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Heat Effect and Impact Resistance during Electromigration on Cu-Sn Interconnections

Tae-Kyu Lee[1,*], Fay Hua[2], and J. W. Morris, Jr.[1]

[1]Materials Science and Engineering, University of California, Berkeley 94720, Berkeley, CA, United States
[2]Intel corporation, Santa Clara, CA

The influence of electron current on the diffusion of Sn and Cu in simply designed Cu-Sn-Cu diffusion couples was investigated. The diffusion couples were designed to permit *in situ* studies of the progress of diffusion. Tests were done at various temperature in air with a current density over 5×10^3A/cm^2. The results showed Cu movement into Sn in the direction of the electron current accompanied by grain boundary sliding of the Sn grains. Intermetallic compound growth was observed at the anode side, with intermetallic dissolution at the cathode side. The temperature increase during current stressing was measured using thermo-couples and IR(Infra Red) photography. The impact strength of the Cu-Sn interconnections was measured after current stressing using a modified micro-Charpy impact testing method.

Keywords: electromigration, joule heating, infra-red microscopy, impact test, solder joint

1. INTRODUCTION

Electromigration is a well-known phenomenon[1-3] whose occurrence in solder joints has become increasingly important as the joints have decreased in size and the current densities within them have increased in magnitude[4]. The identification of potential failure modes in Cu-Sn systems is particularly important in light of the trend toward Pb-free solder systems[5]. Several factors affect the diffusion induced by electron current flow through a solder joint. These include the microstructure, the detailed mechanisms of vacancy formation and migration, and the thermal consequences of Joule heating, among others. Joule heating at the interface between Cu and Sn may be particularly complex since this interface is coated with intermetallic compounds. It is reported that intermetallic phases, mainly Cu_6Sn_5 and Cu_3Sn phase in this system, grow at the anode side during current stressing. The intermetallic phases not only degrade the mechanical strength of the interface but also create a local heat source because of their relatively high electrical resistivities. Local heating produces a thermal gradient which may accelerate diffusion near the interface, leading to exaggerated intermetallic growth and void formation. The resulting loss of impact resistance is a serious concern in many devices[6].

In this study Cu-Sn-Cu couple specimens were tested under known currents. The simple configuration of the couples made it possible to monitor the electromigration behavior continuously using SEM and other analytical techniques, especially Infra Red (IR) techniques for thermal imaging. A modified Micro-Charpy tester was developed to measure the change in impact strength during testing.

2. EXPERIMENTAL PROCEDURE

2.1. Sample preparation

The specimen used in this study is illustrated in Fig. 1. Two pure cooper plates were cut with identical 5×10×10 (mm) dimensions. One side of each Cu plate was polished and chemically cleaned. The two cleaned sides were then clamped with a stainless steel fixture so that the polished sides faced one another across a fixed gap (in this study the gap was 150 μm). The gap was filled by dipping the plates into a molten Sn bath at 300 °C for 30 seconds, followed by cooling in air (the actual interface temperature at the time of solidification is about 250 °C). Using a precision cutter the Cu-Sn-Cu sample was sliced into plates 500 μm wide and 500 μm thick. These were polished to a thickness of 400 μm. The initial microstructure after the dipping included a thin layer of intermetallic compounds at the interface between Cu and Sn. A relatively thin Cu_3Sn layer developed at the Cu side and a scallop-shaped Cu_6Sn_5 layer appeared on the Sn side.

Each end of the sample is bonded to Cu terminals which are connected to a power supply. A current is applied to

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*Corresponding author: taekyulee@berkeley.edu achieve a current density of 5×10^3A/cm^2 depending on each final samples configuration.

2.2. Infrared spectroscopy

For measuring the thermal distribution at the interface, a high speed infrared camera (Indigo Systems) was used. The simple sample configuration used here permitted thermal mapping of the sample surface with a spatial resolution of about 5 μm. In this study, a current of 0 to 5×10^3A/cm^2 was applied at room temperature in air and a series of IR images were taken. A conversion chart was required to convert the signal intensities to the actual temperature. Fort this purpose, standard specimens were prepared and IR images were taken at temperatures between 25 °C and 70 °C.

3. RESULTS AND DISCUSSION

Figure 2 is an SEM image of the joint surface after current stressing at 120 °C for 100 hours. The current density was 5×10^3A/cm^2. A continuous layer of Cu_6Sn_5 and a relatively small amount of Cu_3Sn appeared at the anode side. A channel of continuous voids was also observed inside the Sn at the edge of Cu_6Sn_5. The overall intermetallic growth rate was slow compared to that reported elsewhere[7] because of the relatively low current density used in this study.

IR images taken from this sample show the thermal profile developed during current stressing. Figure 3(a) shows the initial condition of the specimen. Figure 3(b) shows the thermal profile just after imposition of a current density of

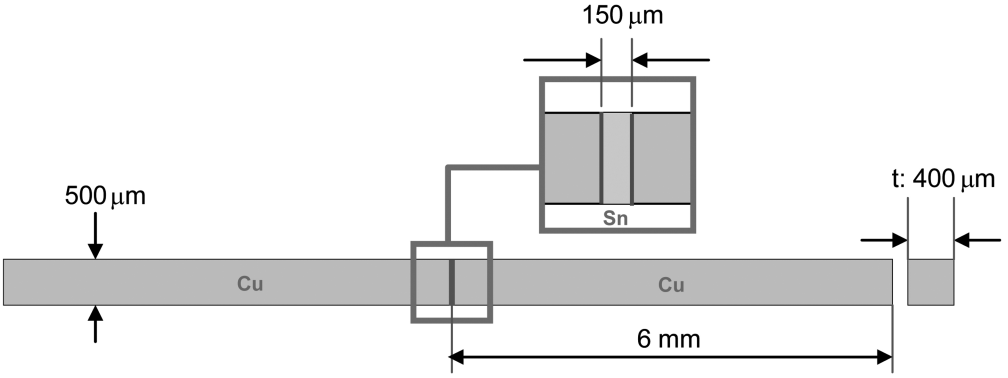

Fig. 1. Sample geometry.

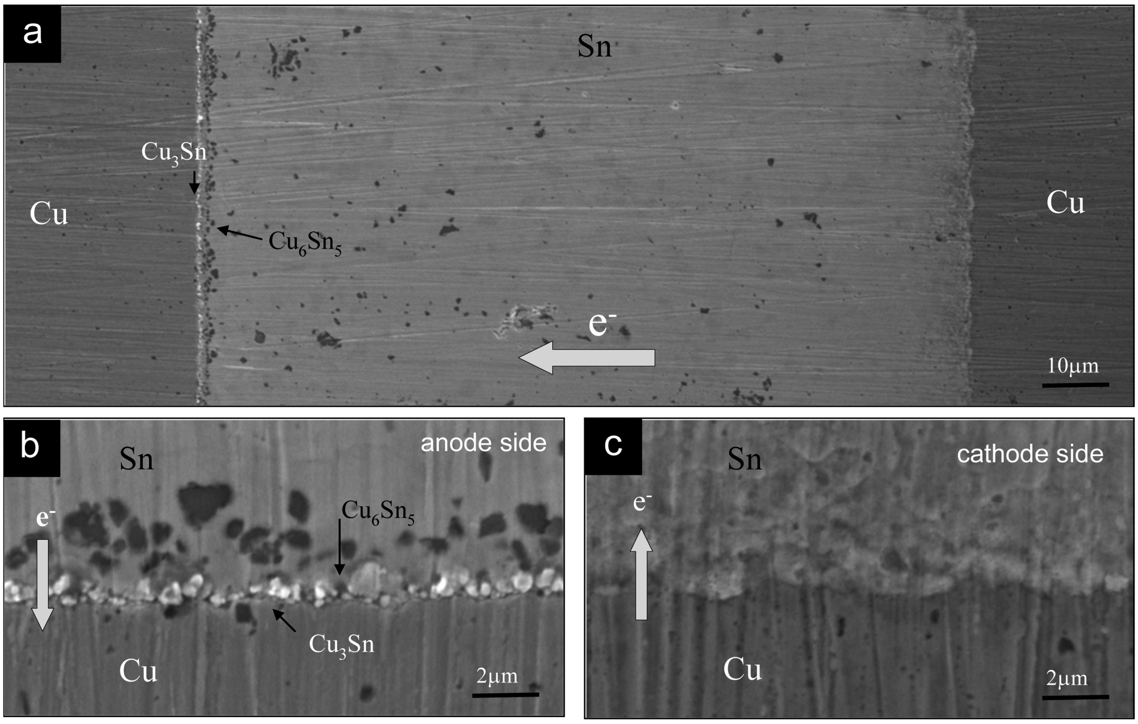

Fig. 2. (a) Current stressed at 120 °C for 100hours with 0.5×10^4A/cm^2 current density. (b) anode side (c) cathode side. (electron flow direction indicated by arrow).

5×10^3A/cm^2. Figure 3(c) shows the temperature distribution after exposure to this current density at 120 °C for 100 hours. The temperature has increased significantly from the initial condition (Fig. 3(b)). The high intensity area in Fig. 3(c) represents Joule heating at the Cu-Sn interface, especially at the location where intermetallic layers are present. The growth of Cu_6Sn_5 produced a higher temperature which resulted in a steep local temperature gradient. This local heating affects the thermal diffusion at that area and increases the rate of growth of the intermetallic layer at the anode side.

Figure 4 is an intensity line scan along the midsection of the sample. The high peak observed at the anode side is approximately 50 °C above the base temperature at the cathode, based on the IR intensity versus temperature conversion chart for Cu_6Sn_5. The temperature on the cathode side is approximately 41 °C, giving a thermal gradient across the solder interface of around 600 °C/cm.

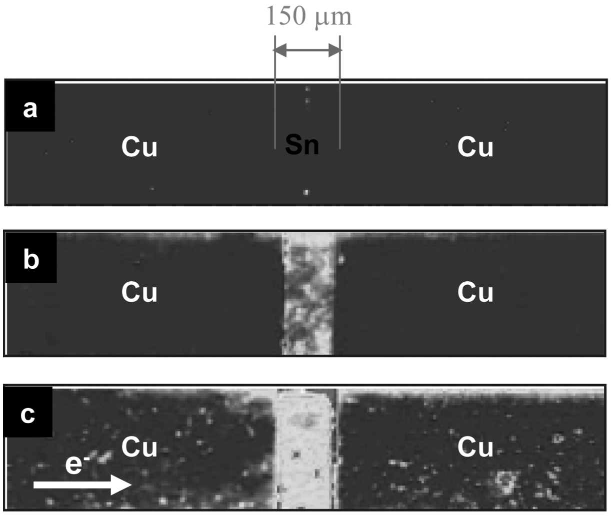

Fig. 3. Infra-Red image (a) Initial condition sample (no current stress damaged) at room temperature with no current applied. (b) with current applied (0.4×10^4A/cm^2 current density) (c) Current stressed sample at 120°C for 100 hours with 0.5×10^4A/cm^2 current density. IR image taken with current applied (0.4×10^4A/cm^2 current density).

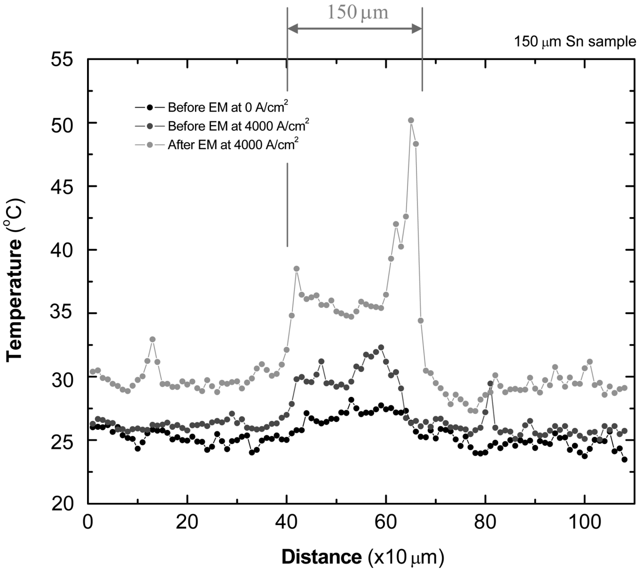

Fig. 4. Infra-Red image intensity line-scan. Taken from Fig. 3(a)(b)(c) mid section.

3.1. The influence of current stressing on impact strength

A micro-Charpy tester was developed to measure impact strength. The tester uses a double-shear sample with the geometry shown in Fig. 5(a). The sample holder (shown in

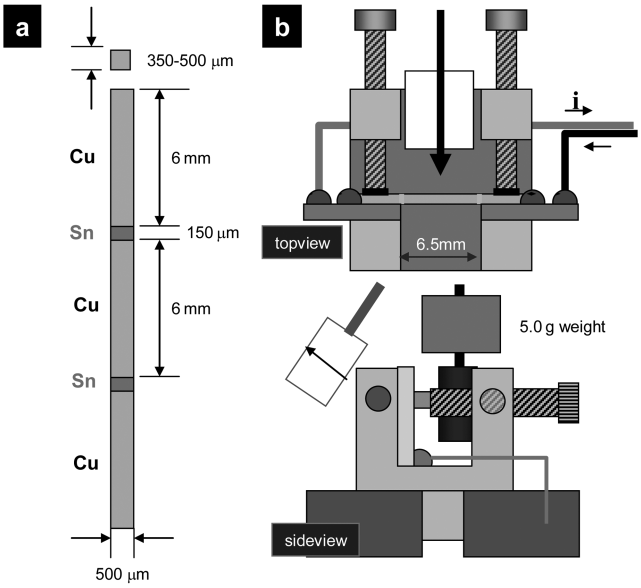

Fig. 5. (a) Double shear sample geometry. (b) Impact test sample holder (top view and side view).

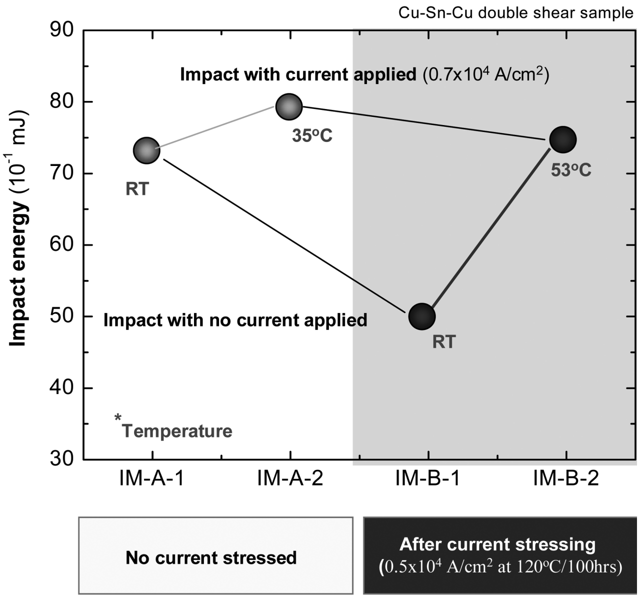

Fig. 6. Impact energy to Fracture.

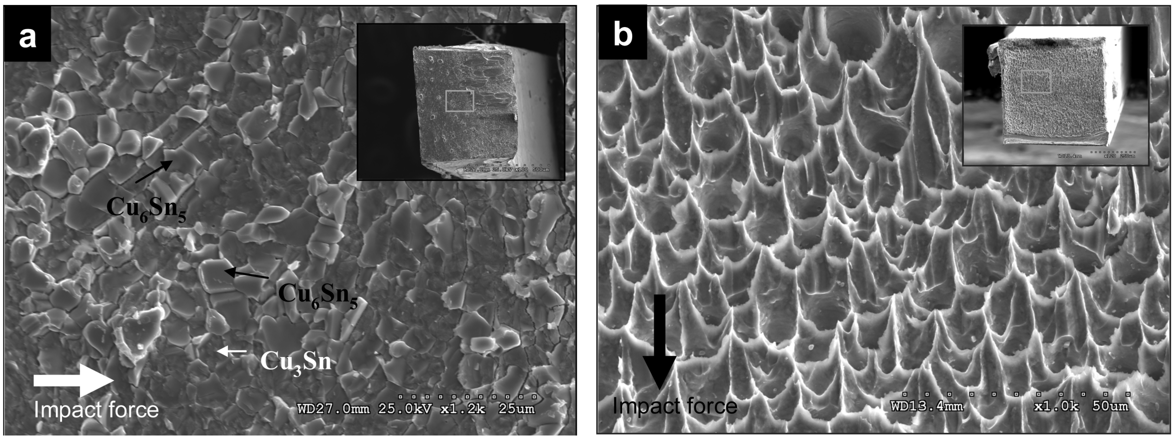

Fig. 7. Fracture surface of (a) initial condition sample (no current stress damage sample) impact tested with no current applied (b) Current stressed sample at 120 °C for 100 hrs with a current density of 0.5×10^4 A/cm^2. Impacted During current stressing (at current density 0.7×10^4 A/cm^2).

Fig. 5(b)) allows a current to be passed through the sample during an impact with a 5 g hammer, which swings through the sample. The elevation of the traveling hammer after the impact is used to measure the energy absorbed during fracture.

Figure 6 presents the results of tests done under two conditions. One set of samples was tested in the initial condition with no current stressing damage and the second set was tested after exposure to a current density of 5×10^3A/cm^2 at 120°C for 100 hours. As shown in Fig. 6, the samples tested in the initial condition had higher toughness both with and without current. Current stressing for 100 hours caused a significant loss of toughness when the test was done with no current applied. However, the toughness increased significantly when the sample was tested under current.

Figure 7 shows fracture surfaces of the tested samples. Figure7(a) is the fracture surface of a sample tested in the initial condition with no current applied. It shows a clear brittle fracture inside the intermetallic compound, mainly inside Cu$_6$Sn$_5$. On the other hand the sample exposed to current for 100 hours prior to testing showed a fully ductile fracture that occurred inside the Sn (Fig. 7(b)). This can be explained by the local Joule heating that is produced at the interface which resulted in a higher temperature at that region. The temperature increase causes the shift from a brittle fracture at the intermetallic interface to a ductile fracture inside the Sn, with a substantial improvement in toughness.

4. CONCLUSION

Electromigration induced failure mechanism in Cu-Sn joints was studied using a simple joint configuration that could be monitored by optical, SEM, EDX and IR imaging analysis during tests. Local Joule heating causes a significant temperature increase at the intermetallic layer between Cu and Sn. IR images of the Cu-Sn joint show a clear thermal gradient that leads to a thermally driven migration mechanism. Impact tests are done in a micro-Charpy tester and the results show a loss of toughness due to intermetallic growth during current stressing. However, the impact resistance is significantly higher when the test is done under current stressing. In this case the higher temperature of the sample leads to a change in fracture locus and mechanism, from brittle fracture in the intermetallics in the absence of current, to ductile fracture in the bulk Sn when the current is applied.

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