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Study of electromigration in thin tin film using edge displacement method

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Threshold current density and other electromigration parameters of pure Sn films were measured using edge displacement method. Sn film with a thickness of 5000 Å was evaporated on a 1200-Å-thick Ti film on a Si substrate. Electromigration behavior was investigated under the current densities of $2.5\times10^4-1.5\times10^5$ A/cm^2 at room temperature (RT 27–32 °C), 50, 75, and 100 °C. Both needle-type and hillock-type whiskers grew in the anode end when the films were stressed at RT and 50 °C, but only hillock-type whiskers were observed when they were stressed at 75 and 100 °C. The electromigration rate increased linearly with the applied current density for the four stressing temperatures. The threshold current density (J_c) was measured to be 1.93×10^4, 9.65×10^3, 9.57×10^3, and 7.93×10^3 A/cm^2 for RT, 50, 75, and 100 °C, respectively. The measured activation energy was 0.32 eV. In addition, the measured critical length of the Sn film was 18 μm at RT and the products of DZ^* were 1.95×10^{-10}, 4.84×10^{-10}, 1.27×10^{-9}, and 1.99×10^{-9} cm^2/s for RT, 50, 75, and 100 °C, respectively. These results are fundamental to electromigration in Pb-free solders, since most of their matrices consist of almost pure Sn. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1954871]

I. INTRODUCTION

In the semiconductor industry, flip-chip technology has been widely used for high-density packaging because of its capacity to handle large number of input-output (I/O) ports.[1,2] Due to the trend of miniaturization and the high performance, the dimension of solder bumps keeps decreasing and the current that each bump needs to carry keeps increasing, causing the current density in the solder bump to increase dramatically. Therefore, electromigration (EM) has become an important reliability issue in flip-chip solder joints.[3–6]

On the other hand, the eutectic SnPb solders have gradually been replaced by Pb-free solders due to environmental concern of Pb pollution.[7,8] Among the most promising candidates for Pb-free solders, such as SnAg3.5 and SnAgCu, Sn constitutes over 95%, and the matrix of the solder is almost pure tin after reflow.[9] Since the Ag and Cu atoms react with Sn or other materials in under bump metallization (UBM) to form Ag_3Sn, Cu–Sn, or Cu–Ni–Sn intermetallic compounds (IMCs),[5,10,11] the electromigration study in pure Sn is fundamental for understanding the electromigration in Pb-free solders.

In 1976, Blech designed a test structure for electromigration study, from which electromigration rate and other parameters can be measured.[12] It is often called the "Blech specimen" or "edge displacement method." The activation energy can be obtained by the Nernst–Einstein equation[13]

$$V = J/N = BeZ^*\rho j = (D_0/kT)eZ^*\rho j \exp(-E_a/kT), \qquad (1)$$

where V is the drift velocity, J is the atom flux, N is the density of metal ions, B is the mobility, eZ^* is the effective charge number of ions, ρ is the metal resistivity, j is the electric current density, D_0 is the diffusion preexponential factor, k is Boltzmann's constant, T is the absolute temperature, and E_a is the activation energy. Z^* can be also obtained provided the diffusivity of the material is known. Equation (1) can be written as follows:

$$\ln\left(\frac{VT}{j}\right) = -\frac{E_a}{kT} + \ln\left(\frac{D_0 eZ^*\rho}{k}\right). \qquad (2)$$

Thus, E_a can be obtained from the slope of the linear relation on the plot of $\ln(VT/j)$ against $1/T$. In addition, the threshold current density (J_c) can be obtained by extrapolating the plot of drift velocity against the applied current density to zero drift velocity, which represents the maximum allowable current that Sn can carry without electromigration damage. The critical length can also be estimated by measuring the electromigration rate at different lengths of Sn stripes.[14]

Sun and Ohring obtained an activation energy of 0.45 eV/at. and an effective charge number of −49–−85 for pure thin Sn film by tracer self-diffusion.[15] Liu *et al.* also reported the electromigration rate in Sn film by using the edge displacement method.[16] However, threshold current density and critical length for pure Sn have not been reported. Threshold current density represents the maximum current density below which no electromigration occurs, and critical length denotes the length of the stripe below which no EM damage takes place. They are very important parameters for characterizing the electromigration behavior in pure Sn.

In this study, we employed the edge displacement method to measure the electromigration parameters for Sn film, including drift velocity at various temperatures and current densities, threshold current density, activation energy,

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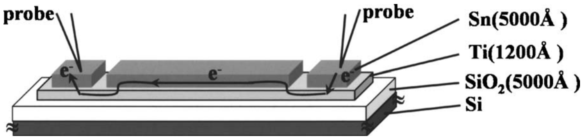

FIG. 1. Schematic illustration of the cross-sectional view of the Sn Blech specimen. The direction of the electron flow is indicated by the arrows in the figure.

effective charge number, and critical length. These parameters will be fundamental for the electromigration in Pb-free solders.

II. EXPERIMENT

An *n*-type 4-in. (100) wafer was prepared as the substrate. After standard cleaning process, a 5000-Å-thick SiO_2 film was grown on the silicon wafer by wet oxidation method as the insulator. A Ti film of 1200 Å in thickness was deposited on the silicon substrate by e-beam evaporation, followed by the deposition of a 5000-Å-thick Sn film without breaking the vacuum. Afterwards, the first-level mask was used to define Sn stripes and the selectively etching solution was $FeCl_3+H_2O$ at the ratio of 1:10. The second-level mask was used to define Ti pads and the selective etching solution was $NH_4OH+H_2O_2$ at the ratio of 1:5. The schematic of the test samples is shown in Fig. 1, in which the Sn films on the left and right ends served as probing pads, and the center Sn film may deplete in the cathode end and grow hillocks in the anode end. The control of the applied current density is important in the electromigration study. Because of the rough surface of the evaporated Sn films, atomic force microscope (AFM) was used to measure the cross-sectional area of the cathode side of the Sn stripes to make sure that the applied current density in the Sn films was accurate. The scanning electron microscope (SEM) image for the Sn test samples is shown in Fig. 2. An electric current was applied from the left side (anode) to the right side (cathode). The depletion area was measured by a commercial computer software. The power supply used in this study was a Keithley 2400 $I-V$ source meter, which has a current resolution of 500 nA.

To measure the increase of temperature in the Sn stripe due to the current stressing, temperature measurement by infrared technique was performed by recording the temperature distribution (map) after the temperature reached a stable state.[17] The temperatures in the Sn stripe during current stressing were mapped by the Quantum Focus Instruments (QFI) thermal infrared microscopy, which has a 0.1 °C temperature resolution and a spatial resolution of 2 μm.

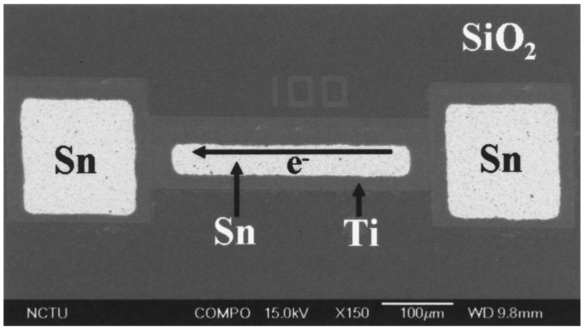

FIG. 2. Plan-view SEM image of the fabricated sample. The Sn films on both ends served as the probing pads, and the center Sn film was used to investigate the electromigration behavior.

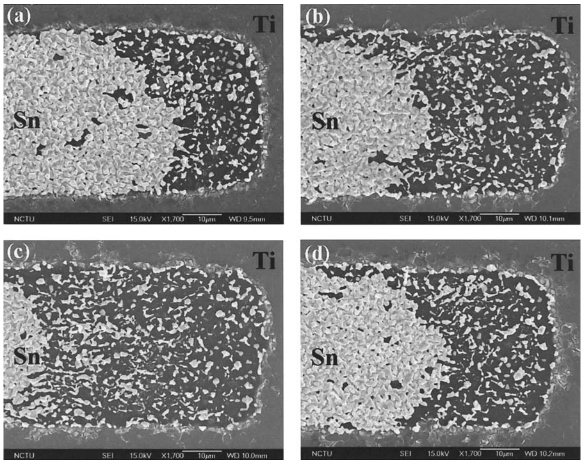

FIG. 3. Plan-view SEM images of the cathode side after the current stressing by 1.25×10^5 A/cm^2 (a) at RT for 37 h with a depletion area of 800 μm^2, (b) at 50 °C for 28 h with a depletion area of 1164 μm^2, (c) at 75 °C for 15 h with a depletion area of 1570 μm^2, and (d) at 100 °C for 6 h with a depletion area of 960 μm^2.

III. RESULTS

A. Microstructure evolution

When the electrons flowed from the cathode side to the anode side, the Sn atoms migrated gradually in the same direction. Figures 3(a)–3(d) show the depletion at the cathode side of the Sn stripes under the current density of 1.25×10^5 A/cm^2 at room temperature for 37 h, 50 °C for 25 h, 75 °C for 15 h, and 100 °C for 6 h, respectively. It can be shown that the depletion area increased upon increasing the stressing temperature. On the anode side, two types of whiskers, hillock-type and needle-type ones, were observed. Figures 4(a)–4(d) show the morphology on the anode side stressed under the current density of 5×10^4 A/cm^2. It was found that the hillock-type whiskers could be grown at room temperature up to 100 °C. However, the needle-type whisker can be only observed frequently on the Sn stripes stressed at room temperature, as shown in Fig. 4(a). Only one needle-type whiskers was found on the samples stressed at 50 °C, and no needle-type whiskers were observed on the samples stressed at 75 and at 100 °C.

B. Electromigration rate

The depletion area can be measured from the SEM images in the cathode end, as shown in Figs. 3(a)–3(d). For the stripe stressed by 1.25×10^5 A/cm^2 at room temperature for 37 h, the measured depletion area was 800 μm^2, and it increased to 1164, 1570, and 960 μm^2 for the stripe stressed by 1.25×10^5 A/cm^2 at 50 °C for 28 h, 75 °C for 15 h, and 100 °C for 6 h, respectively. The corresponding drift velocities were 0.14, 0.28, 0.69, and 1.03 nm/s for RT, 50, 75, and 100 °C, respectively. It was found that the higher the stress-

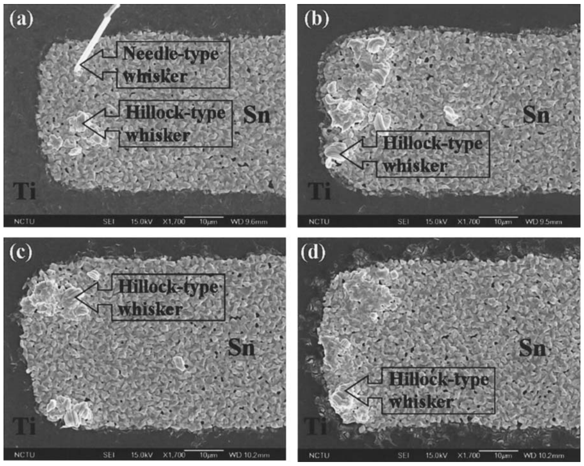

FIG. 4. Plan-view SEM images of the anode side after the current stressing by 5×10^4 A/cm^2 (a) at RT for 37 h, both hillock-type and needle-type whiskers are formed, (b) at 50 °C for 28 h, hillock-type whiskers are formed (needle-type whiskers may be observed when the film was stressed longer), (c) at 75 °C for 15 h, only hillock-type whiskers are formed and (d) at 100 °C for 12 h, only hillock-type whiskers are formed.

ing temperature, the faster the drift velocity. The plots of the drift velocities against the applied current densities at different temperatures are shown in Fig. 5. The drift velocity increased linearly with the increase in the applied current density.

C. Threshold current density (J_c)

The threshold current density can be obtained by extrapolating the four curves in Fig. 5 to zero drift velocity.[12] As shown in Fig. 5, the four threshold current densities were estimated to be 1.93×10^4, 9.65×10^3, 9.57×10^3, and 7.93×10^3 A/cm^2 for RT, 50, 75, and 100 °C, respectively. These values represent the maximum current density that the Sn film can carry without any electromigration damage. The higher the stressing temperature, the lower the threshold current.

D. Activation energy (E_a) and DZ^*

To measure the activation energy, the increase in temperature due to Joule heating was first measured. Figure 6 shows the temperature increase as a function of applied current density measured on a hot plate at 75 and 100 °C. It is found that the Joule heating caused an increase in temperature of approximately 1.3 °C, when the sample was placed on a hot plate of 100 °C stressed by 1.5×10^5 A/cm^2. Because there was no enough infrared emitted at RT and 50 °C for the temperature measurement, the temperature increase under current stressing at these two temperatures was assumed to be the same as that stressed at 75 °C. By using the calibrated temperatures, the activation energy can be obtained by the slope in the plot of $\ln(VT/j)$ against $1/T$, as shown in Fig. 7. Its value was calculated to be 0.32 eV (7366 cal/mole). In addition, the measured average values of DZ^* were 1.95×10^{-10}, 4.84×10^{-10}, 1.27×10^{-9}, and 1.99×10^{-9} cm^2/s for RT, 50, 75, and 100 °C, respectively. These values are listed explicitly in Table I.

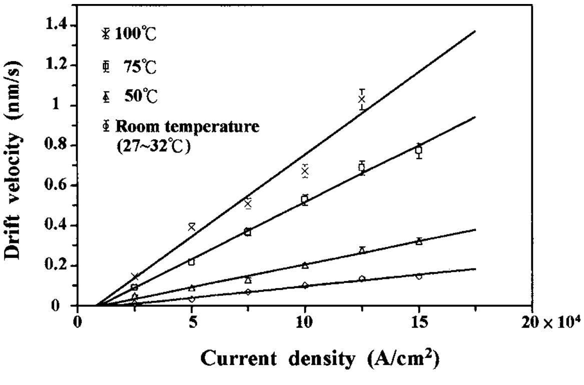

FIG. 5. Drift velocity of the Sn stripe as a function of current density at RT, 50, 75, and 100 °C. The threshold current densities can be obtained by extrapolating from the fitting curves to the zero drift velocity.

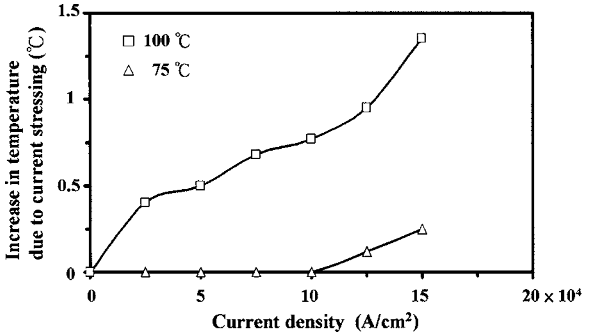

FIG. 6. The increase in temperature due to the applied current density detected by the infrared technique.

E. Critical length

To obtain the critical length, the electromigration behavior was investigated under different stripe lengths stressed at the current density of 1×10^5 A/cm^2 at room temperature. It is found that the drift velocity decreased as the stripe length is decreased. The linear relation between drift velocity and the reciprocal of stripe length is shown in Fig. 8. The critical length was estimated by extrapolating the plot of drift velocity against the reciprocal of stripe length to zero drift velocity.[14] The value was 18 μm, which means that when the stripe length is below 18 μm, no electromigration phenomenon would occur.

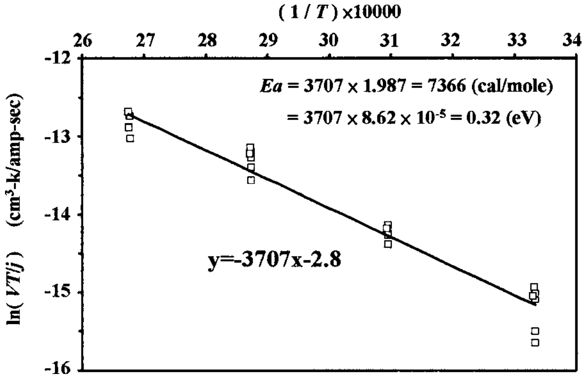

FIG. 7. The plot of $\ln(VT/j)$ against $1/T$. The activation energy can be obtained by the slope of the fitting curve.

TABLE I. Testing currents, temperatures, corresponding drift velocities, and the values of Z^*.

Temperature	Current density ($\mathrm{A/cm^2}$)	Drift velocity (nm/s)	$-DZ^*$ ($\mathrm{cm^2/s}$)
Room temperature	2.5×10^4	0.013	1.20×10^{-10}
	5×10^4	0.031	1.41×10^{-10}
	7.5×10^4	0.070	2.12×10^{-10}
	1×10^5	0.100	2.27×10^{-10}
	1.25×10^5	0.136	2.49×10^{-10}
	1.5×10^5	0.146	2.22×10^{-10}
50 °C	2.5×10^4	0.049	4.85×10^{-10}
	5×10^4	0.088	4.29×10^{-10}
	7.5×10^4	0.131	4.28×10^{-10}
	1×10^5	0.202	4.93×10^{-10}
	1.25×10^5	0.278	5.43×10^{-10}
	1.5×10^5	0.323	5.26×10^{-10}
75 °C	2.5×10^4	0.092	9.7×10^{-10}
	5×10^4	0.218	1.15×10^{-9}
	7.5×10^4	0.368	1.29×10^{-9}
	1×10^5	0.528	1.39×10^{-9}
	1.25×10^5	0.688	1.47×10^{-9}
	1.5×10^5	0.774	1.36×10^{-9}
100 °C	2.5×10^4	0.146	1.65×10^{-9}
	5×10^4	0.391	2.21×10^{-9}
	7.5×10^4	0.509	1.92×10^{-9}
	1×10^5	0.673	1.90×10^{-9}
	1.25×10^5	1.030	2.30×10^{-9}

IV. DISCUSSION

As mentioned in Sec. III A, the needle-type whiskers grew more when the Sn stripes were stressed at room temperature. However, in our previous study, we found that the growth rate of whiskers was faster when the stripes were stressed at 50 °C.[16] The discrepancy may be owing to different stressing times. The stressing times in our previous study were longer than 90 h. However, in this study, the stressing times were shorter than 91 h. The pure Sn stripes with longer stressing time may accumulate higher stress for breaking the surface oxide of Sn, and then start to grow whiskers. Moreover, when stressed at 75 and 100 °C, no needle-type whiskers were observed even when the stripes were stressed at $1.5\ \mathrm{A/cm^2}$ for 150 h. The reason for that is not clear at this moment. This may be attributed to the softer surface oxide, resulting in the formation of the hillock-type whiskers at higher temperature.[18,19]

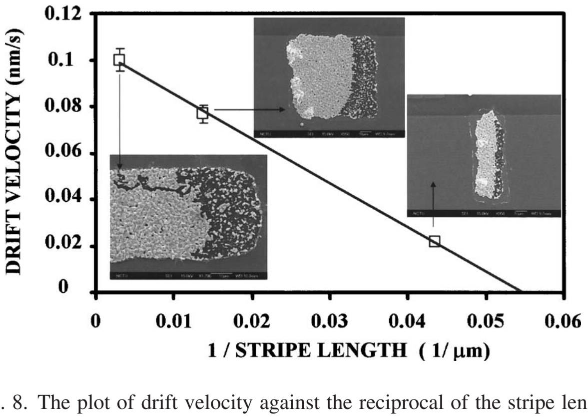

FIG. 8. The plot of drift velocity against the reciprocal of the stripe length. The critical length was estimated to be 18 μm.

Sun and Ohring measured the product of DZ^*, activation energy, and other parameters for 16000-Å-thick Sn films by tracer-diffusion method.[15] The values of activation energy E_a of 0.46 eV and $DZ^* \approx 3.5\times10^{-9}-1.8\times10^{-8}\ \mathrm{cm^2/s}$ were obtained when the Sn films were stressed by $1\times10^4\ \mathrm{A/cm^2}$ at 142–213 °C. The lower value of activation in the present work may be due to smaller grain size and lower stressing temperatures. The grain size of Sn film in the present work is expected to be smaller since its thickness was only 5000 Å. Blech observed a larger drift velocity in thinner Al film.[12] Therefore, grain-boundary diffusion may dominate in the thin Sn film, resulting in a smaller activation energy.

V. CONCLUSIONS

Drift velocities and other important electromigration parameters of pure Sn have been investigated at RT, 50, 75, and 100 °C. The threshold current densities were 1.93×10^4, 9.65×10^3, 9.57×10^3, and $7.93\times10^3\ \mathrm{A/cm^2}$ for RT, 50, 75, and 100 °C, respectively. The activation energy of 0.32 eV was obtained due to the smaller grain sizes of the Sn film. The products of DZ^* were 1.95×10^{-10}, 4.84×10^{-10}, 1.27×10^{-9}, and $1.99\times10^{-9}\ \mathrm{cm^2/s}$ for RT, 50, 75, and 100 °C, respectively. In addition, the measured critical length of Sn film was 18 μm at RT. These results are very important for electromigration in Pb-free solders because their matrix consists of almost pure Sn.

ACKNOWLEDGMENTS

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