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Mechanism of improved electromigration reliability using Fe-Ni UBM in wafer level package

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ABSTRACT

Fe-Ni films with compositions of 73 wt% of Ni and 45 wt% of Ni were used as under bump metallization (UBM) in wafer level chip scale package, and their reliability was evaluated through electromigration (EM) test compared with commercial Cu UBM. For Sn3.8Ag0.7Cu(SAC)/Cu solder joints, voids had initiated at Cu cathode after 300 h and typical failures of depletion of Cu cathode and cracks were detected after 1000 h EM. While the SAC/Fe-Ni solder joints kept at a perfect condition without any failures after 1000 h EM. Moreover, the characteristic lifetime calculated by Weibull analysis for Fe-73Ni UBM (2121 h), Fe-45Ni UBM (2340 h) were both over three folds to Cu UBM's (698 h). The failure modes for Fe-Ni solder joints varied with the different growth behavior of intermetallic compounds (IMCs), which can all be classified as the crack at the cathodic interface between solder and outer IMC layer. The atomic fluxes concerned cathode dissolution and crack initiation were analyzed. When Fe-Ni UBM was added, cathode dissolution was suppressed due to the low diffusivity of IMCs and opposite transferring direction to electron flow of Fe atoms. The smaller EM flux within solder material led a smaller vacancy flux in Fe-Ni solder joints, which can explain the delay of solder voids and cracks as well as the much longer lifetime under EM.

1. Introduction

Solder joining technology is used in various packaging applications such as wafer level chip scale package (WLCSP) and its evolutions. With the trend of multi-functionalization and miniaturization, electronic devices might endure much high current density and operation temperature during service with the decrease in bump size. Under such high current density and operation temperature, diffusion of atoms can occur easily.

Hence, electromigration (EM) performance becomes more and more important as a reliability issue. For SnAgCu solder on traditional Cu under bump metallization (UBM), EM significantly enhances the cathode consumption and the initiation of cracks [1]. Therefore, new materials aimed at improving EM resistance are under development. One of the strategies is to develop new solders by adding minor elements [2], while the other is to propose some novel materials as UBM barrier layer [3,4]. For a superior UBM material, performances such as diffusion barrier, wettability and EM resistance should be considered. Fe-Ni alloys were identified as superior diffusion barrier layers at the interface between lead free solder and Cu for their extremely slow growth rate of intermetallic compounds (IMCs) during aging test [5,6]. Besides, the alloys also have enough wettability for interfacial reaction [7,8]. However, researchers still wonder the EM reliability of Fe-Ni UBMs before accepting the alloys for industry application, which has never been investigated according to our knowledge.

In this study, a series of EM tests were applied to the special designed WLCSP vehicle in order to evaluate the reliability performances of Fe-Ni UBMs under EM. Compared with the commercial Cu UBM, the microstructural evolution and failure behavior at the interface of solder joints were characterized in detail. Weibull analysis shows that Fe-Ni UBMs possessed much longer lifetime than Cu UBM. And the mechanism of superior EM resistance of Fe-Ni UBMs was discussed considering the diffusion and reaction of metal atoms under the coupling of thermal and current stressing.

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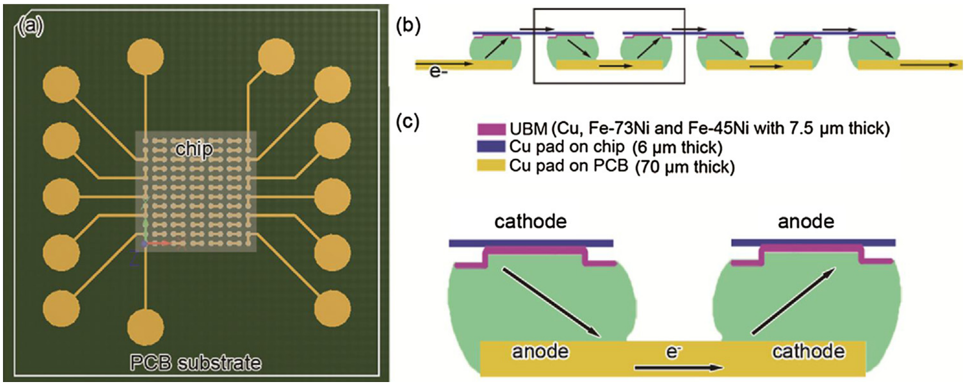

Fig 1. Test vehicle (a) the PCB substrate, (b) the electric flow within daisy-chain design, (c) the cross section of a pair of solder joints.

2. Experimental

2.1. Preparation of test vehicle

Firstly, two Fe-Ni UBMs as well as commercial Cu UBM were electroplated on 8-in. patterned wafers. The two Fe-Ni UBMs with composition of 73wt%Ni and 45wt%Ni were denoted as Fe-73Ni and Fe-45Ni, respectively. Details of the electroplating process were reported elsewhere [9,10], and the thickness of all different UBMs was about 7.5 μm. In addition, the lead free solder used here was Sn3.8Ag0.7Cu, which was mentioned as SAC for simplicity. Then, the chip was reflowed upon the Cu/OSP pad within the printed circuit board (PCB) substrate (20 mm × 20 mm × 0.8 mm). The peak temperature of the reflow process was 245 °C, and the time above the eutectic temperature (217 °C) was 67 s. The PCB substrate and test sketch map are shown in Fig. 1. Notably, 70-μm-thick Cu pad on PCB substrate was designed intentionally. On the one hand, Cu pad on PCB side can be used as a reference to observe the EM behavior of Fe-Ni UBMs. On the other hand, it prevents the early depletion of Cu material under current stressing for the sake of the lifetime statistic of Fe-Ni UBMs.

2.2. Electromigration test

To keep uniform ambient temperature and prevent oxidation, all the vehicles were immersed in an oil bath (40 °C) and the direct-current (DC) was 1.2×10^4 A/cm^2 during the EM test. The electrical resistance and temperature of vehicles were monitored through an in situ recorder (HIOKI LR8400-21). Due to the Joule heat, the temperature of each vehicle was around 150 °C.

As for lifetime calculation, fifteen vehicles for each kind of UBM were tested until failure. For each vehicle, sixty solder joints were electrified in series through the daisy chain design with the flip-chip solder joints between the chip and the PCB as shown in Fig. 1(b). Once the open circuit happened on one of the sixty solder joints, it was set as the failure criterion of that vehicle. Thus, lifetime of each vehicle would be the minimum value of the sixty solder joints, which also provided a much reliable model to analyze the lifetime of vehicles in application.

2.3. Microstructural characterization

The microstructural observation was conducted after 300 and 1000 h current stressing. Cross sections of different solder joints were prepared by the standard metallographic techniques, and then were observed with a ZEISS supra 55 scanning electron microscope (SEM). The characterization focused mostly on the SAC/UBM interface at the chip side. A pair of solder joints was observed at the same time, where cathode was always on the upper left and anode on the upper right as shown in Fig. 1(c). Also, the elemental mapping and point analysis of EDS (energy dispersive spectroscopy) were applied during the identification of IMCs. Moreover, all SEM images presented in the following section were backscattered electron image, which can provide information about the distribution of different elements. Hence it is useful to distinguish different IMCs. In order to get clear morphologies of the interfacial IMCs within Fe-Ni solder joints, the cross sectional solder joints were etched sometimes during the SEM observation. However, non-etched morphologies are shown in the following section to present the failures induced during the EM test.

3. Results

3.1. Microstructural evolution of solder joints during electromigration

3.1.1. Interfacial microstructures before current stressing

Microstructures of three different solder joints after reflow are displayed in Fig. 2(a–c). There is a 1.9-μm-thick scalloped Cu_6Sn_5 layer generated at the SAC/Cu interface. And a very thin Cu_3Sn was formed initially at the interface between Cu and Cu_6Sn_5 as depicted by black arrowheads in Fig. 2(a). As for Fe-73Ni UBM, both $FeSn_2$ and $(Cu,Ni)_6Sn_5$ were formed at the interface as shown in Fig. 2(b), where the $FeSn_2$ layer next to the UBM was indicated by black arrowheads. Previous TEM results showed the thickness of $FeSn_2$ layer was about 250 nm [11]. The $(Cu,Ni)_6Sn_5$ was rod-like grains with 3–5 μm in length dispersing within the solder material near the interface, which was distinctly different from the eutectic microstructure of SAC solder material. As for Fe-45Ni UBM (Fig. 2(c)), only a 250-nm-thick $FeSn_2$ layer formed at the interface. Notably, the Ag_3Sn granules in white contrast were dispersing within the solder matrix initially. While during the interfacial reaction, the dimension of Ag_3Sn might grow larger and can be wrapped within IMC layers. Since they have little effect on the interfacial evolution, we will ignore them in the following description and discussion.

For comparison, the interfacial images of three different solder joints after annealing at 150 °C for 1000 h are shown in Fig. 2(d–f). At the SAC/Cu interface, Cu_6Sn_5 was thickened from 1.9 μm (after reflow in Fig. 2(a)) to 3.8 μm after 1000 h aging (Fig. 2(d)). A 3.3-μm-thick Cu_3Sn layer was generated between Cu UBM and Cu_6Sn_5 layer, accompanying with a large amount of Kirkendall voids within Cu_3Sn as seen in Fig. 2(d). At SAC/Fe-73Ni interface (Fig. 2(e)), rod-like $(Cu,Ni)_6Sn_5$ were interconnected into a continuous outer layer. Moreover, plenty of $FeSn_2$ granules were also diffused into outer $(Cu,Ni)_6Sn_5$ layer during long time aging, which forms a mixed layer composed of $FeSn_2$ granules and $(Cu,Ni)_6Sn_5$ net structure as separated from the $FeSn_2$ layer and $(Cu,Ni)_6Sn_5$ layer by black and

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