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Microstructural and mechanical integrity of Cu/Cu interconnects formed by self-propagating exothermic reaction methods

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ABSTRACT

A rapid and flexible Cu/Cu soldering process has been developed through self-propagating exothermic reaction (SPER) using Al–Ni multilayer nano-film as heat source. The localized intensive heat generated by SPER has a short affecting time and thus a low thermal impact, which promises various potential benefits for electronics interconnects, including the reduction of stress caused by CTE (coefficient of thermal expansion) mismatch and the high temperature soldering by reflow process. In this study, the strong metallurgical Cu/Cu joining interfaces of hundreds nanometers IMCs (intermetallic compounds) layers were formed, which exhibit a shear strength greater than 32 MPa. This work has also characterized the interfacial IMC morphology, thickness, porosity and the fracture behaviour of the joint to allow an analysis and evaluation of the feasibility and reliability of SPER interconnects. In addition, the formation mechanisms of defects and the influence of applied pressure, solder thickness and ambient temperature in SPER process have been investigated, which can further assist the optimization of process and the improvement of joining quality.

1. Introduction

Joining methods based on self-propagating exothermic reactions (SPERs) have been attractive to enhance the solderability, thermo-stability as well as reduce the mismatch of CTEs (coefficient of thermal expansions) among substrate materials [1–4]. During the SPER process, the chemical reaction is ignited by an electronic spark or laser beam, and produces a rapid burst of energy. This local heat will then melt surrounding materials such as inserted solders or substrates to form a metallurgical bond after a rapid cooling.

Compared to the traditional joining processes, the reaction velocity of SPER can be as high as 30 m/s, the maximum local temperature can reach 1400 °C prior to cooling to room temperature within 50 ms, and the thermal affected zone is confirmed within a 0.1 mm area [5–9]. Therefore, as a rapid and localized heat source, SPER can be a unique bonding process for high temperature interconnections of devices having special structure or heat sensitive components, such as the interconnects of ceramic, infrared sensor, wafer and heat sink [10–12].

Al–Ni nano-film, which is the most widely used SPER materials, is suitable for electronics interconnects owning to its high thermal efficiency and uniform reaction products. Wang had used Al–Ni nano-films with different thickness to bond stainless-steels at room temperature, by which the shear strength could reach 48 MPa [13]. Qiu and Wang achieved the bonding of silicon wafers using SPER with AuSn solder layer and UBM (under bump metal) [14]. Besides, there have been more published works which are concerned about the joining of glasses, Ti, super-alloy, intermetallic [15–19] and the reaction mechanism of SPER nano-film [20–25]. However, although the metallurgical interconnections were achieved in all these attempts, many voids and cracks formed in the joints and thus significantly reduced the strength and reliability of the obtained SPER joints. And the feasibility and optimization of SPER process need to be further investigated, which will ultimately govern the performance of the obtained interconnects in terms of their reliability and thermostability, especially for bonding between heat-sensitive MEMS or high-power large size BGA with a heat sink.

In this paper, Cu/Cu joints were interconnected using SPER process under different processing parameters to enable the application of SPER bonding in high-power devices. The morphology, total thickness and porosity of the interconnected joints were analyzed, and soldering behaviour, interfacial reactions and the effect

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of SPER processing parameters were investigated. To evaluate the bonding strength and fracture mode, mechanical shear tests were also carried out, which can be utilized to verify the quality and reliability of SPER joints. Based on these results, the reduction of thickness and defects can be finally achieved to improve the reliability and the thermal properties of joints through the optimization of SPER joining process.

2. Experimental methods

2.1. Material preparation

During the SPER joining process, the Al–Ni nano-film (supplied by Indium Corporation) provides intensive heat source for re-melting of solder alloy and its bonding with substrates. As shown schematically in Fig. 1, the 60 μm Al–Ni nano-film consisting 600 Al–Ni bilayers (100 nm thick per bilayer) was electro-coated with 10 μm thick Sn layers on either sides prior to the SPER process to enhance the wetting of solder on Al–Ni nano-film. And the thickness ratio of Al and Ni was controlled at 3:2 in each bilayer in order to maintain 1:1 atomic ratio between Al and Ni.

Copper sheets of 0.1 mm and 1.0 mm thick (99.95 wt.%) with different sizes were prepared before they can be processed for SPER joining. The dimensions of the Cu substrate on the top (10 mm × 8 mm) was designed slightly smaller than the bottom substrate (10 mm × 12 mm), which can allow the shear tests for strength evaluation. Finally, pure Sn was coated onto copper surfaces as inserted solder interlayers using electro-deposition.

2.2. SPER Joining process

As shown schematically in Fig. 2, by inserting the Sn coated Al–Ni nano-films between two copper substrates prepared above, the SPER joining process can be initiated to form solder joints. Before SPER joining, the entire structure was preheated under an applied pressure to enhance the wetting and melting of Sn. And the SPER was subsequently ignited in air using a spark produced by a DC power supplier. Details of ambient temperature, applied pressure and solder used for SPER joining are provided in Table 1.

2.3. Test methods

After SPER joining, these bonded Cu/Cu joints were analyzed by a Sonoscan D9500 CSAM (C-type Scanning Acoustic Microscope) to assess the porosity and then tested in tension at room temperature to get their shear strength using a tensile machine with shear speed at 5 mm/min. Cross-sections of Cu/Cu SPER joints were further characterized using a JEOL-SEM 7600F to observe the IMCs, microstructure, fracture surface as well as the defects. Meanwhile, chemical composition of phases and the thickness of joints were also measured using EDX and SEM.

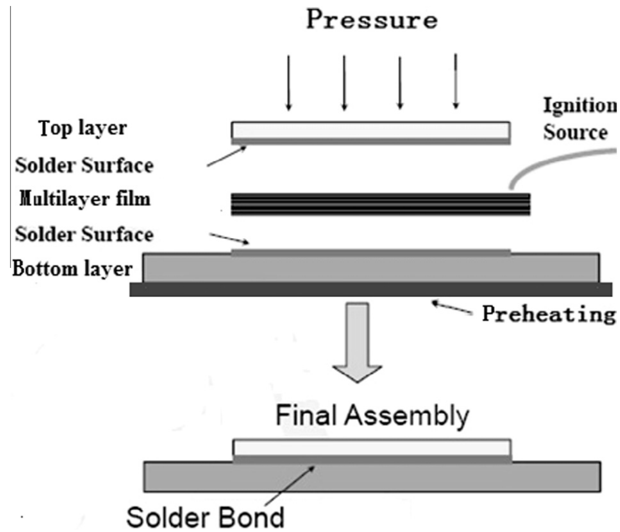

Fig. 2. Schematic of SPER joining process: stacking base materials with preheating and applied pressure.

Table 1
The processing parameters for Cu/Cu SPER joining.

Solder material	Thickness (μm)	Type	Ambient temperature (°C)	Applied pressure (MPa)
Sn	10/20/30	Electro-plating	25/50/75/100/125/150	0.1/0.25/0.4/0.5/0.75/1

3. Results and discussion

From the typical cross-section shown in Fig. 3, high-quality Cu/Cu SPER joints were obtained using Al/Ni nano-film as the heat source. During SPER process, the reactions of nano-film provided sufficient energy for melting Sn layers. The molten Sn then reacted with substrates and flew to fill large-size defects (e.g. air gaps, cracks) under applied pressure. Therefore, Cu/Cu joints with interfacial IMC layers and dense solder layers can be formed, indicating the reliable metallurgical interconnection between Cu substrates.

However, the potential defects, mainly voids and cracks, can still be generated in the solder layer or at interfaces of joints. In rapid heating and cooling process during SPER joining, the air trapped at the interfaces of Cu/Sn and Sn/nano-film before reaction are difficult to escape during the rapid solidification, thus they remained as voids or cracks in the solder layer. In addition, due to the volume shrinkage of Al–Ni alloy in nano-film, relative sizable cracks across nano-film were also formed after SPER process.

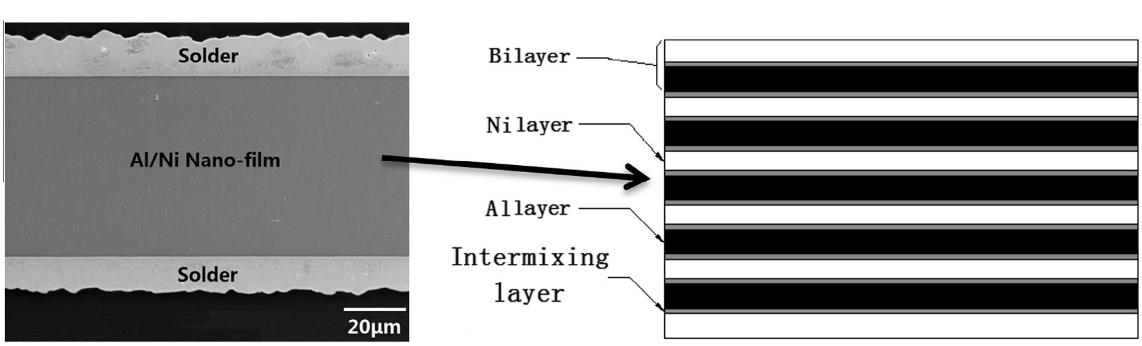

Fig. 1. Al/Ni nano-films used in the SPER: cross-sectional SEM image and the schematic illustration of the multi-layered structure.