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Investigation of Stress Evolution Induced by Electromigration in Sn-Ag-Cu Solder Joints Based on an X-Ray Diffraction Technique

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The critical current density and temperature endured by solder joints are identified as the two most important parameters that determine the occurrence of electromigration (EM). It is well known that movement of metal atoms/ions during current stressing can induce obvious stress concentrations at the anode and cathode interfaces of the solder joint. Therefore, the global average effects of EM on stress evolution at both the anode and cathode interfaces were investigated with different current densities by employing a nondestructive x-ray diffraction technique. The ultimate results indicated that the compressive stress increased gradually at the anode side under low current density. However, stress fluctuation could be observed under high current density due to an obvious Joule heating effect. For further understanding of the mechanism of stress evolution in the solder joint during current stressing, a four-stage model is considered. First, Cu expansion led to increase of the compressive stress at both electrodes. Second, stress relaxation compensated the compressive stress and caused it to decrease. Third, the EM effect promoted compressive stress and tensile stress at the anode and cathode, respectively. Finally, a steady state of stress was achieved at the anode, while the state of tensile stress at the cathode remained transient.

Key words: Electromigration, stress evolution, Joule heating

INTRODUCTION

With the trend towards microminiaturization of solder joints in electronic packaging, the current density increases rapidly, making electromigration (EM) reliability issues increasingly important.[1–3] EM is commonly defined as mass transport due to momentum exchange between conducting electrons and diffusing metal atoms when high current density is applied.[1] Great effort has been applied to understand and predict the degradation process of solder joints due to this phenomenon. Despite many studies of EM behavior, the exact degradation mechanisms during EM and stress-induced migration are very complicated and still not well understood.[4–6] Metal atoms diffuse along the direction of electron flux, which results in formation of voids or cracks at the cathode side and formation of hillocks at the anode side. Such formation of voids and hillocks may induce an opening to form in the solder joint, or may increase its net resistance, thus leading to malfunction or significant failure issues.[7–9]

The forced migration of atoms under the electron wind force is expected to cause compressive stress in the direction of the electron flow and tensile stress in the upstream direction with respect to the electron flow. When atoms reach the anode interface,

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compressive stress results, and a stress gradient is created due to the excess atomic flux. To relieve this stress gradient, hillocks or whiskers may be extruded out of the surface near the anode interface.[1,10] Therefore, elaboration of the stress formation process and its evolution mechanism is very important to understand EM behavior. X-ray diffraction technology has been applied for degradation studies to understand EM-induced stress concentration in copper or aluminum interconnects. Many reports of investigations into stress evolution in solder joints using synchrotron x-ray diffraction technology have been reported in literature. Wu et al.[11] studied the stress evolution in Sn strips at current density of 1×10^3 A/cm^2 or 5×10^3 A/cm^2. Results indicated that the corresponding measured back-stress gradient was 5.5 MPa/cm and 16.5 MPa/cm, suggesting that the protective oxide layer on the surfaces significantly influenced the kinetics of the stress evolution. Chen et al.[12] observed the transient state of stress buildup in Sn-Cu flip-chip solder joints at current density of 1.25×10^4 A/cm^2 for 100 h. The stress in the grain at the cathode end remained constant except for temperature fluctuations, while the compressive stress in the grain at the anode end built up as a function of time during EM until a steady state was reached. However, understanding of the stress evolutions observed for these types of bumps may be overshadowed due to the current crowding effect, which causes an irregular configuration of the solder joints. Different solder joints may exhibit different stress distributions after the same current stressing experiment. So, it is important that a reproducible joint structure be used. Besides, few studies have reported on use of conventional x-ray diffraction technology to measure such stress evolution. On the one hand, most work has focused on microsized solder joints, which are commonly fabricated in industry. On the other hand, the orientation or stress evolution initiated by EM has mostly been observed at the grain level, whereas observation of stress evolution through multigrains may directly reflect the combined influence of temperature and electric current on solder joints. Therefore, the purpose of the current study is to describe the stress evolution at the interface area by conventional x-ray technique exploration, using a solder joint with a size that is relatively larger than used in industry.

In this work, the stress evolution of Sn-Ag-Cu solder joints was investigated at current density of 5×10^2 A/cm^2, 4×10^3 A/cm^2, and 1×10^4 A/cm^2 using a conventional x-ray diffraction instrument. The stress fluctuation of the joints was measured in real time to obtain *in situ* data every few hours.

EXPERIMENTAL PROCEDURES

Oxygen-free high-conductivity copper sheet with thickness of 0.5 mm was cut into 25 mm × 2 mm strips by electrospark discharge machining (EDM). Before soldering the joints, these Cu substrate specimens were cleaned by dipping them into 30% nitric acid solution for 1 min, followed by acetone rinse and drying. Sn-3.0Ag-0.5Cu solder alloy was fabricated by alloying method. During the alloying process, a ceramic crucible was used as the container. After melting the solder, the liquid was cast into a rod ingot, which was then rolled to different thicknesses according to the requirements of the experimental conditions. The thickness of the solder sheet could be further precisely controlled using a spiral micrometer, and afterwards one solder disk and two Cu strips were placed into an aluminum elbow bracket. With the help of a stereomicroscope, the solder disk was placed between the two Cu strips, which were then fastened against the walls of the elbow bracket using bolts. In so doing, the structure of the solder joint could be manually controlled. Furthermore, a K-type thermocouple was fixed near the soldering region. The temperature of the setup was raised to 280°C in about 5 min before quenching in cold water to obtain fine microstructure. Detailed information about the joint preparation method can be found in a previous publication.[13]

As shown in Fig. 1, the cross-sectional geometry of the ultimate joint was a right-angled equilateral triangle, whose area could be calculated from the hypotenuse obtained by optical microscopy (OM); for example, as shown in Fig. 1, the length of the hypotenuse was measured to be 447 μm, and accordingly the cross-sectional area was 5.0×10^{-4} cm^2. It is obvious that the dimension of such a solder joint is relatively larger than those used in industry (such as in flip-chip joints) to accommodate the relatively larger beam size for the conventional x-ray diffraction analysis, enabling measurement of the stress evolution at interface areas. High current density of 10^4 A/cm^2 was produced by applying 5 A electric current to the solder joint. To obtain different current densities, the cross-sectional area of the solder joint and the applied electric current were varied. The parameters of the experimental conditions are listed in Table I. The Joule heating, ΔT, shows the difference in temperature between the air and the solder joint during the period of stress measurement, as detected by the thermocouple attached to the solder joint.

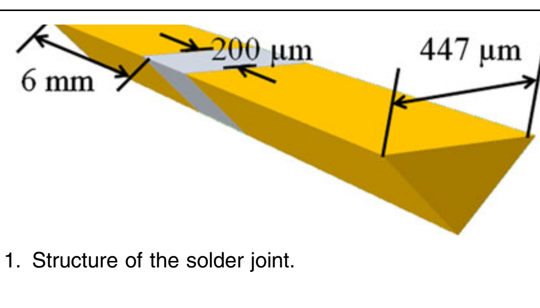

Fig. 1. Structure of the solder joint.

Table I. Experimental conditions

Cross-Sectional Area of the Solder Joint (cm^2)	Applied Electric Current (A)	Current Density (A/cm^2)	Joule Heating Effect, ΔT (°C)
2×10^{-2}	10	5×10^2	2
5×10^{-3}	20	4×10^3	50
5×10^{-4}	5	1×10^4	18

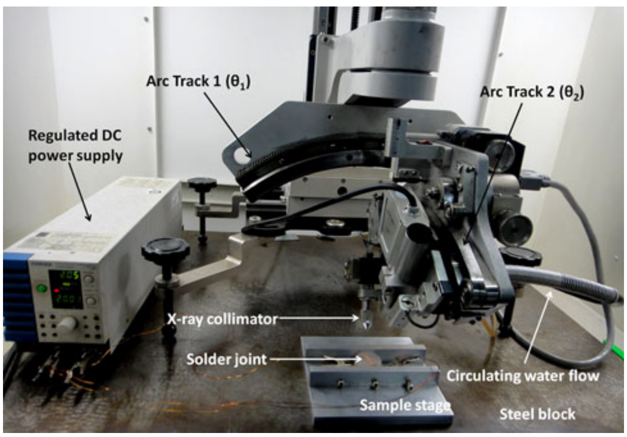

Fig. 2. Schematic of experimental setup.

The EM test was conducted under tightly controlled conditions. The sample was fixed on a self-designed stage and connected to a regulated direct-current (DC) power supply to provide a constant electric current output. The stress evolution was measured *in situ* using an x-ray diffraction instrument by aligning the laser spot with a measurement point near the interface of the solder joint. Figure 2 illustrates this experimental setup.

RESULTS AND DISCUSSION

It should be pointed out that the stress measurements carried out in this study were not taken from the solder matrix, but rather from the surface of the Cu substrate near the interface between the Cu substrate and the solder matrix. In some work,[14,15] Sn grains provided the x-ray diffraction crystal plane. However, Sn-Ag-Cu solder alloy is a multiphase material, i.e., intermetallic compound (IMC), which may influence the accuracy of the measurement results. Therefore, the change of the stress in the Cu substrate near the solder matrix was used to demonstrate the stress evolution in the interface. Figure 3 shows the stress evolution at the anode side of a solder joint under current density of 5×10^2 A/cm^2. It can be seen from the data in Fig. 3a that the stress distribution is scattered. Positive and negative sign indicate tensile and compressive stress, respectively. The stress variation at the Cu substrate was significant, with both compressive and tensile stresses shown at the same measurement point before current stressing. Hence, a precise calibration process was applied to provide a more precise Lorentz polarization factor, absorption coefficient, atomic scattering factor, etc. Besides, the average stress was used to illustrate the stress evolution directly. Figure 3b shows the stress evolution beside the anode in another sample. It is clear that the compressive stress decreased as the current stressing time increased. Such a scenario can be attributed to the temperature rise induced by the Joule heating effect. It is believed that the stress tends to relax after the sample is subjected to a dwell time at high temperature.[8] Nevertheless, one abnormal feature that can be observed is that the obtained stress values were much larger than expected for normal stress values in solder joints. This was because these data represent localized stress values. Macroscopically, the stress (of the whole solder joint) produced by EM should not be this large, but locally the stress (of a small, local area near the interface) might be larger than expected.

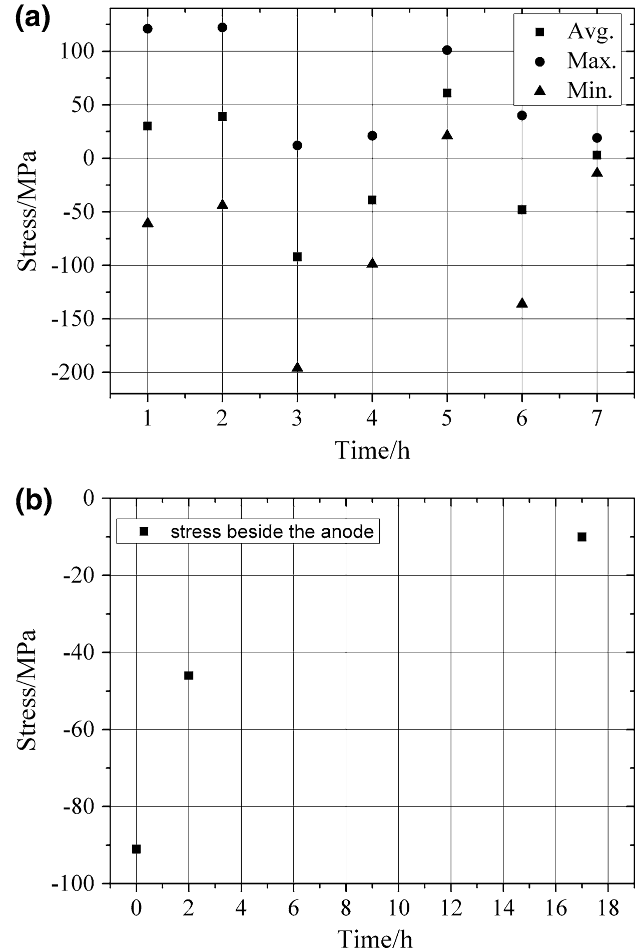

Fig. 3. Stress evolution of the solder under current density of 5×10^2 A/cm^2: (a) before calibration and (b) after calibration.

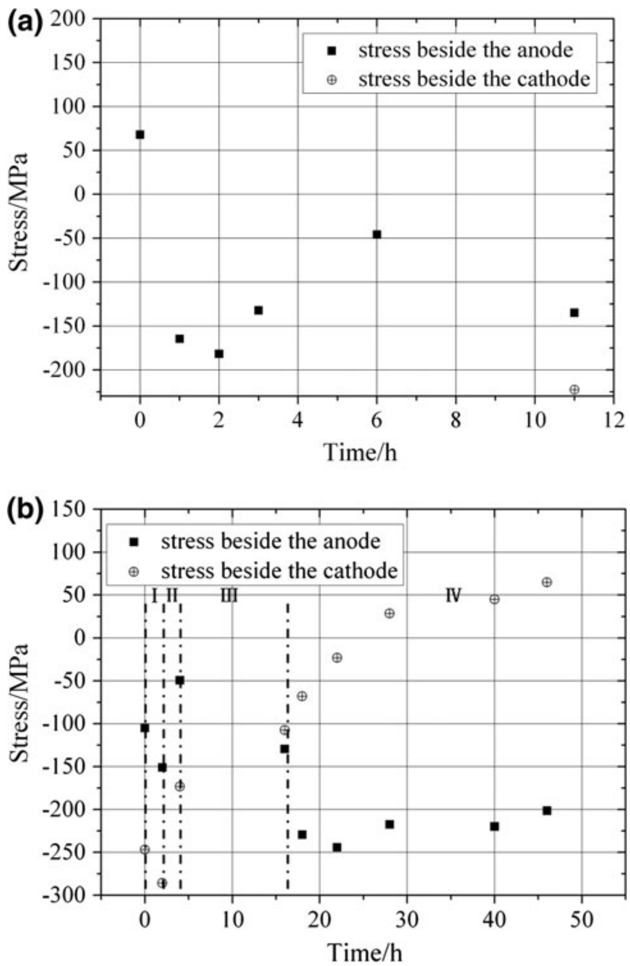

Fig. 4. Stress evolution of the solder under current density of 4×10^3 A/cm^2: (a) current stressing for 11 h and (b) current stressing for 46 h.

Figure 4 shows the stress evolution of a solder joint under current density of 4×10^3 A/cm^2. Tensile stress was obtained before current stressing, as shown in Fig. 4a. After applying the electric current to the solder joint, the stress firstly transformed into compressive stress and then exhibited an abrupt increase in a short time. Then, the compressive stress exhibited a period of decrease followed by another stage of increasing. Moreover, it was interesting to note that the stress beside the cathode also exhibited a compressive stress state after current stressing for 11 h. As is well known, atoms migrate from the cathode to anode under the electron wind force, leaving vacancies behind at the cathode.[1] As a result, tensile stress should be formed at the cathode. Therefore, the stress development tendency was measured in another sample under the same condition to verify these current stressing results for a longer time. The stress development tendency at both the anode and cathode is shown in Fig. 4b. The change of stress beside the anode was similar to that shown in Fig. 4a. The compressive stress rose abruptly at the initial stage, then decreased immediately, and then increased again. Finally, the fluctuation of the compressive stress became stable after current stressing for a longer time as compared with Fig. 4a. However, except for the initial increase of the compressive stress, the compressive stress at the cathode decreased continuously and became tensile stress with increasing current stressing time.

Based on the experimental results, the stress evolution depended on the relationship between the effects of Joule heating and EM. The evolution process can be divided into four stages. At the beginning of the current stressing, Joule heating increased rapidly to a high value due to the high applied electric current (20 A). A severe temperature rise was detected by the thermocouple, as shown in Table I, which could reach 50°C. This rapid increase of temperature can promote volume expansion of the Cu substrate and solder matrix in a short time. The coefficient of thermal expansion (CTE) of Cu and Sn is 17.5 ppm/°C and 2.0 ppm/°C, respectively.[16] For the experimental sample, the length of the Cu substrate and solder joint was 8 mm and 1 mm, respectively. According to the CTE equation,

$$\Delta l = \alpha l \Delta T, \tag{1}$$

where Δl is the length expansion, l is the original length, α is the CTE, and ΔT is the Joule heating. Therefore, the expansion of the Cu substrate and solder joint along the length orientation is 7 μm and 0.2 μm, respectively. The volume expansion of the Cu and solder made the compressive stress increase abruptly at both anode and cathode interfaces during the initial stage of current stressing; that is, the Joule heating played the dominant role in the compressive stress increase in the first stage.

The second stage is a stress relaxation stage. After current stressing for a period of time, the temperature became stable throughout the solder joint and Cu substrates. Few atoms could be transferred by the EM force during this current stressing time. Thereafter, stress relaxation led to a decrease of the compressive stress as illustrated in Fig. 4. Usually, the stress decreases rapidly at the beginning of the stress relaxation period, after which the stress relaxation slows down and reaches a constant value.[17] Therefore, stress relaxation played a significant role in the compressive stress decrease at both the anode and cathode sides.

The third stage was driven by EM. At this stage, an amount of atoms were transported from the cathode to the anode under the electron wind force, leaving vacancies at the cathode. The stress evolution at both interfaces was determined by the combined effects of mass transportation and stress relaxation. At the anode side, many more atoms accumulated at the anode side due to the continuous electric current stressing. Meanwhile, the relaxation rate decreased. The EM effect became more prominent than the effect of stress relaxation during this period. The EM effect not only compensated the decrease of compressive stress which resulted from the stress relaxation, but also contributed to the total compressive stress increase as well. This coupling effect between EM and stress relaxation triggered a compressive stress increase again at the anode side. At the cathode side, the concentration of vacancies induced tensile stress at the interface area. Overall, both the EM effect and stress relaxation accelerated the compressive stress decrease and made the stress transform from compressive to tensile stress at the cathode side.

In the fourth stage, the compressive stress became stable at the anode but the tensile stress increased continuously, as shown in Fig. 4b. The microstructure of the solder joint had undergone a series of changes due to the thermal and electric effects. At the anode side, because of the accumulation of atoms, a sufficient compressive stress had been established. The compressive stress was released by the formation of hillocks and whiskers after a long time of current stressing. Therefore, the stress reached an equilibrium state between the mass transportation and various stress relaxation modes. From Fig. 4b, the compressive stress values fluctuated in a small range in the fourth stage. On the other hand, the long-time concentration of vacancies at the cathode side formed voids. When compared with Fig. 4(b), it was believed that the stress changed from negative to positive was due to the improvement of tensile which caused by the migration of vacancies under the electron wind force. These voids speeded up the formation of cracks at this side and finally induced failure of the solder joint.

The stress evolution of a solder joint under current density of 1×10^4 A/cm^2 is illustrated in Fig. 5. The characterization of the stress beside the anode is similar to that of the solder joint under current density of 4×10^3 A/cm^2 when compared with Fig. 4. The difference between these two evolution tendencies lies in the increasing and decreasing rates. At the higher current density, the stress beside the anode changed faster and more profoundly, which may due to the difference of the size of the solder joint as presented in Table I. The smaller the solder joint, the more sensitive it is to Joule heating and electric current. To obtain a different current density in the solder joint, different sizes of solder joint and electric current were employed in the experiment, possibly changing the mechanism of Joule heating and EM effect in the solder joint. The measurement results may also be confused by these different conditions. Therefore, the size effect should be eliminated in future work. Besides, except for the annealing treatment, some other pretreatments should be done to ensure that the initial stress value is consistent between different samples.

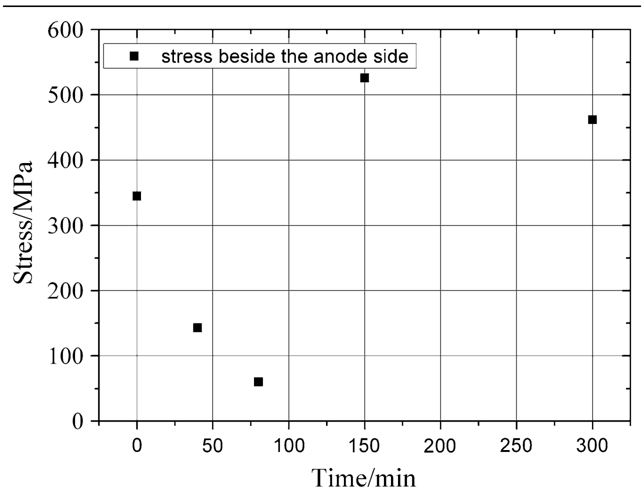

Fig. 5. Stress evolution of the solder under current density of 1×10^4 A/cm^2.

CONCLUSIONS

The stress evolution at both anode and cathode was used to demonstrate the Joule heating and EM effects on the solder joint. The stress evolution in Sn-3.0Ag-0.5Cu was investigated at different current densities. The compressive stress beside the anode side tended to decrease with increasing current stressing time when 5×10^2 A/cm^2 current density was applied to the solder joint. Higher current densities of 4×10^3 A/cm^2 and 1×10^4 A/cm^2 made the stress evolution more complicated. The stress evolution could be divided into a four-stage model. First, the compressive stress increased rapidly due to the expansion of the Cu substrate and solder joint at both interfaces, dominated by the Joule heating effect. Second, the stress relaxation process compensated the compressive stress and caused it to decrease. Third, the EM effect promoted an increase of the compressive stress at the anode and produced tensile stress at the cathode. Finally, the stress achieved a steady state at the anode through the interaction of the EM effect and various stress relaxation modes, but the tensile stress was enhanced continuously by the EM at the cathode.

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