu_3Sn (679 °C). After the short metallurgical reaction between solid Cu and molten Sn, solder joints with different microstructures were expected. No fluxes were used in this experiment because the sparking plasma generated by the pulsed current at the Cu/Sn interfaces can remove surface oxide layers [22].

3.2. Ultrafast formation of Cu_3Sn-based joints

Fig. 2 shows the cross-sectional SEM images of deep-etched Cu/Sn/Cu joints after bonding for 100 ms under different current

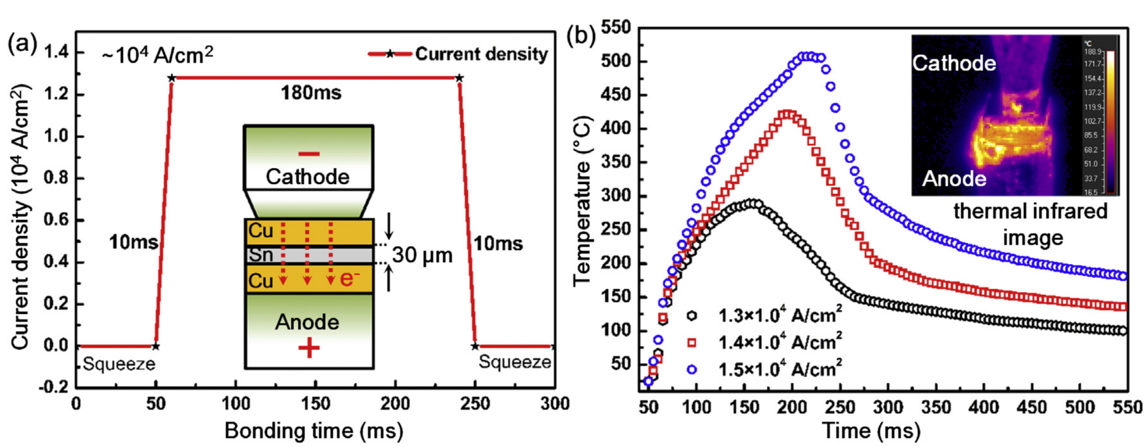

Fig. 1. (a) Schematic of the Cu/Sn/Cu configuration used and the waveform of the bonding current; (b) the overall temperature profiles of Cu/Sn/Cu joints during the bonding process.