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Effect of current stressing on the reliability of 63Sn37Pb solder joints

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Abstract The effect of current stressing on the reliability of 63Sn37Pb solder joints with Cu pads was investigated at temperatures of –5 °C and 125 °C up to 600 h. The samples were stressed with 3 A current (6.0×10^2 A/cm^2 in the solder joint with diameter of 800 μm and 1.7×10^4 A/cm^2 in the Cu trace with cross section area of 35 × 500 μm). The temperatures of the samples and interfacial reaction within the solder joints were examined. The microstructural change of the solder joints aged at 125 °C without current flow was also evaluated for comparison. It was confirmed that the current flow could cause the temperature of solder joints to rise rapidly and remarkably due to accumulation of massive Joule heat generated by the Cu trace. The solder joints stressed at 125 °C with 3 A current had an extensive growth of Cu_6Sn_5 and Cu_3Sn intermetallic compounds (IMC) at both top and bottom solder-to-pad interfaces. It was a direct result of accelerated aging rather than an electromigration or thermomigration effect in this experiment. The kinetic is believed to be bulk diffusion controlled solid-state reaction, irrespective of the electron flow direction. When stressed at –5 °C with 3 A current, no significant change in microstructure and composition of the solder joints had occurred due to a very low diffusivity of the atoms as most Joule heat was eliminated at low temperature. The IMC evolution of the solder joints aged at 125 °C exhibited a subparabolic growth behavior, which is presumed to be a combined mechanism of grain boundary diffusion and bulk diffusion. This is mainly ascribed to the retardant effect against the diffusion course by the sufficiently thick IMC layer that was initially formed during the reflow soldering.

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Introduction

Recently, the high current density induced electromigration of solder lines and solder joints has received lots of research interests as a reliability concern with association to the ever-increasing demands for current carrying capacity and miniaturization of the electronic interconnect structures [1, 2]. A great deal of work has been carried on the phenomenological and fundamental aspects of the solder electromigration [3–9]. The thin solder stripes or flip chip solder joints were stressed at high temperature above 100 °C with high current density at the order of 10^4 A/cm^2. It has been reported that transportation of the metal atoms along the electron flow direction could take place seriously, leading to dissolution hence depletion of the metals at the cathode end and enrichment of the moving species at the anode end. Moreover, the current crowding or non-uniformly distributed current density could enhance the migration process locally. As a result, micro-voids formed at the cathode side and hillocks piled up at the anode side would eventually bring on the failure of interconnect either by open joint or short circuit [10–14]. Chen and co-workers verified a directional polarity effect of electric current upon the IMC thickness at the interfaces of Sn with Ni, Ag, and Cu with the current density of 10^2–10^3 A/cm^2 [15]. Kao's group found a fast and localized dissolution of Cu at the cathode side of flip chip solder joints within a very short time under a current density of 2.5×10^4 A/cm^2 [16]. Liquefaction of solder alloys and rapid IMC formation has

been observed during the electromigration test [17]. Basaran's group analyzed the lead phase coarsening and concluded that electric current had greater influences on phase growth than that of temperature [18]. More recently, the thermomigration has been put forward with temperature gradient across the solder joints due to Joule heat in the high resistance conductor during current stressing. Concerning different structural and thermal properties of the interconnects, a temperature gradient of 1,000–1,200 °C/cm across a flip chip solder joint of 100 μm in diameter could exist and this was proved to be an enough driving force for the thermomigration [19–21].

However, most of the work were conducted on solder lines or flip chip solder joints having much small dimensions with current density as high as at the electromigration sensitive order of 10^4 A/cm^2. To date, less data has been related to a relatively larger solder joints stressed with low or moderate (10^2–10^3 A/cm^2) current density. Further more, the Joule heat induced temperature rise of the samples was not considered sufficiently. Lin et al. suggested that the effect of temperature on the time-to-failure was very strong [22]. Our previous study has also demonstrated that a large amount of Joule heat was produced if very narrow and thin copper conductors were used as daisy-chains connecting the ball grid array (BGA) solder joints to the electrodes during current stressing. Consequently, overheating induced melting of the solder joints occurred because of poor thermal dissipation capacity of the interconnect materials. Thus, excessive IMC growth within the solder joints was found as a result of reaction in liquid state [23]. It is expected that if a moderate current density is applied to large solder joints and they remain un-melted, the Joule heat would introduce a kind of thermal aging effect and it might turn out to be predominant over the electromigration or thermomigration. This study was intended to identify this possible aging effect using wide and thick copper daisy-chains to promote the heat dissipation and avoid melting of the solder joints. The impact of current stressing at different thermal conditions on the reliability of 63Sn37Pb (hereafter SP) solder joints has been evaluated in terms of local temperature measurement and interfacial reaction characterizing.

Experimental

Conventional eutectic SP solder balls with a diameter of about 760 μm were used to prepare solder joints between a small and large organic substrate. Both substrates are single side FR4 boards with 1 mm in thickness. The area of the small and large one is 15 × 15 and 44 × 44 mm, respectively. The Cu pad on the substrates is about 650 μm in diameter and 35 μm in thickness, covered by a very thin layer of organic solderability preservative (OSP) coating. The daisy-chains on both substrates are made of Cu traces with a width of 500 μm and a thickness of 35 μm. Except for solder pads and test pads, all area on the substrates was covered by common solder mask.

At first, the solder balls were placed onto the desired pads on the small substrate with the aid of WS60 paste flux (Alpha Metals). And, they were soldered in a 5-zone forced convection reflow oven (BTU VIP-70N) to form solder bumps. The temperature profile recorded from the substrate during reflow soldering has a peak value of 258 °C and the duration above 183 °C was about 128 s. Then, the small substrate was flipped down and attached to the large substrate by aligning the bumps with the corresponding pads using a Karl Suss 9493 Mauren Flip-Chip Bonder. Next, the whole assembly was soldered with the same reflow parameters to form solder joints and thereby provide interconnection between the two substrates. The configuration of the sample is shown in Fig. 1. In each sample, a total 12 solder joints were made, where each 6 was distributed in line along two sides of the small substrate. After cleaning and drying, the samples were divided into several groups for subsequent experiments.

Some samples were subjected to 3 A constant current stressing through designated daisy-chains and electrodes for different time period. An IXL-LDX-3500 type precision current source was used to assure constant and stable electric current, in any case of resistance fluctuation of the circuit. Two thermal conditions, –5 °C and 125 °C, were achieved by putting the samples into different temperature ovens with highly stable and precisely controlled system. Figure 2 describes the current flow directions within a pair of neighboring solder joints from the cross-sectional view. The diameter and stand height of the solder joint is about 800 and 450 μm, respectively. The average current density in the solder joints with 3 A current was calculated to be

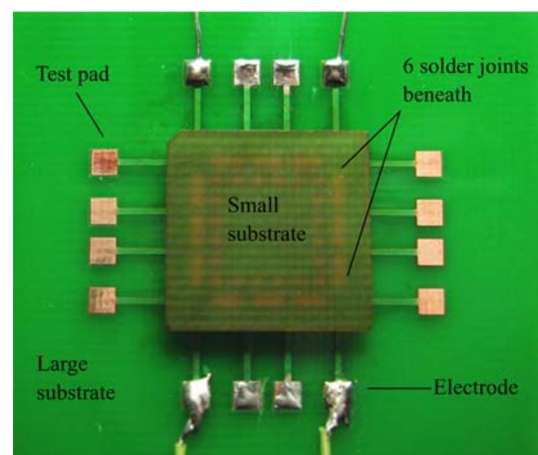

Fig. 1 Sample for temperature measurement and current stressing

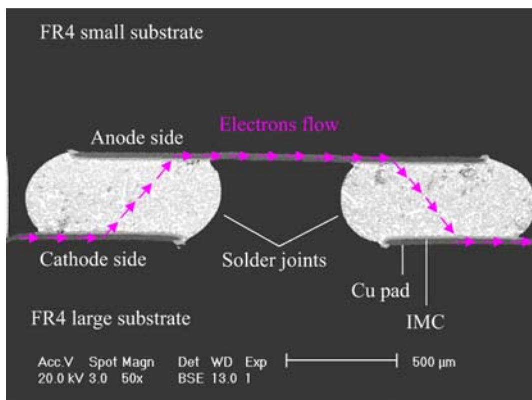

Fig. 2 Cross section view of a pair of solder joints for current stressing tests

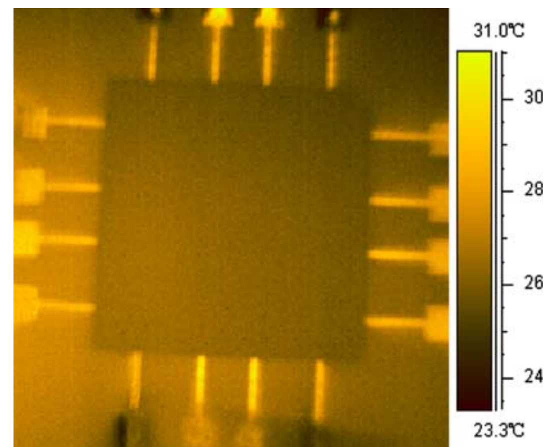

Fig. 3 Temperature distribution before current stressing

about 6.0×10^2 A/cm^2, whereas it is about 1.7×10^4 A/cm^2 in the Cu traces. Some other samples were isothermally aged at 125 °C without current flow for the same time period.

In order to check the temperature increase induced by the Joule heat, some solder joints were stressed at room temperature (20 ± 2 °C) with 3 A and 6 A current. A ThermaCAM 390 type thermal microscopy was used to characterize the temperature variation of the samples. The samples were put on a glass stage and infrared thermal imaging photo was taken from time to time during the test. In a separate experiment the temperatures of the backside of large substrate was measured continuously when the current stressing test was conducted at temperatures of –5, 20, and 125 °C with 3 A and 6 A current. Micro thermocouples were fixed at the bottom of large substrate right beneath the solder joints row using Aron Alpha instant glue. And the temperatures were monitored by an M.O.L.E. Thermal Profiler system.

After current stressing test, the samples were metallographically cross-sectioned, mounted in a cold setting epoxy, and polished towards the middle of the solder joints. To reveal the thicknesses and morphologies of IMC, the polished surfaces were slightly etched in a 3 vol.% HCl aqueous solution. At last, the cross-section of solder joints were viewed by a Philips XL40 FEG type scanning electron microscope (SEM) equipped with an energy dispersive X-ray (EDX) analysis system.

Results and discussion

Figure 3 shows a typical photo of the sample taken by the thermal microscopy, depicting the initial temperature status before current stressing at room temperature. It seems that the Cu traces displayed a slightly higher temperature than the FR4 substrate. This discrepancy in temperature distribution is reasonable due to the experimental variation in thermal radiation/reflection capabilities of the substances and difference in distances from the objective lens. Once the current was powered on, the temperature of the sample increased immediately with an average ramp rate about 0.3 °C/s for the case of 3 A current stressing. After about 180 s, the thermal imaging became stable and very little variation of the temperature was observed with the time. This suggests a dynamic equilibrium achieved between the heat generation and heat dissipation. Figure 4 displays the temperature distribution of the sample after about 360 s with 3 A current flow. The highest temperature was about 75.9 °C, locating at the places on small substrate right above the solder joints row. This was a mean increment of 47.9 °C from the initial condition. When 6 A current was applied, the highest temperature could reach as high as 127.2 °C after about 600 s, as shown in Fig. 5.

Figure 6 traces out the local temperature of the large substrate right beneath the solder joints row with respect to

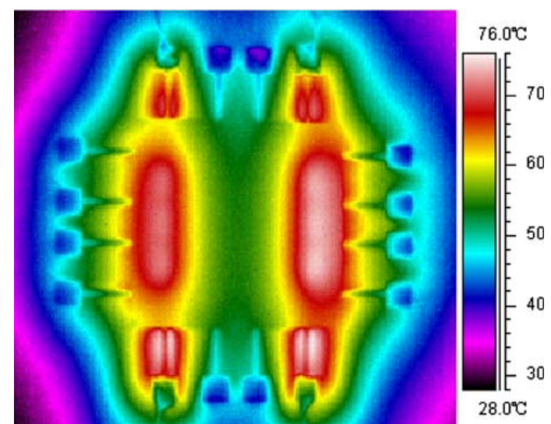

Fig. 4 Temperature distribution with 3 A current stressing after about 360 s

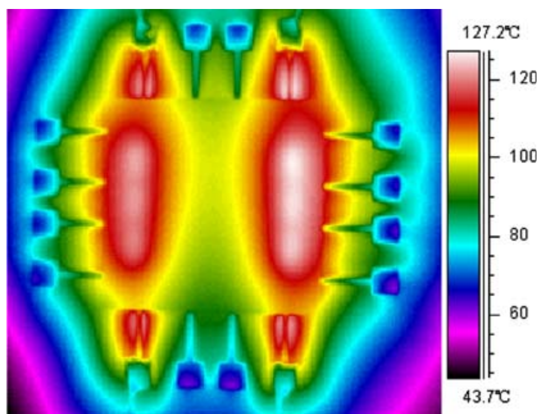

Fig. 5 Temperature distribution with 6 A current stressing after about 600 s

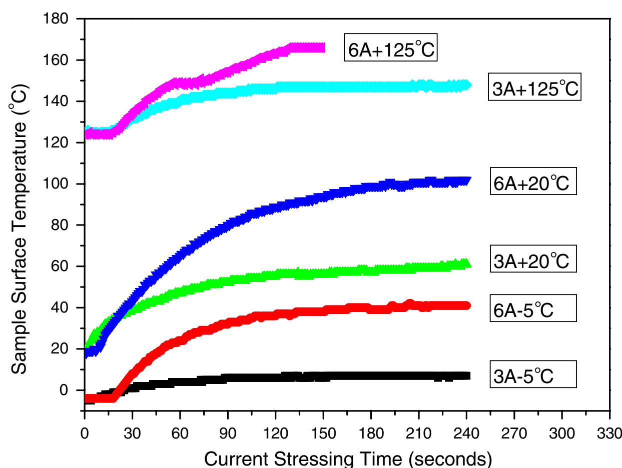

Fig. 6 Temperatures of backside of large substrate right beneath the solder joint row during current stressing (measured by the M.O.L.E. thermal profiler)

the current stressing time monitored by the M.O.L.E. thermal profiler at three testing temperatures. All temperatures rose rapidly at first and then slowly, and finally they tended to stabilize within a few minutes except the case of 6 A current stressing at 125 °C. For the cases with 3 A current stressing, the final temperatures, for –5, 20 and 125 °C, remained nearly constant around 7, 61 and 148 °C, respectively. It was noted that with 6 A current stressing at 125 °C, the circuit broke down after about 150 s, probably due to the melting of solder joints arising from over-heating. At that moment, the highest temperature detected was about 167 °C. Since the FR4 substrate is not a good heat conductor and there is a thermal gradient between the solder joints and the backside of the large substrate, the real temperature of the solder joints is at least 10–15 °C higher than those recorded at the backside of the substrate. Although it is difficult to measure the temperature of the solder joints directly, this is convincible from the fact that the solder joints was melted down because of its temperature higher than 183 °C, while the substrate temperature measured was only 167 °C. Thus, any possible migration process during current stressing at local region should not merely be considered taking place at the oven temperatures.

For simplification of calculating the Joule heat generated by the circuit, the solder joints are treated as cylinders with length of 450 μm and diameter of 800 μm according to Fig. 2. The total length of the Cu traces between two electrodes is 44 mm. The electrical resistance, R, of a conductor can be expressed as:

$$R = \rho l/A$$

Where ρ is the electrical resistivity, l the length and A the cross section area of the conductor. The amount of heat energy, Q, being absorbed by the solder joints and Cu traces to have a temperature change of ΔT is given by:

$$Q_{\text{solder}+\text{Cu}} = (M_{\text{solder}}\ C_{\text{solder}} + M_{\text{Cu}}\ C_{\text{Cu}})\Delta T$$

Where M is the mass and C the specific heat. The Joule heat, J, generated herein can be determined with the following formula:

$$J_{\text{Joule}} = I^2\,(R_{\text{solder}} + R_{\text{Cu}})t$$

Where I is the current and t the current flowing time. It is calculated that a temperature rise of 50 °C just needs about the total amount of Joule heat produced with 3 A current for 1 s. In other words, within 100 s, the temperature of the structure can rise about 50 °C if only 1% of the total Joule heat is used to rise the temperatures of the solder joints and Cu traces. Thus, it is not surprising to observe quick temperature rise and then it maintained at a high level. And, when 6 A is applied at 125 °C, the final Joule heat accumulated locally was enough to rise the temperature of the Cu traces exceeding the melting point of the SP, and thereby the solder joints connected to the Cu traces were melted.

Figure 7 plots the average thickness of IMC layer at both top and bottom interfaces versus the time of aging or 3 A current stressing. It presents clearly that the IMC layers was thickened markedly as stressed at high temperature, whereas it remained almost constant when stressed at low temperature.

Figure 8a and b show a typical cross section SEM picture of the top and bottom interface in the as-reflowed solder joints with OSP/Cu pads of small and large substrate, respectively. The IMCs at both interfaces were confirmed by EDX to be Cu_6Sn_5. The top interface had

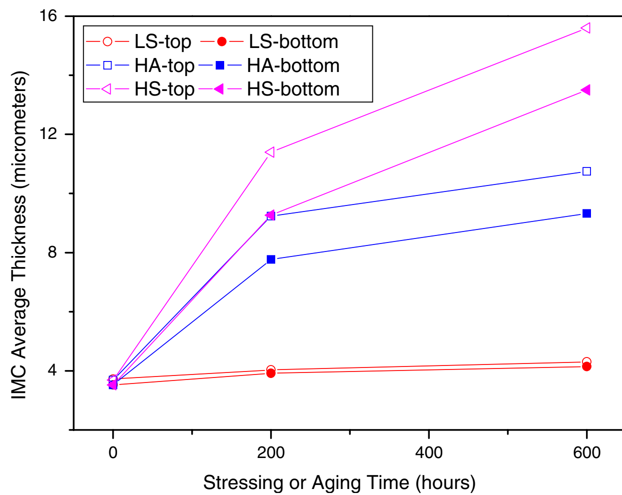

Fig. 7 Average thickness of IMC layer at top and bottom interfaces in the solder joints

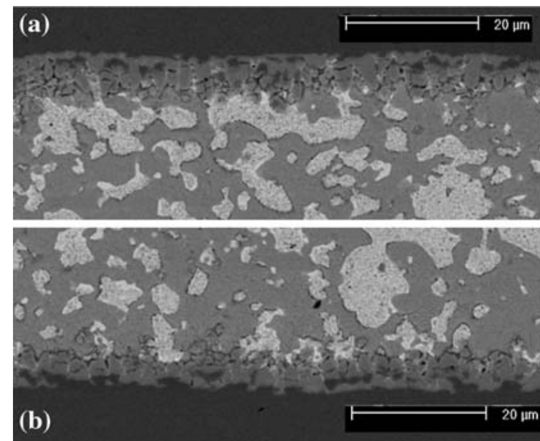

Fig. 9 Top and bottom interfaces in the solder joint after 600 h 3 A stressing at –5 °C

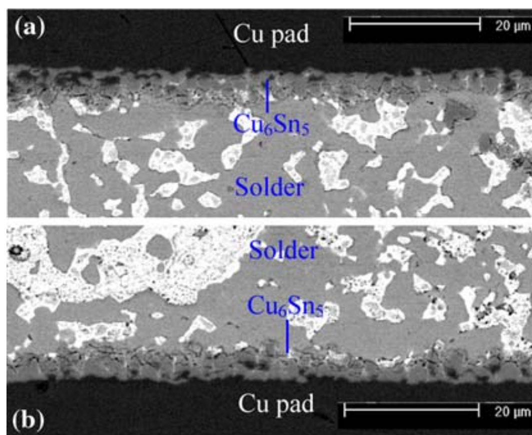

Fig. 8 Top and bottom interfaces in the solder joint as reflowed

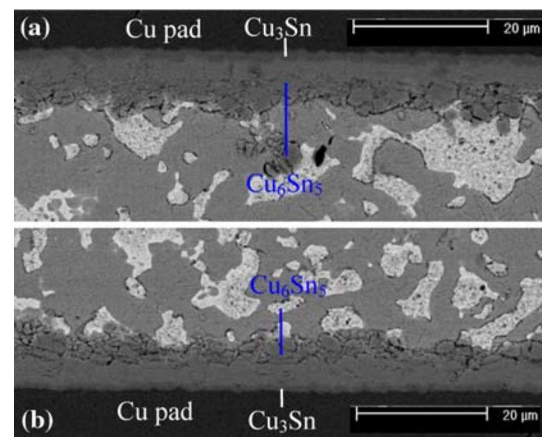

Fig. 10 Top and bottom interfaces in the solder joint after 200 h aging at 125 °C

undergone twice reflow processes, producing a thick IMC layer with average thickness of 3.72 µm, somewhat thicker than that at the bottom interface (3.52 µm). Although the IMC layers were thick due to high temperature and long time soldering, they were not compact and the boundaries between IMC and Cu pads were not flat. This was largely because of the non-uniform reaction and the time delay for volatilization of some OSP patches during soldering. Both the composition and thickness of the IMC layers did not change significantly when the sample were stressed at –5 °C, even after 600 h, as can be seen in Fig. 9a and b.

Meanwhile, the IMC morphology and composition evolved noteworthily when the samples were aged at 125 °C for 200 and 600 h, as shown in Figs. 10 and 11, respectively. A thin layer of Cu_3Sn IMC emerged between the Cu_6Sn_5 IMC and Cu pads. The part of IMC near the Cu pad is compact and flat and the part near the solder is loose and irregular (flake-like). The IMC layers at both interfaces

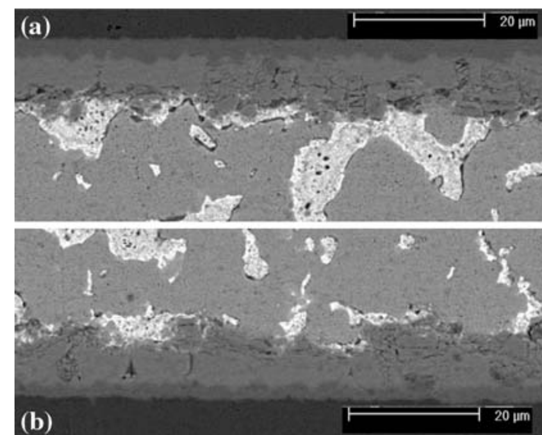

Fig. 11 Top and bottom interfaces in the solder joint after 600 h aging at 125 °C

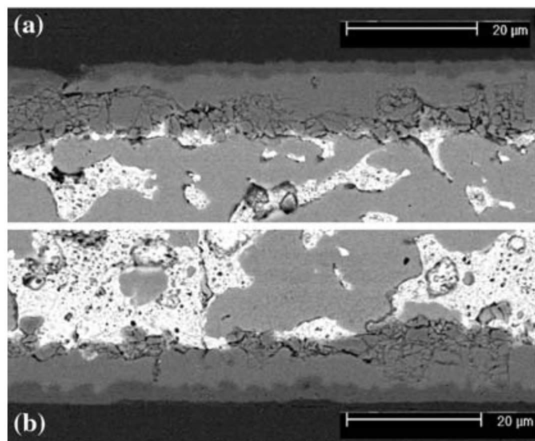

Fig. 12 Top and bottom interfaces in the solder joint after 200 h 3 A stressing at 125 °C

were at least two times thicker than that in the original samples as reflowed. By contrast, the interfaces in current stressed samples evolved dramatically, as displayed in Figs. 12 and 13. When comparing Figs. 10 and 11 with Figs. 12 and 13, it was found that the current flow contributed to an additional growth of IMC with a thickness of about 4.2–5.1 μm. It indicates that the interfacial reaction between the solder and Cu pads was accelerated by the current flow. More precisely, the inter-diffusion coefficient between them increased quite a lot since it is exponentially proportional to the temperature. It can be understood from the thermal measurement that the high current density induced Joule heat helped rise the local temperature of the solder joints to be more than 125 °C, which enhanced the diffusion process. At the same time, the enormous collision between high flux of electrons and metal atoms facilitated the atoms with large mobility and high energy to move along the electron flow direction. The dissolution of Cu

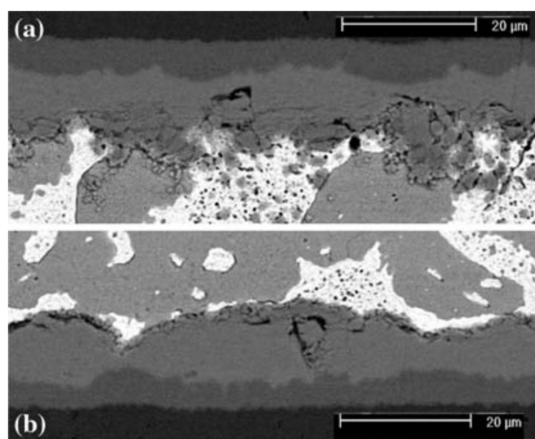

Fig. 13 Top and bottom interfaces in the solder joint after 600 h 3 A stressing at 125 °C

atoms from pads and IMC layer into the solder at the cathode side and Sn atoms motion from the solder and IMC toward Cu pads at the anode side resulted in the occurrence of extensive IMC growth at both sides. This dissolution and retardant effect of initial IMC could cause an enrichment situation of Cu atoms at the Cu pads to IMC interface, resulting remarkable Cu_3Sn growth as thick as 5.2 μm for 600 h. It was suggested that the ratio of diffusivities D_{Cu3Sn}/D_{Cu6Sn5} increases with the increase of temperature [24, 25]. The high concentration of Cu atoms and high temperature benefited the emergence and development of the Cu_3Sn other than the thickening of Cu_6Sn_5 in solid reaction. This is why the ratio of Cu_3Sn to whole IMC layer increased quite a lot when comparing Fig. 13 with Fig. 12.

Also, the coarsening of both lead-rich (white area) and Sn-rich phase (gray area) was noticeable after aging and current stressing. Since the underlying kinetics is grain boundary or interfacial boundary solute diffusion [25], the coarsening phenomenon herein became more serious with the increase of time and temperature.

It should be pointed out that the current directions in two adjacent solder joints were opposite; but the IMC growth tendency of both solder joints was similar in this work. It is believed that although the electron flow might counteract partially the effect of diffusion-induced thickening, it still could not compete over the thermal diffusion since the electromigration effect was not so prominent with this moderate level of current density. The local temperature of the solder joints with 3 A at 125 °C was estimated to be around 170 °C, which was enough for a fast inter-diffusion process. Nevertheless, as the sample was stressed at low temperature of –5 °C, a large portion of the Joule heat was removed and the diffusivity and mobility of atoms were very small. Therefore, the IMC morphology and composition remained almost unchanged.

If we ignore the electromigration effect, the governing power law of the IMC growth kinetics at a particular temperature can be empirically expressed as [26]:

$$x - x_0 = kt^n$$

where x is the total thickness of the reaction layer at time t, x_0 the initial thickness (i.e., at the aging time of $t = 0$), k the growth rate constant and n the time exponent.

The above equation can be rewritten into the following logarithmic expression:

$$\ln(x - x_0) = \ln k + n \ln t$$

The values of k and n for a particular temperature can be obtained by means of multivariable linear regression analysis. It was calculated (using the data with bottom interfaces) that for the 125 °C aging, n value was about

0.28, which is smaller than the values obtained by others [27]. This exhibits a subparabolic kinetics ($n < 1/2$) of the IMC thickening. The retardant effect against the diffusion process by initial IMC layer with sufficiently large thickness was most likely responsible for this subparabolic growth at solid state. Recalling Figs. 10 and 11, the growth rate of Cu_3Sn was higher that of Cu_6Sn_5, which indicates that the situation was chemically and thermodynamically preferable for this phase. It was said that the n value of Cu_3Sn growth kinetic is smaller that of Cu_6Sn_5. A time-dependent apparent diffusivity of reacting species could also be a reason for the different values reported in the literature [28]. It is presumed here that once the Cu_3Sn emerged, it became increasingly difficult for the diffusion of constituent elements to pass through the existing thick IMC layer to reach the reaction sites. Thus, under the condition of short supply of Sn atoms, some part of the Cu_6Sn_5 was consumed to react with Cu atoms and form Cu_3Sn. In addition, according to Roming et al., the Boltzmann transformation in deriving the parabolic growth relationships assumes the constancy of molar volume within the system, which is not always valid when intermediate phases of vastly different crystal structures form. The absence of molar volume constancy during the IMC growth process may also contribute a little bit to the low growth rate with the increasing of aging time [26]. In a word, the reaction kinetics for the pure aging with initially thick IMC was presumed to be a combined mechanism of grain boundary diffusion and bulk diffusion. Meanwhile, for the case of 3 A current stressing at 125 °C, n value was about 0.50. This is similar to the results found for temperature around 170 °C [27], which proved the accelerated aging effect induced by the current flow. In this case, the IMC evolution could be taken as a diffusion-controlled behavior. It can be rationalized that high temperature and enormous collision help excite the atoms readily for fast diffusion.

Conclusions

Based on the test results and analysis, the following conclusions can be reached.

The electromigration and thermomigration effect in the solder joints with diameter about 800 μm were not significant with the moderate current density of 6.0×10^2 A/cm^2 up to 600 h at 125 °C. The current stressing may cause the temperature of sample to increase rapidly and eventually maintain at a high level due to massive accumulation of Joule heat. And the local temperature of the solder joints stressed with 3 A current in 125 °C is believed to be around 170 °C. The direct phenomenon was extensive IMC development at both top and bottom interface in the solder joints, regardless of the current flow direction. Therefore, an accelerated inter-diffusion between solders and both top and bottom pad materials dominated the reaction rather than an electromigration or thermomigration process.

The IMC evolution showed a subparabolic behavior in the aged solder joints at 125 °C with initially thick IMC layer, which is presumed to be governed by a combined mechanism of grain-boundary diffusion and bulk diffusion. The IMC development exhibited a parabolic manner in the stressed solder joints with 3 A current at 125 °C, which is considered as bulk diffusion controlled reaction. For those stressed with 3 A at –5 °C, no significant change occurred in microstructure due to the elimination of most Joule heat.

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