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Effect of temperature on interface diffusion in micro solder joint under current stressing

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Abstract: The effects of temperature on Cu pad consumption and intermetallic compound (IMC) growth were investigated under current stressing. The Cu/Sn−3.0Ag−0.5Cu (SAC305)/Cu solder joints were used, with a certain current density of 0.76×10^4 A/cm^2 at 100, 140, 160 and 180 °C. The constitutive equations of cathode Cu pad consumption and anode interface IMC growth are established, respectively, based on the loading time and sample temperature. The cathode Cu pad consumption (δ) increases linearly with the loading time and the consumption rate shows parabolic curve relationships with sample temperature. The anode interface IMC thickness (δ_1) increased is linearly with the square root of loading time and the interface IMC growth coefficient shows parabolic curve relationship with sample temperature. The δ and δ_1 have different variation laws under current stressing, due to the current facilitating larger amount of IMC formation in the bulk solder.

Key words: electromigration; element diffusion; intermetallic compounds; Cu pad consumption

1 Introduction

The trend of miniaturization and the pursuit of greater performance in the microelectronics industry lead to a significant increase of the current density in micro solder joints. Electromigration (EM) has been a key and persistent reliability problem in micro-electronic technology, due to high current density in the micro solder joints [1−3]. The EM accompanies with the growth of anode IMC and the consumption of cathode pad, and both of them can lead to the solder joint failure owing to the decrease of mechanical properties and electrical properties [4−6].

Some studies showed that anode interfacial IMC thickness increased linearly with the square root of time [7−9]. CHAO et al [10] showed that the thickness of anode IMC layer increased linearly with the time. The IMC growth was faster at the higher current density or temperature during EM [11]. The fast dissolution of Cu and Ni was found at the cathode within the μBGA package [12]. The consumed thickness of Cu pads increased with the decrease of initial Cu concentration and the increase of soldering volume [13].

From the above, a number of researches [7−13] reported that the EM impacted on interface IMC growth and soldering pad consumption; however, each of research results is inconsistent and the influence rules of temperature on the consumption of Cu pad and the growth of IMC remain unidentified. Thus, it is necessary to establish the constitutive equation of the cathode consumption pad and the anode interface IMC growth under current stressing, for which has significant meaning on the EM test and electronic components life prediction.

In this work, the cathode Cu pad consumption and anode interface IMC growth were investigated at different temperatures. The constitutive equation of cathode Cu pad consumption and anode interface IMC growth were established, respectively, based on the loading time and sample temperature. Meanwhile, the reason of different variation rules between pad consumption and IMC growth during current stressing was analyzed.

2 Experimental

In this work, the solder joints Cu/Sn−3.0Ag−0.5Cu (SAC305)/Cu were used. The schematic diagram of test sample is shown in Fig. 1. The diameter of the solder

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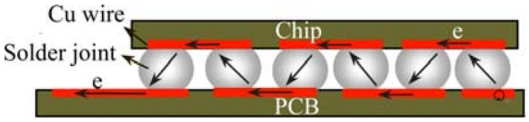

Fig. 1 Schematic diagram of test sample

joint was 400 μm, the opening diameter of the contact window to the solder was 310 μm, and the Cu wire had a thickness of 70 μm. The samples were prepared by reflow in a hot-air convective reflow oven. The peak temperature was 265 °C, and the sample was kept at the peak temperature for 30 s. The first reflow was carried out to solder the solder joints on simulate chip, and the second reflow was carried out to assemble the simulate chip and simulate printed circuit board (PCB). Figure 2 shows the microstructure of solder joint after reflow.

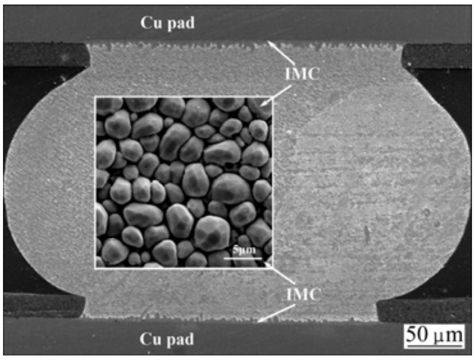

Fig.2 Cu/SAC305/Cu solder joint and IMC morphology after reflowing

In order to ensure a stable temperature of the specimen during the test, a virtual test system built by NI Compact DAQ platform combining with NI−9213 temperature module was used to monitor the temperature of the test. The first group of samples was carried by EM test. Testing current was set as 5.7 A, which produced a current density of 0.76×10^4 A/cm^2. Under the combined effect of Joule heating and furnace, the specimen temperature was maintained at 100, 140, 160 and 180 °C, respectively, for 25, 50, 100 and 200 h. The second group of samples was sustained thermal aging test (160 °C) to obtain Cu pad consumption and interface IMC growth in thermal aging process. In this test, twenty-four solder joints were used under the same test condition. The average of consumption Cu pad and thickness of IMC were calculated by dividing the area of IMC by the length of interface. Deep-etching method was performed to observe the 3D morphology of the IMC.

3 Results and discussion

3.1 Cu pad consumption and IMC growth during thermal aging

After reflow, a thin layer Cu_6Sn_5 is formed between Cu pad and SAC305 solder, and a small amount of Cu pads are consumed, as shown in Fig. 2. The Cu_6Sn_5 shows bump–like appearance. The thickness of Cu_6Sn_5 is about 5.72 μm and the consumption of Cu pad is about 2.75 μm. Figure 3 shows the micrograph of solder joint after thermal aging at 160 °C for 200 h. After thermal aging, Cu_6Sn_5 shows layer-type morphology and the grain size of Cu_6Sn_5 increases, meanwhile, a layer of Cu_3Sn forms between Cu_6Sn_5 and Cu pad. Figure 4 shows the thicknesses of interface IMC (Cu_6Sn_5+ Cu_3Sn) and the Cu pad consumption vs the annealing time. As the aging time rises, both the thickness of interface IMC and the consumption of Cu pad increase. The kinetics of IMC growth obeys the parabolic-growth law, which indicates that the formation of IMC is a diffusion-controlled reaction. The growth kinetic matches well with that reported by ONISHI and FUJIBUCHI [14]. The consumption of Cu pad has similar variation law with the growth of IMC, as shown in Fig. 4. The main reason is that Cu pad reaction with Sn formed Cu_6Sn_5 at the Cu−solder interface, so the consumption of Cu pad and the growth of IMC have close relation and similar rule.

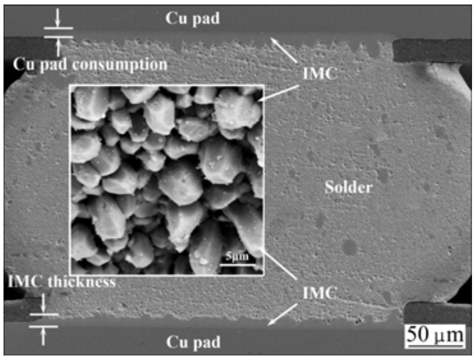

Fig. 3 IMC growth, Cu pad consumption and IMC morphology after thermal aging at 160 °C for 200 h

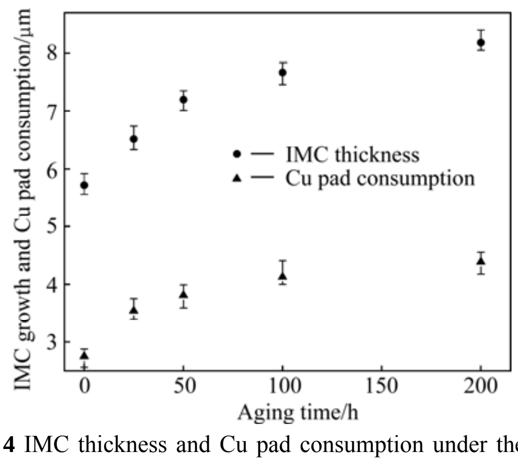

Fig. 4 IMC thickness and Cu pad consumption under thermal aging at 160 °C after different aging time

3.2 Cu pad consumption and IMC growth under current stressing at different temperatures

The microstructure of solder joint stressed with current density of 0.76×10^4 A/cm^2 at 180 °C for 200 h is shown in Fig. 5. The arrows marked by "e" in Fig. 5 indicates the direction of electron flow. At the cathode, a significant amount of Cu is consumed and the Cu pad consumption (δ) is 10.72 μm, meanwhile, the Cu pad exhibits serrated morphology. The grain size of Cu_6Sn_5 at the anode is bigger than that at cathode. The consumed Cu atoms are drifted to the anode by current, producing a significant growth of Cu_6Sn_5 at the anode interface, and the thickness of anode interface IMC is 15.95 μm. As the temperature increases, the cathode Cu pad consumption and the anode IMC growth increase after the same stressing time, as shown in Table 1. Because the higher temperature accelerates the Cu migration from the cathode Cu pad to solder bulk and Cu finally reaches anode reaction with Sn forming Cu_6Sn_5 [15−17].

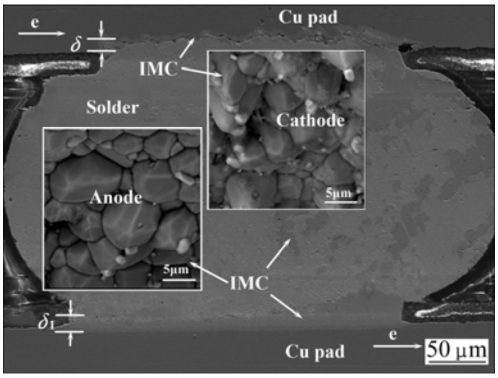

Fig. 5 Cu pad consumption and IMC thickness under current stressing for 200 h (J=0.76×10^4 A/cm^2, θ=180 °C)

3.2.1 Cathode Cu pad consumption under different temperatures

Figure 6 shows the relationship between the consumption of cathode Cu pad and loading time at different temperatures. The Cu pad consumption followed a linear relationship with the stressing time by data fitting, as shown in Fig. 6. The relationship between consumption of Cu pad and loading time can be written as

$$\delta=At+B \tag{1}$$

where δ is the consumption of Cu pad; A is the consumption rate; t is loading time and B is a constant that is the Cu pad consumption after reflow. The higher the temperature is, the faster the consumption of Cu pad is. The consumption rates are 0.007, 0.015, 0.026 and 0.038 μm/h at the temperatures of 100, 140, 160 and 180 °C, respectively. The correlation between the Cu pad consumption rate (A) and temperature (θ) is shown in Fig. 7. The function of A and θ is obtained by fitting experiments data as following which is roughly accordance with parabolic correlation:

$$A=4.68\times10^{-6}\theta^2-9.24\times10^{-4}\theta+0.053 \tag{2}$$

where θ is temperature. Combining Eqs. (1) and (2), the consumption of Cu pad can be written as

$$\delta=(4.68\times10^{-6}\theta^2-9.24\times10^{-4}\theta+0.053)t+B \tag{3}$$

3.2.2 Growth of interface IMC of anode under different temperatures

Under different temperatures, the correlation between thickness of anode IMC layer (δ_1) and square root of stressing time ($t^{1/2}$) is shown in Fig. 8. The δ_1 and $t^{1/2}$ approximately satisfy the linear correlation, which is consistent with the literature result [10]. The relationship between δ_1 and $t^{1/2}$ can be written as

$$\delta_1=A_1t^{1/2}+B_1 \tag{4}$$

where A_1 is the growth coefficient; t is loading time and B_1 is the thickness of IMC after reflow (a constant). The growth coefficient (A_1) increases with the temperature rising. The growth coefficients are 0.007, 0.015, 0.026 and 0.038 μm/h$^{1/2}$, respectively, at the temperatures of 100, 140, 160 and 180 °C. Figure 9 shows the growth coefficients at different temperatures, which shows the parabolic correlation between A_1 and θ, and the relationship between A_1 and θ can be expressed as

$$A_1=5.91\times10^{-5}\theta^2-0.01\theta+0.84 \tag{5}$$

Combining Eqs. (4) and (5), the growth thickness of anode interface IMC can be written as

$$\delta_1=(5.91\times10^{-5}\theta^2-0.01\theta+0.84)t^{1/2}+B_1 \tag{6}$$

The consumption of Cu pad directly affects the growth of interface IMC. It should have the similar variation law between Cu pad consumption and interface IMC growth if the consumed Cu is used to react with Sn forming interface IMC, and both of them obey the parabolic-growth law during thermal aging test.

Table 1 Cu pad consumption and IMC thickness (J=0.76×10^4 A/cm^2)

θ/°C	Consumption of cathode Cu pad/μm					Thickness of anode IMC/μm				
	0 h	25 h	50 h	100 h	200 h	0 h	25 h	50 h	100 h	200 h
100	2.75	3.34	3.51	3.82	4.33	5.72	7.88	8.65	9.35	9.91
140	2.75	3.57	4.22	4.31	6.14	5.72	8.65	9.55	10.46	11.56
160	2.75	3.97	4.51	6.09	8.18	5.72	9.50	10.57	11.70	13.54
180	2.75	4.80	5.35	7.73	10.72	5.72	10.52	11.98	13.55	15.95

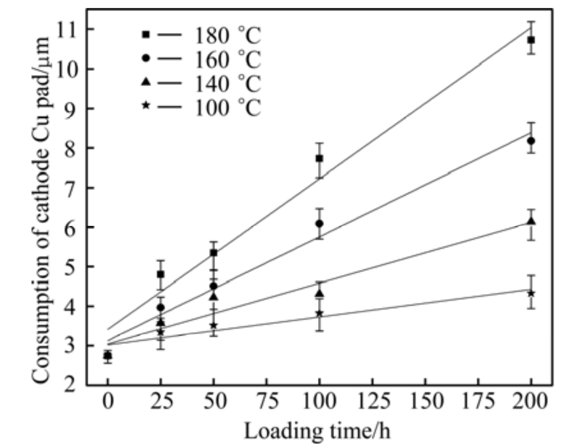

Fig. 6 Consumption of Cu pad vs loading time under different temperatures (J=0.76×10^4 A/cm^2)

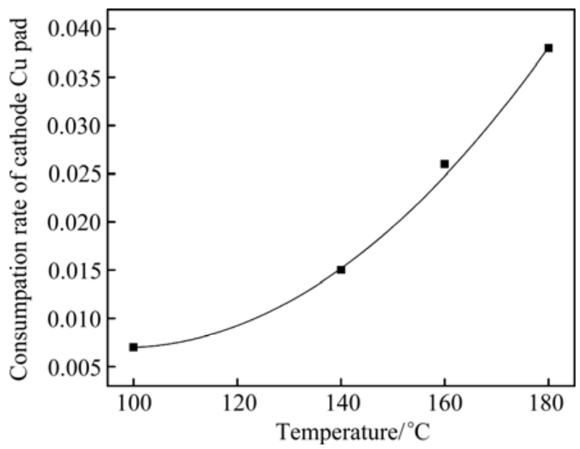

Fig. 7 Consumption rate of Cu pad at different temperatures (J=0.76×10^4 A/cm^2)

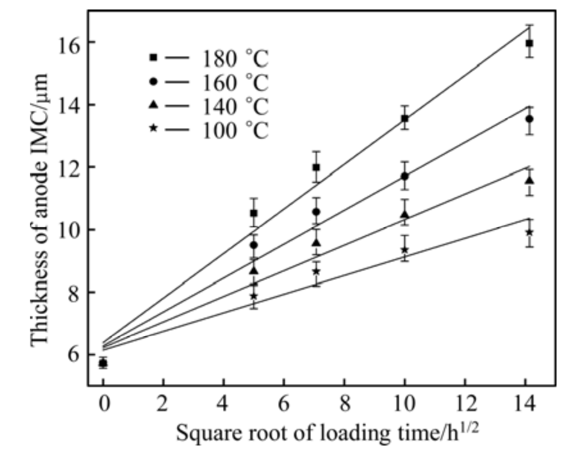

Fig. 8 Thickness of anode IMC vs square root of loading time (J=0.76×10^4 A/cm^2)

However, there are different change rules during the EM test between Cu pad consumption and interface IMC growth. The anode interface IMC growth follows the parabolic rule with the loading time, and the cathode Cu pad consumption has a linear relationship with the loading time. Comparing with the anode interface IMC growth rate, the cathode Cu pad consumption rate is faster. The main reason is that the current facilitated the IMC formation in the bulk solder (as shown in Fig. 5) [18]. The Cu atoms which are from Cu pad form IMC not only at the interface but also in solder bulk. So, the consumption rate of cathode Cu pads is larger than the growth rate of anode interface IMC.

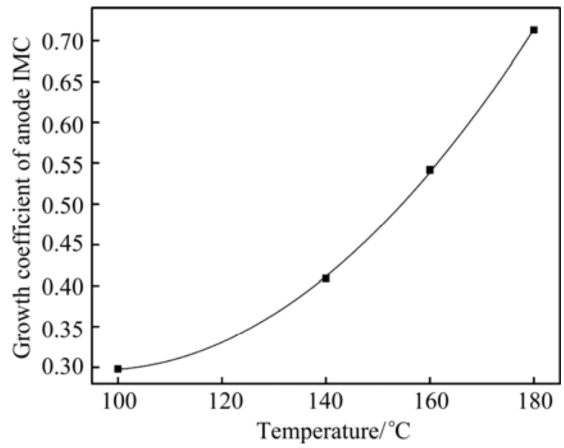

Fig. 9 Growth coefficient of anode IMC at different temperatures (J=0.76×10^4 A/cm^2)

4 Conclusions

1) The consumption of cathode Cu pad increases linearly with the loading time and the consumption rate shows parabolic curve relationship with the sample temperature.

2) The growth thickness of anode interface IMC increases linearly with the square root of loading time and the growth coefficient shows parabolic curve relationships with the sample temperature.

3) Consumption of cathode Cu pad and growth of anode interface IMC have different variation rules during electromigration. This is because that the current facilitates large amount of IMC formation in the bulk solder.

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电载荷作用下温度对微焊点界面扩散的影响

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摘 要：以 Cu/SAC305/Cu 为研究对象，研究温度对电迁移过程中界面金属间化合物(IMC)生长及 Cu 焊盘消耗的影响。试验过程中加载的电流密度为 0.76×10^4 A/cm^2，试验温度分别为 100、140、160 和 180 °C。分别建立焊点阴极 Cu 焊盘消耗及阳极界面 IMC 厚度的本构方程。在电迁移过程中，焊点阴极 Cu 焊盘消耗量与加载时间呈线性关系，Cu 焊盘消耗速率与试样温度呈抛物线关系。阳极界面 IMC 厚度与加载时间的平方根呈线性关系，且界面 IMC 的生长速率与试样温度呈抛物线关系。在电迁移过程中，阳极界面 IMC 生长与阴极 Cu 焊盘消耗有不同的变化规律，这是由于电流作用下焊点体钎料内形成了大量的 IMC。

关键词：电迁移；元素扩散；界面化合物；Cu 焊盘消耗

(Edited by Xiang-qun LI)