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Different Diffusion Behavior of Cu and Ni Undergoing Liquid−solid Electromigration

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The diffusion behavior of Cu and Ni atoms undergoing liquid−solid electromigration (L-S EM) was investigated using Cu/Sn/Ni interconnects under a current density of 5.0 × 10^3 A/cm^2 at 250 °C. The flowing direction of electrons significantly influences the cross-solder interaction of Cu and Ni atoms, i.e., under downwind diffusion, both Cu and Ni atoms can diffuse to the opposite interfaces; while under upwind diffusion, Cu atoms but not Ni atoms can diffuse to the opposite interface. When electrons flow from the Cu to the Ni, only Cu atoms diffuse to the opposite anode Ni interface, resulting in the transformation of interfacial intermetallic compound (IMC) from Ni_3Sn_4 into $(Cu,Ni)_6Sn_5$ and further into [$(Cu,Ni)_6Sn_5$ + Cu_6Sn_5], while no Ni atoms diffuse to the opposite cathode Cu interface and thus the interfacial Cu_6Sn_5 remained. When electrons flow from the Ni to the Cu, both Cu and Ni atoms diffuse to the opposite interfaces, resulting in the interfacial IMC transformation from initial Cu_6Sn_5 into $(Cu,Ni)_6Sn_5$ and further into [$(Cu,Ni)_6Sn_5$ + $(Ni,Cu)_3Sn_4$] at the anode Cu interface while that from initial Ni_3Sn_4 into $(Cu,Ni)_6Sn_5$ and further into $(Ni,Cu)_3Sn_4$ at the cathode Ni interface. It is more damaging with electrons flowing from the Cu to the Ni than the other way.

KEY WORDS: Cu/Sn/Ni; Electromigration; Cross-solder interaction; Interfacial reaction; Diffusion

1. Introduction

With the continuous miniaturization of electronic devices, the diameter of solder joints has been downsized to less than 100 μm, which is known as micro bumps. Meanwhile, the current density through each solder bump is increasing even up to 10^4 A/cm^2, which causes a more serious Joule heating effect during electromigration (EM)[1−3]. The solder bumps with low melting point might locally melt under such a serious Joule heating effect and consequently cause early failure of solder joints. The solder melting phenomenon induced by solid−solid electromigration (S−S EM) has become one of the main failure modes[4,5]. Due to surface tension, the solder joint maintains its initial shape even after melting, resulting in the transformation of S−S EM into liquid−solid electromigration (L-S EM).

Since the diffusivity of atoms in liquid is several orders of magnitude larger than that in solid[6], the interfacial reaction and failure mechanism induced by L-S EM are greatly different from those induced by S−S EM. For instance, Huang et al.[7−9] reported that an abnormal diffusion behavior of Zn atoms was observed in Cu/Sn−9Zn/Cu and Cu/Sn−9Zn/Ni interconnects undergoing L-S EM; Gu and Chan[10] reported that two separate Bi-rich layers formed at the anode when undergoing L-S EM at 140 °C, but only one Bi-rich layer formed when undergoing S−S EM at 75 °C; Liao et al.[11] characterized the preferential Pb migration toward the anode in eutectic Sn−Pb molten solder undergoing L-S EM, and the effective charge number of Pb was calculated to be 2.7, which is one order of magnitude lower than the reported value of 47 for self-electromigration in bulk Pb; Huang et al.[12] investigated the interfacial reaction in Cu/Sn−3.5Ag/Cu interconnects undergoing L-S EM, and found that the dissolution rate of the cathode Cu was one order of magnitude faster than that undergoing S−S EM. Since the damage of solder interconnects induced by L-S EM is more serious than that induced by S−S EM, it is critical to understand the fundamental aspects of L-S EM.

The Cu/solder/Ni structure is widely applied in chip interconnects, and previous studies have shown that the Cu−Ni cross-solder interaction occurred and thus affected the interfacial reaction during wetting reaction, solid−solid reaction and S−S EM[5,13−15]. Lin et al.[5] investigated the cross-solder interaction

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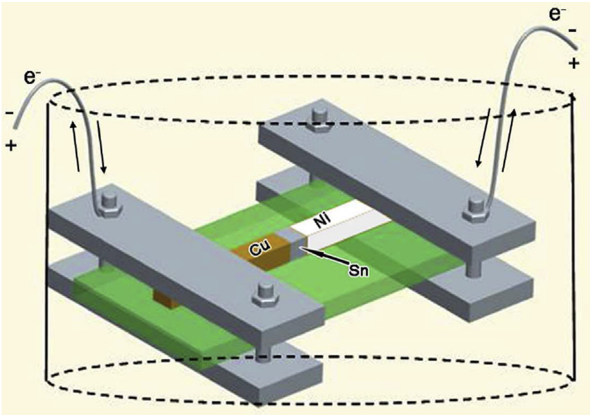

Fig. 1 Schematic of experimental configuration.

between Cu and Ni in Cu/Sn−37Pb/Ni flip chip solder joints and found that when electrons flowed from the Cu to the Ni, EM-induced failure occurred at the cathode Cu interface, while there was no evidence of microstructure change when the electrons flowed from the Ni to the Cu. Wu et al.[15] reported that EM effects significantly enhance the diffusion rate of Cu when the electrons flowed from the Cu to the Ni, promoting the cross-solder interaction between Cu and Ni in Cu/Sn/Ni interconnects. It is indicated that the EM-induced failure mechanism of Cu/solder/Ni flip chip joints strongly depended on the current direction. However, there is no literature on the Cu−Ni interaction undergoing L-S EM. In the present work, the different diffusion behavior of Cu and Ni atoms as well as Cu−Ni cross-solder interaction in Cu/Sn/Ni interconnects undergoing L-S EM was investigated.

2. Experimental

Line-type Cu/Sn/Ni interconnects were prepared by immersion soldering at 250 °C for 10 s. The EM specimens were prepared in the same way as described in the previous study[16]. The cross-section of EM specimens was 300 μm × 300 μm, and the Sn solder between the Cu and Ni substrates was 200 μm thick. Fig. 1 shows the schematic of the experimental configuration. The EM experiments were conducted in silicone oil under a current density of 5.0×10^3 A/cm^2, and the temperature of EM specimens was maintained at 250 ± 2 °C, which was monitored by a thermocouple. The EM duration ranged from 10 min to 4 h. Reference experiments without electron current stressing were conducted at the same temperature for comparison.

The microstructural evolutions of line-type Cu/Sn/Ni interconnects undergoing L-S EM and L-S reaction were examined by scanning electron microscopy (SEM, JSM-5600LV) operated at 15 keV. Electron probe microanalysis (EPMA, EPMA-1600) was used to identify the compositions of the phases. The area of the interfacial intermetallic compound (IMC) layer was measured using image processing software, and the average thickness was determined by dividing the area by the line length of the interface.

3. Results and Discussion

3.1. Microstructure of as-soldered interconnect

Fig. 2 shows the cross-sectional microstructure of an as-soldered Cu/Sn/Ni interconnect. A Cu_6Sn_5 layer of 0.30 μm in thickness formed at the Cu interface, while a Ni_3Sn_4 layer of 0.25 μm in thickness formed at the Ni interface. Obviously, no Cu and Ni atoms diffused to the opposite interfaces in the as-soldered Cu/Sn/Ni interconnect, i.e., no Cu−Ni cross-solder interaction occurred during immersion soldering.

3.2. Liquid-solid interfacial reactions without EM

Fig. 3 shows the microstructural evolution of the interfacial IMCs undergoing L-S reaction (without electron current) at 250 °C for various times. The interfacial IMCs gradually grew thicker with increasing time. After L-S reaction for 10 min (Fig. 3(a) and (b)), Cu atoms dissolved into the solder from the Cu substrate and diffused to the opposite Ni interface, resulting in the interfacial IMC transformation from initial Ni_3Sn_4 into $(Cu_{0.83}Ni_{0.17})_6Sn_5$. Similar dissolution and diffusion process of Ni atoms also occurred, resulting in the formation of $(Cu_{0.92}Ni_{0.08})_6Sn_5$ instead of Cu_6Sn_5 at the Cu interface. The average thicknesses of IMCs at the Ni and Cu interfaces were 2.59 μm and 4.88 μm, respectively. Additionally, some large IMC particles were observed in the Sn matrix, which precipitated during solidification. After L-S reaction for 1 h (Fig. 3(c) and (d)), the average thicknesses of $(Cu_{0.85}Ni_{0.15})_6Sn_5$ IMC at the Ni interface and $(Cu_{0.90}Ni_{0.10})_6Sn_5$ IMC at the Cu interface grew to 6.89 μm and 8.26 μm, respectively. After L-S reaction for 2 h (Fig. 3(e) and (f)), the thicknesses of $(Cu_{0.87}Ni_{0.13})_6Sn_5$ IMC at the Ni interface and $(Cu_{0.92}Ni_{0.08})_6Sn_5$ IMC at the Cu interface continuously increased to 10.33 μm and 11.31 μm, respectively. With increasing reaction time to 4 h (Fig. 3(g) and (h)), the average thicknesses of $(Cu_{0.73}Ni_{0.27})_6Sn_5$ at the Ni interface and $(Cu_{0.91}Ni_{0.09})_6Sn_5$ at the Cu interface reached 17.54 μm and 12.22 μm, respectively. There was no obvious Cu_3Sn layer formed at the Cu interface. Wang et al.[13] investigated the Cu−

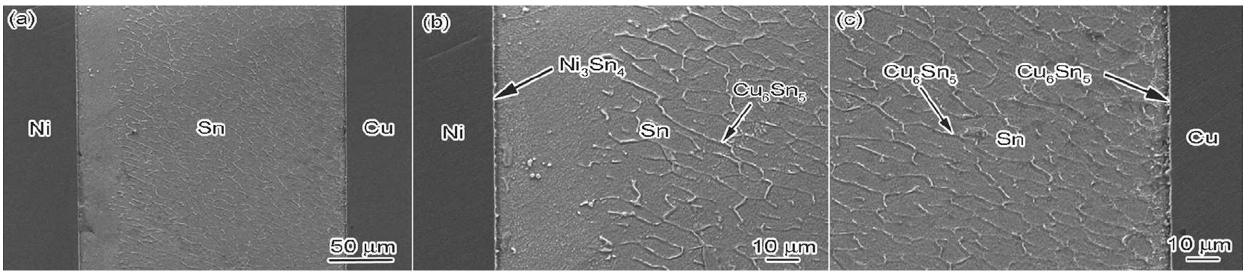

Fig. 2 Microstructure of as-soldered Cu/Sn/Ni interconnect: (a) macrograph; (b) Ni/Sn interface and (c) Sn/Cu interface.