Microelectronics Reliability 55 (2015) 2554–2559

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Electromigration behavior in Cu/Ni–P/Sn–Cu based joint system with low current density

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 2 October 2015
Accepted 4 October 2015
Available online 16 October 2015

Keywords:
Electromigration
Solder
Power module
Ni–P
Sn–Cu

ABSTRACT

Although electromigration in solder joints has great influence on reliability, few study has been reported on the Cu/Ni–P/Sn–Cu based joint system electromigration with realistic current density range lower than 10 kA/cm^2. We investigated a Cu/Ni–P/Sn–0.7Cu/Ni–P/Cu joint with current densities of 5.0 and 7.5 kA/cm^2 at 423 K. Solder joint breakdown at the cathode side was detected for both stress conditions. Ni–P plating disappeared completely at the cathode side and a Cu–Sn intermetallic compound (IMC) formed at the interface. Cu–P IMC formed on the solder breakdown interface. Ni diffusion in Ni–P plating at the cathode was accelerated and the P-rich layer grew thicker than at the anode side before breaking down under electromigration stress. The P-rich layer reached the Cu electrode resulting in cracking along the interface between solder layer and Cu. Sn was diffused from the Ni_3SnP IMC to the P-rich layer cracks and formed Cu_3Sn IMC with the Cu electrode. Thus, the electromigration mechanism in an electroless Ni–P plating/Sn–Cu based joint system with low current density was clarified.

1. Introduction

Electromigration in the semiconductor field has been studied extensively in recent decades to understand and to avoid any fatal damage caused by this phenomenon in metallization. Electromigration is the movement of metal atoms in the direction of strong electron flow, which is termed “electron wind”, and results from momentum transfer between conducting electrons and diffusing metal atoms. The mean time to failure caused by electromigration decreases as the temperature or current density increases, and has been expressed well by Black's equation [1–7]. For example, the current density of a fine pitch solder bump between a chip and substrate has been one of the major concerns in the semiconductor field.

It is well known that current densities of 10 kA/cm^2 may cause serious electromigration. Although power modules with insulated gate bipolar transistors (IGBTs) and diodes do not require joints as small as the flip chip joints'. Power modules for hybrid electric vehicles are usually operated above 200 A. In addition, the service temperature of engine compartments is very high. Thus, there are serious concerns about electromigration failure of power modules for hybrid electric vehicles. The current density of power devices with solder in the double-sided cooling power modules varies from 0.24 kA/cm^2 to 0.4 kA/cm^2. It is believed that the influence of solder electromigration is minimal in the current operating environment [8–12].

Environmentally friendly vehicles must achieve a good fuel efficiency and a high power density simultaneously. To achieve these demands, low energy consumption, high heat dissipation and high thermostability are required in power modules. The current density of solder joints will increase according to the demand for high thermostability SiC power devices and device miniaturization [13,14]. The miniaturization of power modules can be achieved by integrating 6-in-1 and 2-in-1 circuit compositions, which operate a three-phase alternating current motor, into one package [15,16]. Kadoguchi et al. reported that an emitter electrode in the upper arm IGBT usually jointed a collector electrode in the lower arm IGBT for 2-in-1 power modules. The joint is smaller than that of power devices, so the current density increases and solder electromigration occurs easily [16]. Therefore, it is necessary to investigate the mechanism of solder electromigration and to enhance the electromigration resistance for power modules.

Several studies reported that joints with under bump metallurgy, such as Ni and Ni/Ti, could enhance the electromigration reliability of Sn–Cu, Sn–Ag and Sn–Pb solders with high current. However, few study exists on solder electromigration with current density lower than 10 kA/cm^2, which is a realistic value [17–28]. The Ni–P plating is expected to have a diffusion barrier effect to suppress electromigration [18,29,30]. We therefore studied electromigration in an electroless Ni–P plating/Sn–0.7Cu based joint system with current densities lower than

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http://dx.doi.org/10.1016/j.microrel.2015.10.003

10 kA/cm^2. The diffusion behavior of each element caused by electromigration was mainly identified by comparing the solder joint interfaces at an anode and at a cathode.

2. Experimental procedure

Fig. 1(a) and (b) show an overview of the sample and a schematic cross-section of a cathode side respectively. Oxygen free copper (C1020) was used for the electrodes and processed into 1-mm-long 0.4 mm × 0.4 mm cross sections. Soldering pad for the Cu electrode was finished by electroless Ni–P/Au plating. The Ni–P plating thickness varied from 7 to 14 μm. Two electrodes were jointed with a 0.5-mm-diameter solder ball. The solder composition was M725 (Sn–0.7Cu–Ni–P, wt.%) from Senjyu Metal Industry Co., Ltd. Fig. 2 shows the scanning electron microscope (SEM) image of the cross-section of a joint interface. The intermetallic compound (IMC) at the interface was ~2.5 μm thick. Energy dispersive X-ray spectroscopy (EDX) analysis showed that the IMC consisted of 33.7 at.% Cu–21.4 at.% Ni–44.9 at.% Sn. Therefore, the IMC composition can be estimated as $(Cu,Ni)_6Sn_5$. A P-rich layer was ~1.3 μm thick, and this layer consists of mixture of Ni_3P and Ni [31]. The sample composition was confirmed in Fig. 1(b). We applied currents of 8.0 and 12 A to the solder joint to generate current densities of 5.0 and 7.5 kA/cm^2 respectively. This test sample was placed on a hot plate, which was controlled so that the joint temperature was maintained at 423 K when a specified constant direct current passed through the joint. The temperature profile of the test sample was determined by thermocouple and by measuring the resistance change in the junction line between the Cu/solder/Cu joints. The change in resistance caused by electromigration was measured by monitoring voltage. The failure criterion was defined as a 20% increase in resistance from the initial value. The failed sample cross-section was polished and studied using a SEM. The electromigration failure mode was investigated by analyzing the elemental composition with EDX. To check the electromigration process phenomenon, the joint was studied after applying a stress of 423 K and 5.0 kA/cm^2 for 250, 500, 750, and 2500 h.

3. Results and discussion

3.1. Electromigration stress test

Fig. 3 shows the change in resistance with time for the stress condition at 423 K with current densities of 7.5 and 5.0 kA/cm^2. The failure times were 1060 and 2320 h respectively. The failure samples after the electromigration stress tests are shown in Fig. 4. The solder of both failed samples was detached from the Cu electrode at the cathode side. The samples maintained at 423 K without applying current were not failed at the joint interface. Therefore, the failure mode of both samples with applied current was caused by electromigration. Fig. 5 shows a SEM image of the failed sample for a stress condition of 423 K and 7.5 kA/cm^2. This sample was failed at the solder of a cathode side as shown in Fig. 5(a). $(Cu,Ni)_6Sn_5$ IMC existed entirely in the solder layer. Fig. 5(b) and (c) show enlarged images of the cracking area. The Ni–P plating and P-rich layers, which remained after reflow, disappeared. The Cu electrode reacted with the solder and formed Cu_3Sn and $(Cu,Ni)_6Sn_5$ IMCs. Breakdown by electromigration occurred in the solder though continuous Cu–P layer was detected by EDX measurements on the solder surface. EDX point analysis on the layer indicated the atomic ratio of Cu and P was about 3:1, suggesting the compound may be Cu_3P IMC. Jang et al. reported that electromigration makes P in the Ni–P plating at a cathode side diffused and reacted with the Cu electrode (without Ni–P plating) at an anode resulting in the formation of Cu–P IMC [18]. The position of Cu–P IMC in this sample coincided with that of the P-rich layer. Therefore, it is thought that electromigration makes Cu of the electrode diffuse to the P-rich layer to form Cu–P IMC. $(Cu,Ni)_6Sn_5$ IMC which remained after reflow was migrated by electron and failure occurred at the Cu–P IMC interface.

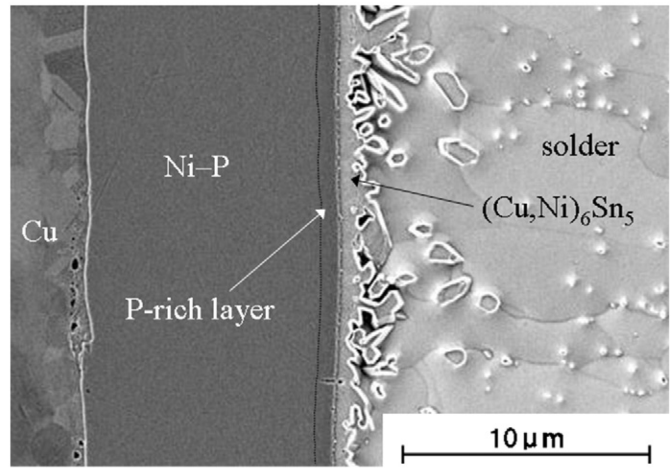

Fig. 2. Cross-section SEM image of the solder joint interface after reflow.

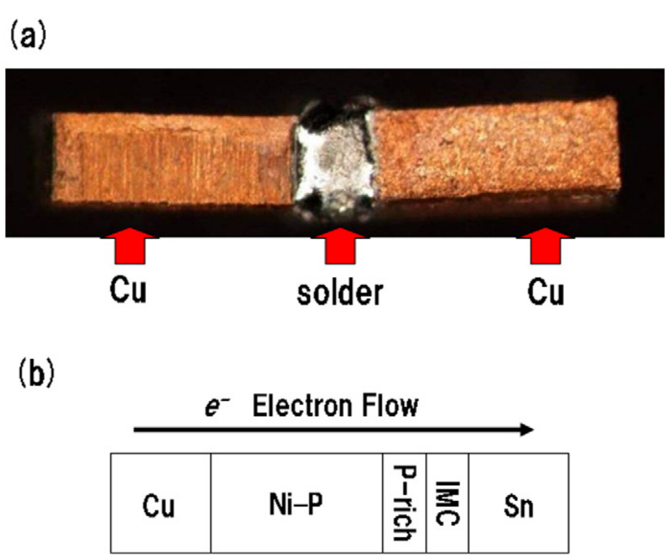

Fig. 1. EM test sample. (a) Overview; (b) Schematic of cathode.

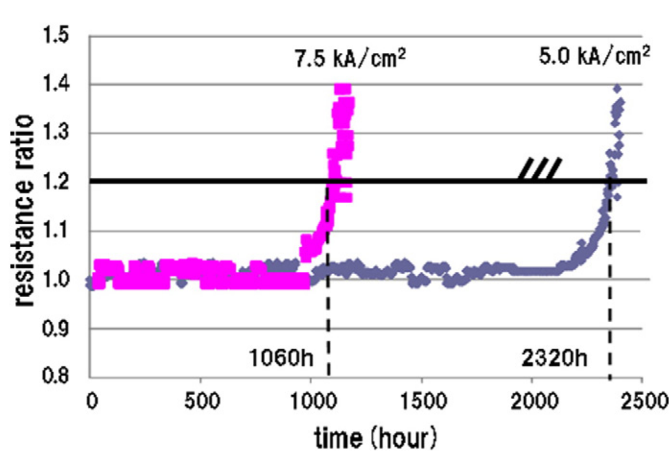

Fig. 3. Change of resistance ratio under electromigration stress.