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Electromigration Behaviors of SnAgCu Solder Lines

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Smaller flip chip electronic packages are likely to have higher current densities through the solder bumps. This causes a failure due to electromigration at these bumps. In this study, the electromigration behaviors of $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ solder lines have been investigated under a current density of 4.5×10^4 A/cm^2 at 110 ~ 160 °C using *in-situ* SEM and an interruptive test method. The SnAgCu solder lines do not have an incubation stage, despite that SnAgCu is composed of an alloyed system of eutectic SnPb and Al(Cu), i.e. materials that conventionally involve an incubation stage. The electromigration activation energy of the SnAgCu solder line is calculated to be 0.56 eV.

Keywords: electromigration, lead-free solder, SnAgCu

1. INTRODUCTION

Currently in the field of microelectronics the most serious reliability problem with respect to metal interconnects is electromigration. In flip chip packaging technology, as the number of input/output contact pads on a chip is increased, the diameter of solder bumps has decreased. Consequently, the current density through the contact area of the solder bumps has increased dramatically. Thus, the current density is expected to be in the order of 10^4A/cm^2. The current density of solder is about two orders of magnitude smaller than that of Al or Cu interconnects. However, electromigration in flip chip solder occurs at low current density[1-4], since the melting point of solder is low and its diffusivity is high. The electromigration characteristics of a solder bump differ from those of Al or Cu interconnects. The solder alloys are binary, ternary or even quaternary. However, chip interconnects are composed of a major element (e.g. Al or Cu) with only a small amount of alloying elements. This is a key difference between interconnect and solder.

Furthermore, owing to environmental considerations, demand for Pb-free solder has increased[1]. Among the Pb-free solders, eutectic SnAgCu solder appears to be the most promising candidate for replacing eutectic SnPb solder. Indeed, the National Electronics Manufacturing Initiative (NEMI) has recommended replacing eutectic SnPb alloy with eutectic SnAgCu alloy. Nevertheless, electromigration of SnAgCu has not been havily studied.

In this work, the electromigration of $SnAg_{3.0}Cu_{0.5}$ was assessed with an edge drift structure. The edge drift structure proposed by Blech and Herring[5] has been widely used to examine electromigration behaviors. Although the edge drift structure is different from the conventional flip chip solder ball bumps in shape, the use of this structure simplifies measurement of both the edge displacement and the change in concentration of solder due to electromigration on the top-view SEM observation. Moreover, the temperature and current density profiles are more uniform in this structure. Several studies have addressed the electromigration parameters (drift velocity, Ea, Z*, threshold current density) of eutectic SnPb[4,6,7], but the relevant parameters of electromigration of SnAgCu solder are still unknown. In the present work, we observe the electromigration behaviors and activation energy of SnAgCu solder lines.

2. EXPERIMENT

A 3000-Å-thick Ni thin film was patterned into a line structure with two contact pads. A SiO_2 layer with a thickness of 1 mm was deposited on the Ni line and the contact pads were removed. However, in order to separate the solder line from the contact pads, the SiO_2 "walls" were intentionally left between the contact pads and the line. The width and length of the line were 100 μm and 1000 μm, respectively. A small amount of $Sn_{96.5}Ag_{3.0}Cu_{0.5}$ solder paste was dropped on the exposed Ni area and reflowed at 220 °C for about 5 s. The solder was then polished down until the thickness of the SnAgCu lines reached approximately 3 - 5 μm. Figure 1 shows a schematic diagram of the cross-section

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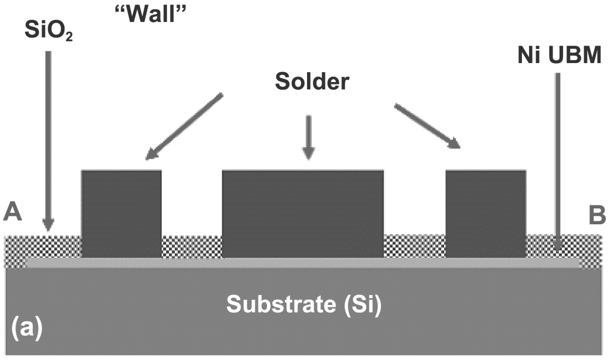


Fig. 1. Image of a SnAgCu edge drift structure with SiO_2 walls: Cross-sectional diagram of the solder line.

view of the SnAgCu solder line.

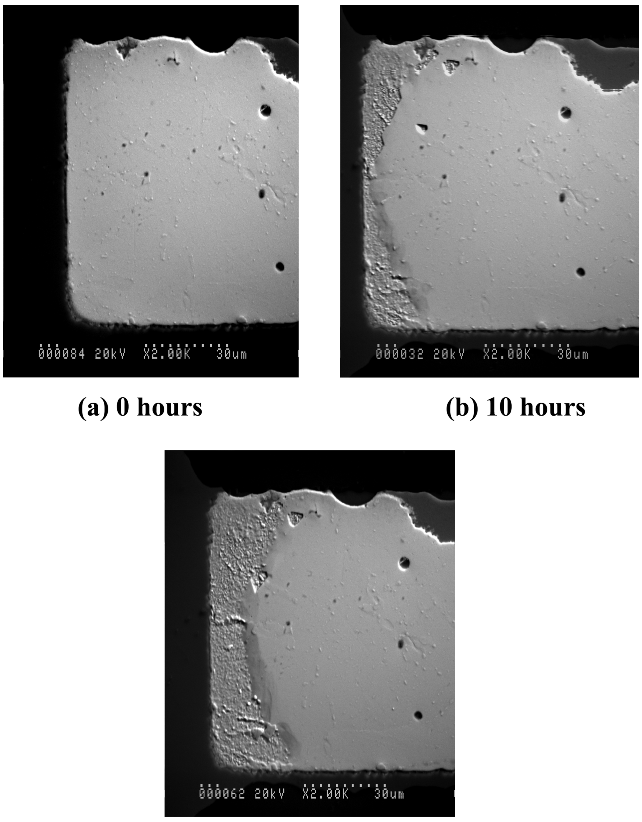
The testing temperatures were 110, 125, 140, and 160 °C. Each sample was annealed for 4 hours at each testing temperature before the electromigration test in order to stabilize the microstructure and the formation of intermetallic compounds between Ni and the solder. The 3000-Å-thick Ni underlayer was fully converted into a $(Ni_xCu_y)_3Sn_4$ layer before the electromigration test[8]. Since the current flows through both the SnAgCu solder and the $(Ni_xCu_y)_3Sn_4$ underlayer, the effective current density of the SnAgCu line was calculated using a parallel model[3,7,9]. It was reported that the electromigration resistance of Cu-Ni-Sn alloy[10] is much larger than that of SnAgCu solder. Therefore, it was expected that the effect of the $(Ni_xCu_y)_3Sn_4$ underlayer on the solder electromigration behavior should be negligible during the electromigration tests. The effective current density applied to the SnAgCu solder line was 4.5×10^4 A/cm^2.

Scanning electron microscopy (SEM : JSM-5600) was employed to observe the interruptive edge displacement of the solder line due to electromigration. *In-situ* SEM (Hitachi 2500C) was configured for real-time evolution of the solder line. The *in-situ* SEM equipment consists of a regulated DC power supply, a heat plate, and a digital multimeter in a SEM chamber.

3. RESULTS AND DISCUSSION

3.1. Electromigration behaviors of SnAgCu solder line

The electromigration behaviors of the SnAgCu solder lines were observed at 4.5×10^4 A/cm^2 and 140 °C. Figure 2 shows *in-situ* SEM images of the region near the cathode of the SnAgCu lines as a function of time. Measurement of the edge displacement of the depleted region at the cathode was carried out using an image processing system. The edge displacements were measured from the images shown in Fig. 2, and are plotted as a function of time in Fig. 3. SnAgCu solder line begins to move shortly after the current is turned on and drifts at a constant rate (Fig. 3). The electromigration behaviors of the SnAgCu lines were different from those of eutectic SnPb solder lines. Figure 4



(a) 0 hours

(b) 10 hours

(c) 30 hours

Fig. 2. In-situ SEM images of SnAgCu solder line near the cathode end during electromigration testing at (a) 0 hours, (b) 10 hours, and (c) 30 hours at a current density of 4.5×10^4 A/cm^2 at 140 °C.

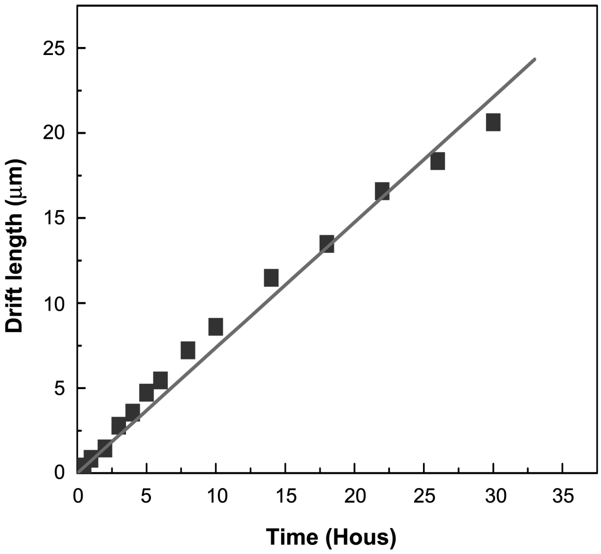


Fig. 3. Edge displacement of the SnAgCu line, measured from Fig. 2, as a function of time at a current density of 4.5×10^4 A/cm^2 at 140 °C.

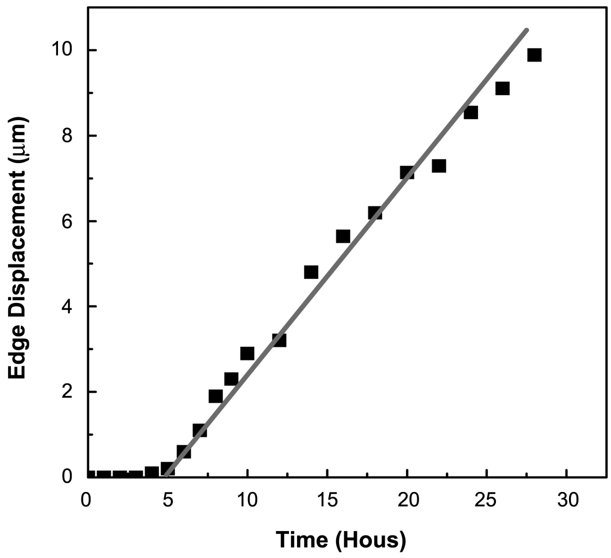


Fig. 4. Edge displacement of the eutectic SnPb line as a function of time at a current density of 3.0×10^4 A/cm^2 at 110 °C.

shows the edge displacement of the SnPb solder line as a function of time at 3.0×10^4 A/cm^2 and 110 °C. SnPb solder requires incubation time during which the migration of solder is delayed. SnPb solder does not shown any migration within 5 hours. The existence of an incubation stage before edge movement was also found; during the incubation stage, Pb migrated prior to Sn. The edge movement may be due to the migration of Sn, not Pb. Detailed results and a discussion of incubation time for edge movement in eutectic SnPb solder has been presented elsewhere[7]. In the case of the alloys Al-Cu and Al-Mg, an incubation time during which practically no microscopic drift was observable has also been noted[11,12]. The incubation time for Al-Cu electromigration can be correlated to the depletion of Cu[11,12].

In general, the electromigration of alloyed materials are characterized by an incubation stage. It is thought that minor elements in alloyed materials might retard electromigration of the major elements. Although SnAgCu is an alloyed material, and is the similar to SnPb and Al(Cu), it has no incubation time. If Ag moves prior to Sn, it is expected that SnAgCu system also have incubation time as in the case of SnPb and Al(Cu). In order to observe the Ag migration in the SnAgCu solder line during electromigration, the Ag concentration along the lines was investigated via an energy dispersive x-ray (EDX) analysis. Figure 5 shows the relative Ag concentration of the SnAgCu line obtained at a current density of 4.5×10^4 A/cm^2 at 140 °C after 35, 70, and 100 hours, respectively. As depicted in Fig. 5, the concentration of Ag is uniform along the line. It thus explains that Ag cannot move significantly during SnAgCu electromigration. Based on these results, Ag cannot contribute to the electromigration of SnAgCu, and Ag might form Ag_3Sn by reflow and post-annealing[13]. Thus, despite that SnAgCu is a ternary system, its electromigration behavior is similar to that of a nearly pure material.

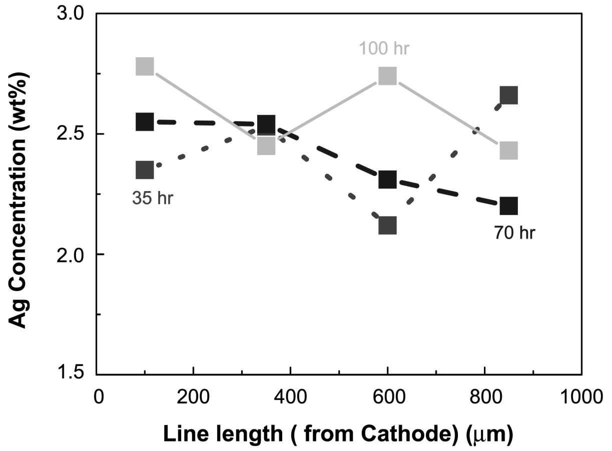


Fig. 5. Relative Ag concentration (wt%) of the SnAgCu line measured along the line. The line was tested at 140 °C at a current density of 4.5×10^4 A/cm^2.

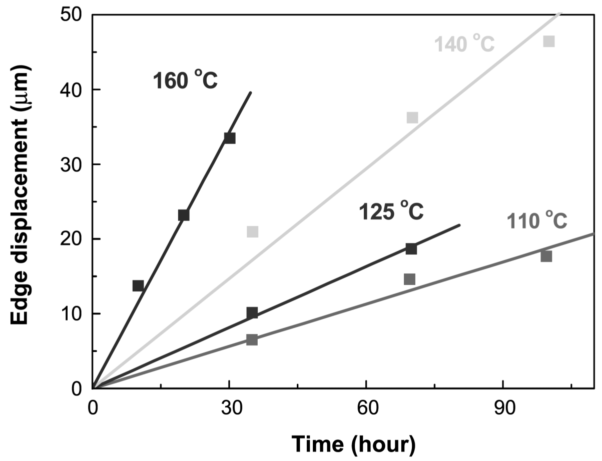


Fig. 6. Edge displacement of the SnAgCu solder line as a function of time under current densities of 4.5×10^4 A/cm^2 at 110, 125, 140, and 160 °C, respectively.

3.2. Activation energy of SnAgCu solder electromigration

For a more detailed analysis, the activation energy of SnAgCu electromigration was calculated using the drift velocity. Figure 6 shows the variation in the drift velocity at a current density of 4.5×10^4 A/cm^2 at 110, 125, 140, and 160 °C, respectively. The electromigration-induced flux can be expressed as [14]

$$J_{EM} = Cv = C\left(\frac{D_0}{kT}\right)exp\left(-\frac{E_a}{kT}\right)Z^*e\rho j \qquad (1)$$

where v, C, D_o, T, k, E_a, Z*, r, and j are the drift velocity, the concentration of atoms, the pre-factor of diffusivity, the

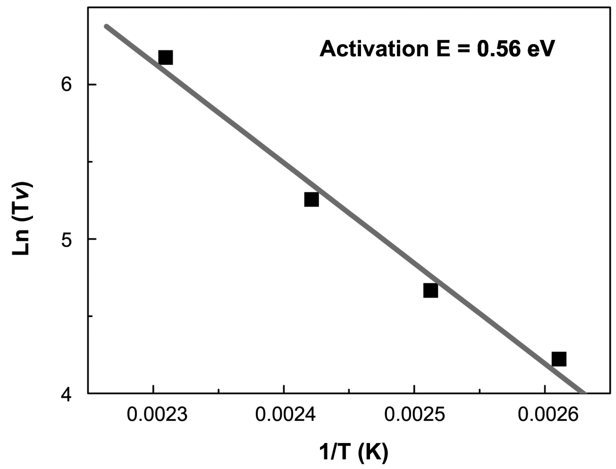


Fig. 7. Activation energy for electromigration of SnAgCu at 110, 125, 140, and 160 °C, respectively, under a current density of 4.5×10^4 A/cm^2.

temperature, Boltzmann's constant, the activation energy, the effective charge number, the resistivity, and current density, respectively[14]. Eq. (1) can be rewritten as

$$v = \left(\frac{D_0}{kT}\right) exp\left(-\frac{E_a}{kT}\right) Z^* e\rho j \qquad (2)$$

Taking the logarithm of both sides of Eq. (2)

$$ln(vT) = -\frac{E_a}{kT} + C \qquad (3)$$

Therefore, the activation energy of SnAgCu electromigration corresponds to the slope of the plot of ln(vT) vs. 1/T. The calculated value of the activation energy, which was obtained from the drift velocities shown in Fig. 7, is shown in Fig. 8. The activation energy (E_a) by electromigration can be determined from the slope of the fitting line, and its value is 0.56 eV in a temperature range of 110 - 160 °C. This value is comparable with other group's results, 0.56 eV[15] or 0.45 eV for $SnAg_{3.8}Cu_{0.7}$ solder alloy [16].

4. CONCLUSION

We investigated the electromigration behavior of SnAgCu solder lines using in-situ SEM, the interruptive test method, and drift velocity measurements. SnAgCu did not require any incubation time contrary to SnPb, as the Ag does not contribute to the electromigration of SnAgCu. The electromigration activation energy of SnAgCu solder lines was 0.56 eV.

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