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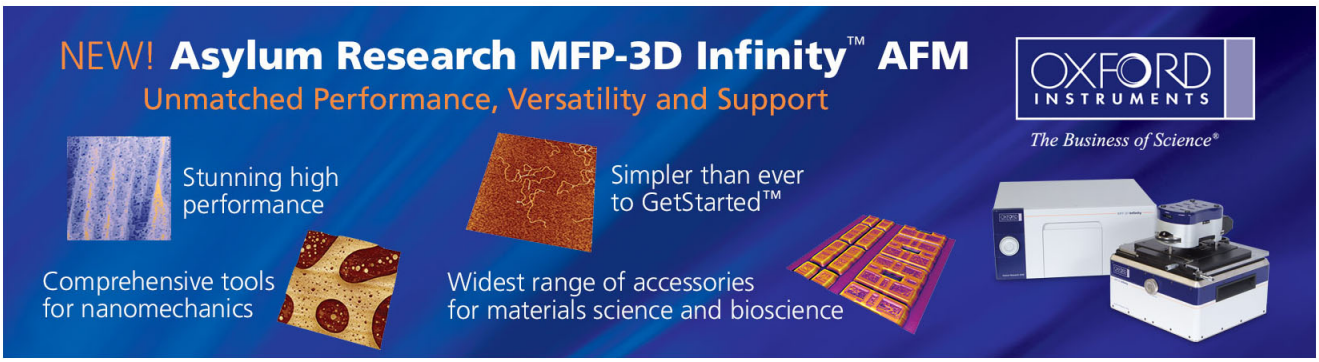

Effect of three-dimensional current and temperature distributions on void formation and propagation in flip-chip solder joints during electromigration

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Effect of *three-dimensional* current distribution on void formation in flip-chip solder joints during electromigration was investigated using thermoelectrical coupled modeling, in which the current and temperature redistributions were coupled and simulated at different stages of void growth. Simulation results show that a thin underbump metallization of low resistance in the periphery of the solder joint can serve as a conducting path, leading to void propagation in the periphery of the low current density region. In addition, the temperature of the solder did not rise significantly until 95% of the contact opening was eclipsed by the propagating void. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2220550]

Electromigration has become a critical reliability issue for high-density solder joints in flip-chip technology.[1,2] Electromigration-induced failures and mean time to failure (MTTF) of flip-chip joints have been investigated for both eutectic SnPb and Pb-free solders.[3–10] It was found that voids were formed inside the solder adjacent to the underbump metallization (UBM),[4] and propagated along the interface between the solder and the UBM, causing opening failure of the joints when the voids eclipsed the entire contact opening. However, the mechanism of void nucleation and growth and especially the corresponding change of current distribution in the solder joint due to void formation are unclear. In particular, it is unknown why some voids are formed at the periphery of the UBM opening under the dielectric, where the current density is low.[8,11] In Blech structure of Al stripes, Tu *et al.* proposed that resistive vacancy might move to the low current density region to form voids due to the high gradient of current density, which was as high as 10^{10} A/cm^3.[12] However, for flip-chip solder joint, the gradient is estimated to be only 1.33×10^6 A/cm^3 owing to its large dimension.[8] Therefore, the growth of voids in the periphery of the UBM opening, which is located at the low current density region, may not be driven by the gradient of current density. In this letter, three-dimensional finite element method was employed to simulate the effect of void formation on redistribution of current density and temperature in a flip-chip solder joint, especially in the periphery area where a low-resistance thin-film UBM exists.

Three-dimensional (3D) thermoelectrical coupled simulation was carried out by finite element analysis to find out the current density and temperature redistributions in our test samples.[13] The model used was a SOLID69 eight-node hexahedral coupled field element with ANSYS software. The electrical and thermal resistivities of the materials as well as the boundary conditions used in this modeling followed those of our previous study.[13] In our samples, the diameters of the passivation opening and the UBM opening were 85 and 120 μm, respectively. Figure 1(a) shows the cross-sectional view of the current density distributions before void growth when 0.28 A was applied to the bump. The Al trace, the UBM in the chip side, and the metallization in the substrate were ignored. It was found that the current crowded into the solder bump in the passivation opening. The current crowding behavior near the entrance of the Al trace can be clearly demonstrated. The maximum current density reached 5.42×10^4 A/cm^2, which is about 22 times higher than the average value. It is proposed that this local high current density was responsible for the initial void formation due to flux divergence.[4,6] Figure 1(b) illustrates the temperature distribution before void formation. The maximum temperature inside the solder bump was 109.6 °C; therefore, the increase in temperature due to Joule heating was only 9.6 °C. The temperature was quite uniform inside the bulk of the solder.

In stage I, a semicylindrical void, 45.5 μm in diameter and 13.0 μm in height, was formed inside the solder near the entrance of the Al trace. The current redistributed due to void formation, and the maximum current density occurred in the solder near the upper left corner of the periphery of the UBM opening under the Al trace. As shown in Fig. 2(a), void for-

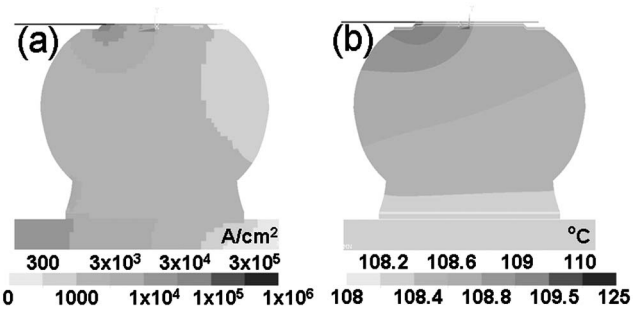

FIG. 1. (a) Cross-sectional view of current density distribution in solder joint before void formation; (b) corresponding cross-sectional view for temperature distribution.

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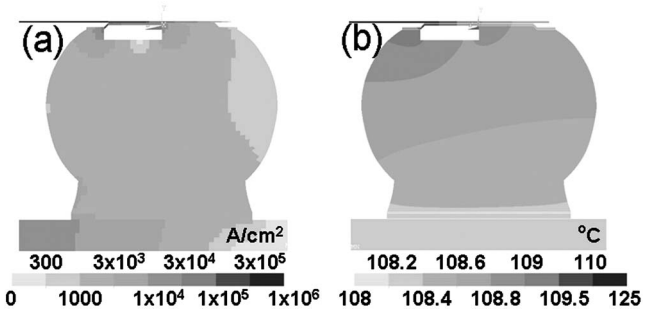

FIG. 2. (a) Cross-sectional view of current density distribution in solder joint at stage I; (b) corresponding cross-sectional view for temperature distribution.

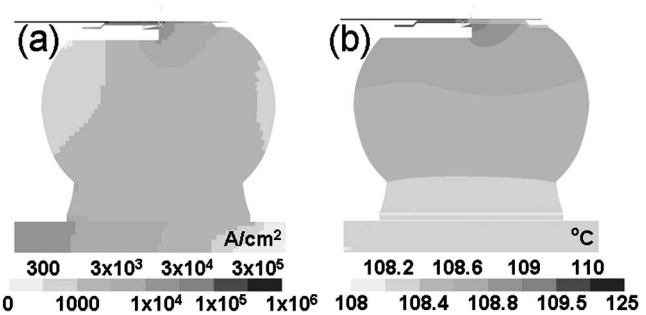

FIG. 3. (a) Cross-sectional view of current density distribution in solder joint at stage II; (b) corresponding cross-sectional view for temperature distribution.

mation resulted in redistribution of current in two ways. First, current may drift farther along the Al trace, passing the void, and entered the solder. Second, the current may drain down to the solder through the surrounding UBM/intermetallic layer (IMC) layer. It is intriguing that the UBM/IMC layers served as a current path, directing the current into the upper left corner of the periphery of the UBM opening. Since the UBM/IMC layers have much higher electromigration resistance,[2] voids are formed mainly inside the solder. It is clear that the solder on the left of the void has higher current density than that under the passivation opening. Therefore, voids may propagate toward the solder in the UBM periphery. Compared with that shown in Fig. 1, the maximum current density inside the solder has been reduced to 4.43×10^4 A/cm^2 due to void formation. On the other hand, the temperature inside the solder decreased slightly to 109.5 °C, which was 0.1 °C lower than that before void formation, as illustrated in Fig. 2(b). This may be attributed to the smaller crowding effect as a result of void formation.

Since the maximum current density occurred near the periphery of the UBM opening, we assume that the void propagates toward the left-hand-side periphery, as illustrated in Fig. 3(a). The void depleted 50% of the UBM opening, which is denoted as stage II. Since the UBM/IMC layers still serve as a current path, the void may be able to propagate to the edge of the solder bump. Therefore, we postulate that the growth of void in the low current density region under the periphery of the UBM opening is mainly attributed to current redistribution, not to the gradient of current density. The maximum current density inside the solder bump reduced further to 4.04×10^4 A/cm^2 due to void formation. Figure 3(b) shows the corresponding temperature distribution in the solder bump. The maximum temperature in the solder was 109.3 °C, which was 0.2 °C lower than that in stage II. Again, this may be due to the smaller crowding effect in the solder joint at this stage. Although there was a slight increase in temperature in the Al pad, the temperature inside the solder did not alter much at this stage. From the results reported by Gee *et al.*,[11] the shape of the void may resemble a pancake shape for solder joints with thin-film UBM. In addition, due to the limitation of our simulation modeling, semicylindrical voids were adopted in this study. However, whether it is circular, semicircular, or irregular remains unclear at this moment, and needs further experimental investigation.

The void was then assumed to propagate to fill 80.5% of the UBM opening, as shown in Fig. 4(a). It is denoted as stage III. The current entered the joints through a smaller contact area, causing an increase in maximum current density. It rose to 8.70×10^4 A/cm^2, and almost the whole passivation opening experienced current density higher than 1.0×10^4 A/cm^2. Therefore, void propagation would expedite in this stage. The maximum temperature in the solder bump increased to 109.4 °C because of the higher current crowding effect at this stage, as shown in Fig. 4(b). In the absence of current flowing through the solder in the left-hand side of the joint, the temperature on the right-hand side was higher than that on the left-hand side. However, there was still no obvious temperature increase in the solder close to the entrance point of the current into the solder.

The solder in the passivation opening was completely depleted at this final stage, leaving a small amount of solder near the periphery of the UBM opening, as illustrated in Fig. 5(a). There was approximately 4.0% of contact area left for conducting the current at this stage. With further decrease in contact area, the maximum current density became 1.69×10^5 A/cm^2. The UBM/IMC layers served as a conducting path to direct the current to the remaining solder. Hence, the remaining solder near the periphery of the UBM opening could be completely depleted and failure followed. Figure 5(b) shows the temperature distribution at this stage. The maximum temperature in the solder bump was 110.4 °C, which was 0.8 °C higher than that before void formation.

TABLE I. The simulated maximum current density inside the solder, the corresponding crowding ratio as well as the bump resistance at each stage.

	Original bump	Stage I	Stage II	Stage III	Stage IV
Void proportion (area%)	0	28.8	50.0	80.5	96.0
Maximum current density inside solder (A/cm^2)	5.42×10^4	4.43×10^4	4.04×10^4	8.70×10^4	1.69×10^5
Bump resistance (mΩ)	11.2	14.6	19.0	25.3	42.9
Maximum temperature inside solder (°C)	109.6	109.5	109.3	109.4	110.4

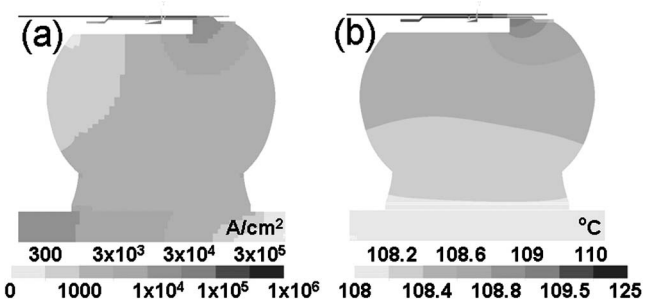

FIG. 4. (a) Cross-sectional view of current density distribution in solder joint at stage III.; (b) corresponding cross-sectional view for temperature distribution.

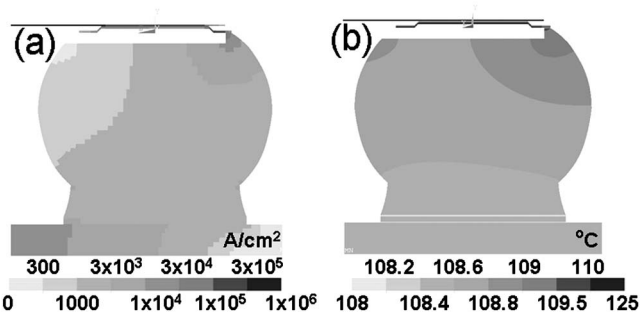

FIG. 5. (a) Cross-sectional view of current density distribution in solder joint at stage IV; (b) corresponding cross-sectional view for temperature distribution.

Our simulation also shows that bump resistance increased gradually in the first three stages, and then increased rapidly in the final stage, as shown in Table I. Bump resistance was defined as the decrease in voltage between the entrance point of the Al trace into the Al pad (disk) and the junction point of the Cu line with the solder joint. In stage I, the bump resistance increased from 11.2 to 14.6 mΩ. It increased to 19.0 and 25.3 mΩ in stages II and III, respectively. It rose to 42.9 mΩ in stage IV. This increase in bump resistance may also enhance the local Joule heating effect. However, no significant local Joule heating was found in the thermal simulation up to stage IV. This may be attributed to the fact that the major heating source was the Al trace.[14] In our model, the total resistance of the Al trace was about 1800 mΩ. Consequently, the increase in bump resistance was quite small compared with that of the Al trace. In addition, the increase in bump resistance was mainly due to the following manner: owing to void formation, the current needed to drift farther in the Al pad (disk), and then flowed down to the solder bump. Therefore, the local Joule heating in the Al pad (disk) increased when voids were formed. Since there was good heat dissipation in the Si side, the increase in temperature due to void formation was quite small. Nevertheless, the increase might be higher when larger current was applied, since the overall Joule heating would be significantly higher at higher stressing current.

In summary, we have employed the 3D finite element method to simulate the current and temperature redistributions due to the formation and propagation of a pancake-shape void in solder joints during electromigration. It is proposed that current redistribution is the main reason accounting for void formation and propagation, especially the propagation into the low current density region below the contact passivation. It is found that UBM provided a conducting path for current to go below the passivation, and it directed the current to the periphery of the solder joint, which is in agreement with the experimental observation of void formation in those regions. Increase in temperature due to void formation was not significant since the major heat source was the Al trace and the applied current was as low as 0.28 A.

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