연 구 논 문

SnPb와 무연 플립칩 솔더의 유효전하수와 임계전류밀도

채 광 표*

건국대학교 광전자물리학과

Effective Charge Number and Critical Current Density in Eutetic SnPb and Pb Free Flip Chip Solder Bumps

Kwang Pyo Chae

*Department of Applied Physics, Konkuk University, Chungju 380-701, Korea

Abstract

The effective charge number and the critical current density of electromigration in eutetic SnPb and Pb Free ($SnAg_{3.8}Cu_{0.7}$) flip chip solder bumps are studied. The effective charge number of electromigration in eutectic SnPb solder is obtained as 34 and the critical current density is j = 0.169 × (δ_σ/δ_x) A/cm^2, where (δ_σ/δ_x) is the electromigration-induced compressive stress gradient along the length of the line. While the effect of electromigration in Pb free solder is much smaller than that in eutectic SnPb, the product of diffusivity and effective charge number DZ^* has been assumed as 6.62 × 10^{-11}. The critical length for electromigration are also discussed.

* Corresponding author : kpchae@kku.ac.kr

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1. Introduction

Electromigration is a subject of serious concern in microelectronics because of the reliability failure of interconnecting lines[1-4]. The 1999 International Technology Roadmap of Semiconductors has included electromigration as a reliability issue in packaging technology.

Electromigration failure in flip chip eutectic SnPb solder joints was reported in 1998[5]. The key observations are void formation at the cathode and Pb accumulation at the anode of the solder joint. Past experiments on solder electromigration mainly focused on solute diffusion in Pb matrixes[6-8], and the concentration of the solute was far less than that in commercial solder alloys. A few experiments of electromigration have been performed in a flip chip configuration with regard to the reliability of flip chip solder thin films and solder bumps[5,9]. While much attention has focused on electromigration in Al or Cu lines[1,3,10], until recently relatively little research has been directed toward electromigration behavior in solder joints[3,5,9]. Due to environmental concerns regarding Pb-containing solders, the electronic manufacturing industry is hurriedly attempting to replace Pb-containing solders with Pb-free solders. The latter typically have high Sn content[11-16].

For electromigration considerations, the design rule in electronic packaging is known to be 1 A over five solder bumps, or 0.2 A per bump. For a solder bump of 50 ㎛ diameter, the current density will be about 3 × 10^3 A/cm^2. Since the contact area of the bump is much smaller than

the cross-section of the bump, the actual current density will reach about 10^4 A/cm^2 in the solder bump contact. While this current density is about one or two orders of magnitude less than that in Al or Cu interconnected lines[2,3,10], electromigration in the solder bumps cannot be ignored. Indeed, electromigration failure in eutectic SnPb solder joints has been reported to occur within a few hundred hours at 150 ℃ under a current density of 8 × 10^3 A/cm^2 [5].

Besides eutectic solder, electromigration in $Pb_{95}Sn_5$ alloy and Pb-free solder joints are also of particular interest.

The electromigration behavior in solder joints is expected to be very different from that in Al or Cu interconnects. This is because solder is typically a two-phase alloy and the temperature of electromigration in the solder is relatively high, with respect to its melting point. Hence, lattice diffusion in the solder will play a significant role during electromigration, unlike that in Al or Cu. In addition, since the solder joint has a ball shape rather than a line shape, it is impractical to use the test structure of Blech strips[17,18] to study electromigration. The advantage of using Blech strips to study electromigration is that the depletion at the cathode end of the strip provides a quantitative analysis of critical products or the effective charge number.

In this work, the effective charge number and the critical current density of electromigration in eutetic SnPb and Pb-Free($SnAg_{3.8}Cu_{0.7}$) flip chip solder bump was studied. Using the results of the experiments, the effective charge number and the critical current density of electromigration was obtained. The critical conditions of electromigration were also discussed obtained with the effective charge number.

2. Experiment and Results

2.1 Experiment

Electromigration has been observed in a eutetic SnPb and $SnAg_{3.8}Cu_{0.7}$ flip solder bump by Lee et. al.[19,20]. A schematic diagram of the test structure employed in the present study is shown in Fig. 1. The solder bump between an electroless Ni UBM on Si and electroplated Cu UBM on PCB was current stressed at 120℃ with 1.5 A on a hot plate in atmospheric ambient. The solder bump was printed with solder paste through a stainless steel mask and reflowed twice in a belt furnace with a peak temperature of 240 ℃. After assembly, the gap between the chip and the board was filled with epoxy.

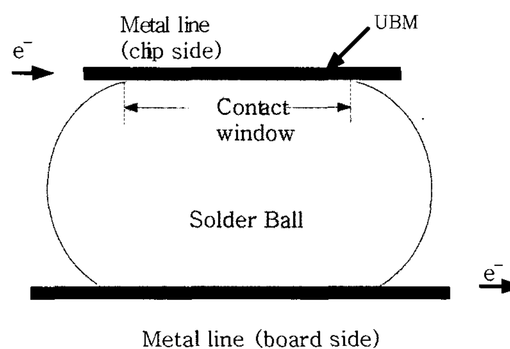

Fig. 1 A schematic diagram of a solder bump for electromigration

When we stressed the two half bumps under current, we were applying current through a half contact opening. The diameter of the opening was 100 ㎛. Hence the average current density through a half contact opening can be calculated to be about 3.8 × 10^4 A/cm^2 when 1.5 A was applied. The polishing has left behind embedded SiC and diamond particles on the solder surface. The size of these particles is roughly 1 ㎛ . We used them as inert makers to calculate the atomic flux driven by electromigration. The maker motion and the surface topographic changes due to electromigration were observed with scanning electron microscopy(SEM), energy dispersive x-ray(EDX) spectroscopy, and optical microscopy.

2.2 Elecromigration in Eutetic SnPb Flip Chip Solder Ball

The electromigration behavior of a eutectic SnPb bump of 0, 20, 30 and 39.5 h was studied with 1.5 A at 120 ℃. Clear SEM images were

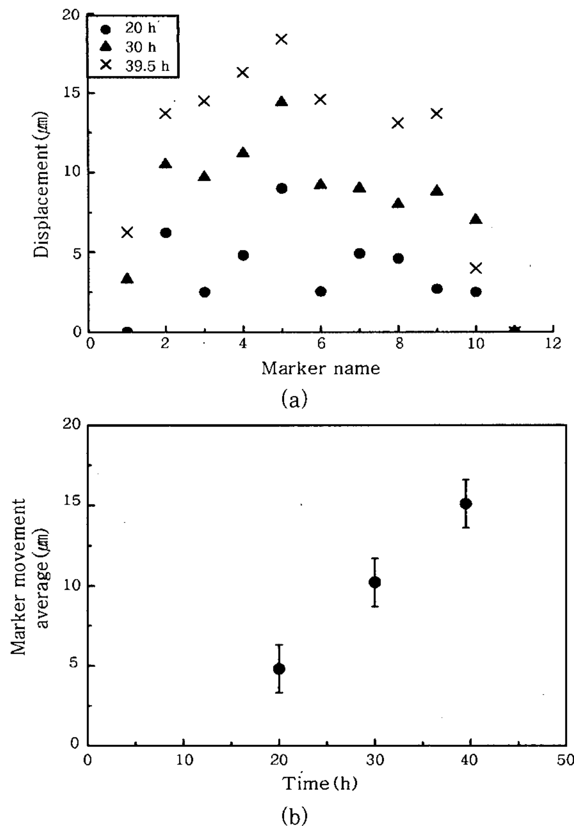

Fig. 2 Marker movement on the cross-sectioned eutectic SnPb surface. (a) marker displacement, and (b) marker displacement vs time

shown in a previous paper[19,20]. The accumulation of Pb in the anode side and the void can be seen. Using the diffusion marker method, the electromigration flux was measured and the effective charge of atomic diffusion in the solder was calculated. Fig. 2(a) shows the displacements of makers measured from their initial position after 20, 30 and 39.5 h. Except marker number 1, 10 and 11, all the other markers are similar in magnitude of movement. The average movement, except marker number 1, 10 and 11, as a function of time is shown Fig. 2(b). A linear displacement is seen in the period from 20 to 39.5 h. More analytical experiments were carried out after this work[21].

2.3 Electromigration in SnAgCu Flip Chip Solder Ball

The electromigration has been observed in a $SnAg_{3.8}Cu_{0.7}$ flip chip solder bump. After current stressing at 120 ℃ with 1.5 A for 200 h, voids were formed at the cathode side and clear SEM images were presented in a previous paper[20].

The void formation is much slower than that of eutectic SnPb solder. However the IMCs were squeezed out in the anode side as hillocks. Below the hillocks, many smaller Cu oxide particles formed on the Cu UBM during current stressing. Some of the IMC hillocks showed a depletion of Cu. The results of the marker method show that the marker motion was much less than that in eutectic SnPb. A few analytical experiments were carried out after this work[21,22].

3. Critical Conditions of Electromigration

The mass transport by electromigration in a polycrystalline metal is governed by the flux equation[23]:

$$J = C(D\,\delta/kTd)Z^{*}eE \qquad (1)$$

where C is the grain boundary condition, D is the grain boundary diffusion coefficient, δ is the effective width of the grain boundaries, d is the diameter of the grains, Z^{*} is the effective charge number of grain boundary electromigration, e is the charge of electron, T is temperature, k is Boltzmann constant, and E is the electric field.

The parameter, Z^{*}, which represents the effective charge number of moving atoms driven by electric current, can be obtained if the flux, the grain size, the temperature, the electric field, and the diffusivity are known. Assume that

$$V = JAt\Omega \qquad (2)$$

Where V is the total volume of hillocks extrudes, A is the cross-sectional area of interphase boundaries per unit area, t is the time of electromigration, and Ω is the average atomic volume. We can then calculate the flux J by measuring V from the data of the total volume of the hillock vs the current stressing time.

Knowing the displacement, time, and cross-sectional

area of the solder ball, the electromigration flux can be measured and the effective charge number calculated.

Combining equations (1) and (2), we obtain[24]:

$$J = V/\Omega At = C(D/kT)Z^{*}eE \quad (3)$$

3.1 Effective Charge Number

To date, the effective charge number Z^* has been a very important factor in most of electromigration experiment analyses. Many attempts have been made to obtain more accurate values of the effective charge number for SnPb solders as shown in Table 1.

Determining the correct value from those in Table 1 is an hard task because the experimental conditions are very different. However, the effective charge number of one material may have only one value.

As shown in equation (3), at constant T and E, the flux J can be measured by the amount of mass transport. It is possible to measure DZ^* and D simultaneously in a single experiment by using the tracer technique. The difficulty of carrying out such an experiment is to maintain a uniform temperature over the entire sample and to measure the distance between the tracer before and after elecrtomigration. The tracer often spread, and hence accurate measurement of the distance and moved volume is very difficult in a solder ball. As such, in our previous papers, we could not obtain a reasonable Z^* value[19,20].

Using the interface diffusion data of Gupta et. al.[25], we can obtain D values of 1.426×10^{-10} cm^2/s, 8.159×10^{-10} cm^2/s, and 1.02×10^{-9} cm^2/s for 120 ℃, 140 ℃, and 150 ℃, respectively. Applying these D values at 150 ℃ and equations (2) and (3) for the results of Huyhn et. al.[26], that is, $V = 2.7 \times 10^{-7}$ cm^3; $A = 3.3 \times 10^{-5}$ cm^2; $t = 8.64 \times 10^5$ s(10 days); $\Omega = 2.78 \times 10^{-23}$ cm^3; $C = 3.6 \times 10^{22}$ atoms/cm^3; $E = 1$ Volt/cm^2 and $kT = 3.6 \times 10^{-2}$ eV. We obtain 34 as the effective charge number of eutectic SnPb solder. For comparison, the reported value of Z^* for SnPb is 33[26] and 50[27], and Pb in bulk Pb is 47[28].

Table 1 Effective charge number data for SnPb solder

Z^*	33	50	34-113(140℃), 102-337(120℃)	184-4910
Ref. No.	25	26	20	19

On the other hand, Lee et. al.[20] reported the effective charge number Z^* was 102 at 120 ℃ and 34 at 140 ℃ for their 20 h experimental data. They suggested that 34 was a more reasonable value. From these results, we have also determined that the effective charge number of eutectic SnPb solder is 34. Using this value we can now consider the critical conditions of electromigration of a SnPb solder ball.

3.2 Critical Current Density

Since the electromigration driving force is proportional to the current density, failure will be accelerated by the effect of current crowding. In addition, the increase of local current density may also cause local joule heating, which may result in a temperature gradient that also enhances atomic diffusion and flux divergence.

In equation (3), if there is no stress variation along the conductor line before electromigration, the atomic flux J during electromigration can be expressed as[17]

$$J = n(D/kT)[Z^{*}ej\rho - b(\delta\sigma/\delta x)\Omega] \quad (4)$$

Where $(\delta\sigma/\delta x)$ is the electromigration-induced compressive stress gradient along the length of the line, and b is a stress state-dependent coefficient, with b=2/3 for an equi-biaxl stress state[29]. In this equation we can assume that the critical current density for electromigration is $j > 0$. That is, the electro wind is larger than the compressive stress gradient, and the net atom flux becomes a positive value. Hence, we can obtain the critical current density is

$$j > (\delta\sigma/\delta x) \times (b\Omega/e\rho Z^{*}) \quad (5)$$

To determine the critical current density, we

can substitute proper values from experimental results. The electromigration-induced compressive stress gradient along the length of the line, $(\delta\sigma / \delta x)$ has to be measured experimentally.

Using the values of $e = 1.6 \times 10^{-19}$ C; $\rho = 1$; $Z^* = 34$; $b = 2/3$, and $\Omega = 2.78 \times 10^{-23}$ cm^2, the critical current density is then obtained as $j = 0.169 \times (\delta\sigma / \delta x)$ for a eutectic SnPb solder ball. Comparing this value to the known design rule for a solder bump with 50 μm in diameter, the current density will be about 3×10^3 A/cm^2 [30].

It has been shown that electromigration occurred within a few hundred hours in eutectic SnPb solder joints kept at 150 ℃ under a current density of 8×10^3 A/cm^2 [5].

The critical current density for electromigration can be measured directly by measuring the rate of resistance change vs the current density as done by Wang et. al.[31]. They reported the critical current density, where no drift can be detected, in an aluminium conductor, to be approximately 1.6×10^5 A/cm^2.

3.3 Critical Length

With regard to back stress in electromigration of short strips, there is an issue related to the critical length of electromigration, as noted by Blech and Herring[18]. Backstress is defined as the stress gradient produced by the compressive stress at the anode. The theoretical critical length for electromigration is

$$\Delta x = \Omega / Z^* eE = \Delta\sigma\Omega / Z^* ej\rho \qquad (6)$$

Where $\Delta\sigma$ is the elastic limit, Ω is the atomic volume, j is the current density, and Z^* is the effective charge number. This concept can be extended to a solder ball, the length will then be the diameter of the solder ball. Substituting these values, the elastic limit $\Delta\sigma = 2 \sim 4 \times 10^8$ dyne/cm^2 [32]; $\Omega = 2.78 \times 10^{-23}$ cm^3; $eE = 1.6 \times 10^{-12}$ dyne and $Z^* = 34$ at 150 ℃, into equation (6), we obtain the critical diameter for eutectic SnPb to be approximately 1.0 μm. This value is comparable to the calculated critical length of 2.8 μm for eutectic SnPb solder[19] and 20 μm for Al[23]. Note that the critical length can be measured experimentally by extending the time of electromigration to a sufficiently long period until the mass transport in the strip cease

4. Discussion and Conclusion

The effective charge number of electromigration in eutectic SnPb solder is obtained as 34 and the critical current density is $j = 0.169 \times (\delta\sigma / \delta x)$ A/cm^2, where $(\delta\sigma / \delta x)$ is the electromigration-induced compressive stress gradient along the length of the line. The critical length for electromigration are also discussed.

As noted above, the electromigration in Pb-free solder $SnAg_{3.8}Cu_{0.7}$ is too small to accurately measure the moved volume by electromigration. However, we can assume rough data from the marker movement. Applying the eutectic SnPb solder data at 20 h to the $SnAg_{3.8}Cu_{0.7}$ data at 200 h, as shown in figure 8 of the results of Lee et. al.[20], we obtain the DZ^* value for $SnAg_{3.8}Cu_{0.7}$ as 6.62×10^{-11}. As expected, this value is very small compared with that for a SnPb solder ball. However, to date we cannot know the D and Z^* separately in Pb-free solder. More experiments are necessary in order to solve these problems.

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