Optimal Design of Passivation/UBM Openings for Reducing Current Crowding Effect Under Electromigration of Flip-chip Solder Joint

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Abstract

Electromigration of flip-chip solder joints has been studied extensively in recent years. It was investigated in plenty of studies that the current crowding effect takes place at the corner near the traces due to huge differences of dimensions between traces and solder joint. The local high current density, which has been known as a serious reliability issue, causes the failure such as void formation and under bump metallization (UBM) consumption to occur much earlier than expected in the current-crowding region in solder bump. As a result, to relieve the current crowding effect can significantly increase the mean-time-to-failure (MTTF) of solder bump, since the MTTF may be doubled when the local current density is reduced to half of its original value. However, there is still no technology can observe the current density directly in a current stressed sample. In order to obtain more precise observation, a three-dimensional finite element model (3D-FEM) was performed to simulate the current density distribution in solder bump.

Several dimensions, radius of Al pad, passivation opening and width of Al trace, in this model were varied to analyze the current density distribution. The UBM opening is 60μm. The width of Al trace, the radius of Al pad and the passivation opening were varied from 50μm to 100μm by 10μm, 60μm to 120μm by 10μm, and 12μm to 48μm by 3μm respectively. The most effective design to relieve the current crowding effect which was found in this study is to fix the ratio of the radius of passivation opening and UBM opening between 0.5 to 0.6. The ratio is relative to the width of Al trace and the radius of Al pad. The ratio is close to 0.6 with a larger radius of Al pad and a narrower Al trace.

On one hand, the ability of relieving current crowding effect is only relative to the radius of passivation opening when the ratio is less than 0.3. On the other hand, the ability of relieving current crowding effect is also limited by the radius of the Al pad. The wider the Al trace is, the lower the current crowding will be. When the radius of Al pad is larger than 100μm, the change of Al trace width makes no influence on relieving current crowding effect. The influence of these dimensions, width of Al trace, radius of Al pad and passivation opening show saturated condition.

This approach facilitates the systemic study of optimized design to relieve the current crowding effect and thus increase the EM resistance of solder joints. In addition, the results provide a guideline for optimal design for solder joints with a specific UBM structure.

Introduction

Recently, EM (EM) has been recognized as a critical reliability issue for flip-chip technology. EM is a phenomenon of mass transport in metallization structures when the metallization is stressed with high current density. As the technology improves, the chip size shrinks and a larger current density capability is required. The size of solder joint has been scaled down significantly in recent years and the amount of current carried by each bump has been increased from 0.2 A to 0.4 A. This makes it possible to induce EM failures. The applied current for accelerating EM tests could be as high as 2 A [1]. Several studies investigated the EM behavior on different sizes of solder bumps. Liang et al. adopted the eutectic SnPb (e-SnPb) solder of about 150μm height for studying the EM phenomenon [2]. Therefore, how to design the solder joint geometry with different passivation opening radius and Al pad radius to improve the failure life of EM is essential.

Due to the unique geometry of a flip-chip, current crowding occurs at the contact interface between the solder bump and the UBM. The current crowding at the interface between the solder bump and the UBM causes the formation of voids. The void propagates across the entire solder/UBM interface and leads to failure. Ouyang et al. study the void formation under EM by using 90μm -high solder joints [3]. Chang et al. used Kelvin structure to monitor the change in resistance and the void propagation progress of 75μm bump height during EM [4]. Moreover, EM in solder joints with bump size less than 30μm is also investigated [5,6]. The volume effect of the solder joints on the reaction of intermetallic compound (IMC) is also examined. However, few works have been done on the current density distribution with the same layout but with different dimensions of Al pad, Al trace and passivation opening.

The current density plays an important role on the failure time. This study proposes a finite element model to simulate the current density distribution in solder joint. With the simulation results, designing a robust structure becomes an urgent issue to relieve the current crowding effect, reduce the EM failure and obtain a longer life time. The simulation results show that the ratio of the radius of passivation opening and UBM opening makes a significant impact on the EM lifetime; and there is an optimized ratio to get the longest EM lifetime. However, the ability to relieve current crowding is limited by dimensions of Al pad and Al trace. Therefore, a robust design against EM should consider optimized dimensions of passivation opening, Al pad and Al trace to get the best solution.

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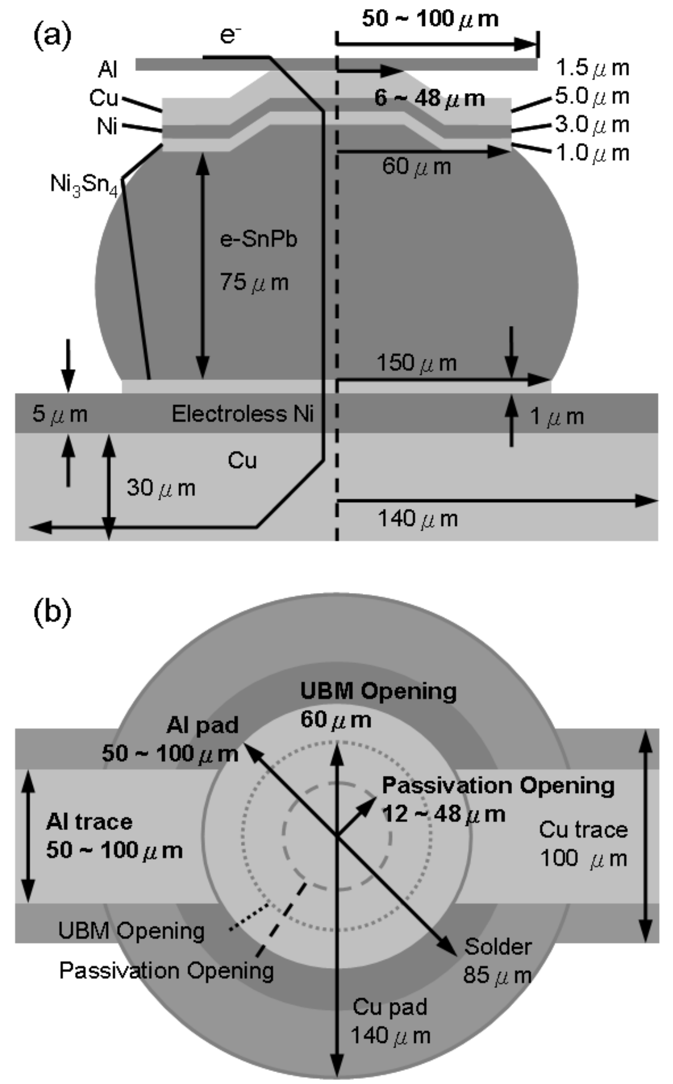

Fig. 1. The schematic models for the solder joint: (a) the cross-sectional view (b) the plane view

Simulation

This study uses parametric simulation method to analyze the effects of relations between diameters of contact opening, and UBM opening. The inferences of Al trace width and Al pad are also performed in this study. The simulation geometry used in this study is schematically shown in Fig. 1. In order to fit the results of our previous studies, a flip-chip solder joint structure with thick-film UBM is built. Only one solder joint is includes in this simulation structure.

The cross-sectional view of model used in this study is shown in Fig. 1(a). The thickness of Al pad is 1.5μm. The UBM is a bilayer structure which is composited by 5.0μm Cu and 3.0μm Ni. Both the thick Cu and Ni layer are electroplated. The metallization of 3.0μm thick electroless Ni was used on the substrate side. The thickness of Cu pad is 30.0μm. It is assumed that 1.0μm Ni_3Sn_4 IMC forms at the interface of solder and the Ni metallization on both chip side and substrate side. IMCs are assumed to be layered-type to avoid difficulties that may arise during meshing process.

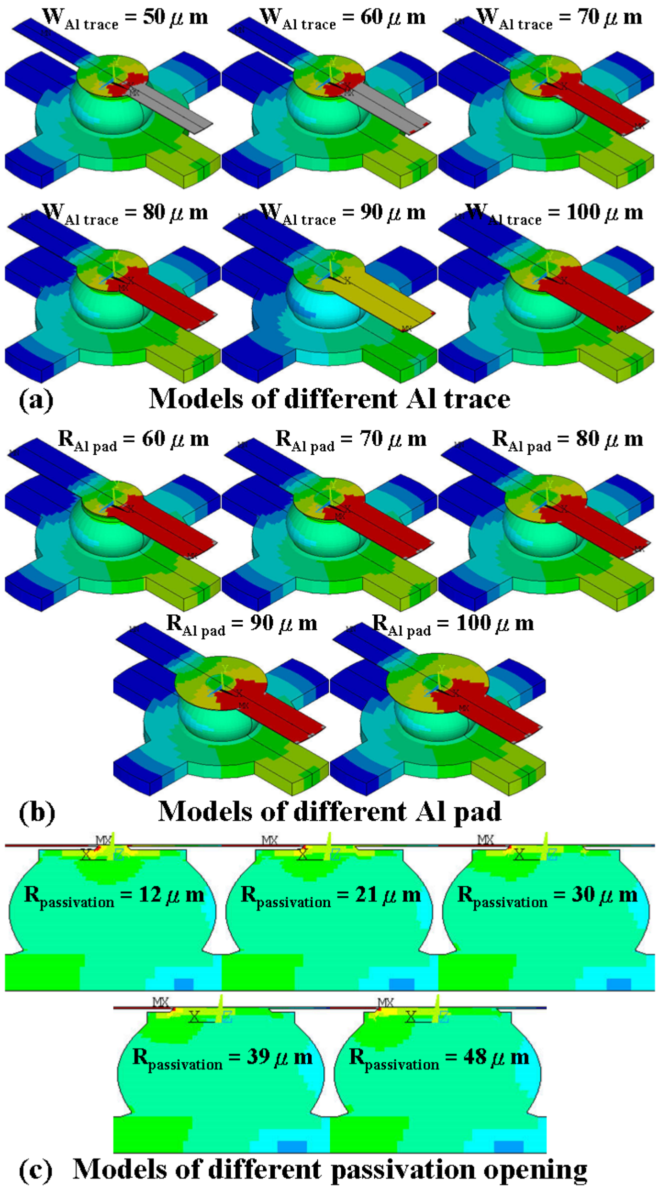

Fig. 2. Simulation models of (a) different width of Al trace (b) different radius of Al pad (c) different radius of passivation opening

The dimensions of passivation opening, UBM opening, Al pad and Al trace are illustrated as Fig. 1(b). Several dimensions, radius of Al pad, passivation opening and width of Al trace in this model are varied to analyze the current density distribution. The UBM opening is 60μm in radius. The width of Al trace, the radius of Al pad and passivation opening varies from 50μm to 100μm by 10μm, 60μm to 120μm by 10μm, and 12μm to 48μm by 3μm respectively. The Cu pad is 140μm in radius. The models of varied dimensions are shown in Fig. 2. Fig. 2(a), 2(b) and 2(c) shows the models of different width of Al trace and different radius of Al pad and passivation opening, which are described above. The Cu traces are built as a cross shape to fit the actual structure used in our previous study [4, 5] and all of the Cu traces are 100μm wide. Besides, the influence ratio of the radius of passivation opening and UBM opening toward EM lifetime is also analyzed.

Table 1. The material properties used in this study

Materials	Resistivity (μΩ-cm)	
Al	3.2	(trace)
Cu	1.7	(electroplated, UBM and trace)
Ni	6.8	(electroplated, UBM)
Ni	70.0	(electroless, substrate side)
IMC	28.5	(Ni_3Sn_4, both sides)
Solder	14.6	(Eutectic SnPb)

The material properties which was used in this study are listed in Table 1. The resistivity of Al trace is 3.2μΩ-cm instead of the bulk resistivity, 2.7μΩ-cm, because the Al trace are sputtered. The resistivity of Electroless Ni, which is the metallization of substrate side, is 70.0μΩ-cm due to the impurities doped during the electroless plating process. It is the Eutectic SnPb solder that is used in this study. The path of electron flow is marked in Fig. 1(a). The electron flow enters this structure from the left top Al trace, flows through the UBM and eutectic SnPb solder, and then exits through the left bottom Cu trace. The current crowding effect takes place at the left top corner of the solder joint.

In order to simplify the analysis, a parameter and crowding ratio should be defined before the simulation. The crowding ratio (C.R.) is defined as following:

$$C.R. = \frac{J_{MAX,Solder}}{J_{average,UBM\_opening}}$$

Where $J_{MAX,Solder}$ is the maximum current density in Solder joint, and $J_{average,UBM\ opening}$ is the average current density in UBM opening. The crowding ratio indicates the level of current crowding effect. The more serious the current crowding effect takes place, the larger the crowding ratio is detected.

Results and discussions

The most effective design to relieve the current crowding effect found in this study is to fix the ratio of the radius of passivation opening and UBM opening between 0.5 to 0.6. In other words, the radius of passivation opening from 30μm to 36μm has the best ability to relieve the current crowding effect as shown in Fig. 3. The curves in Fig. 3 behave as parabolic curves. The crowding ratio increases as the radius of passivation opening decreases when the radius of passivation opening is less than 30μm. It is simple because the contact area of passivation opening is too small to disperse the current. Although the current spread uniformly at the contact area of passivation opening, the average current density of passivation opening is much higher than the one of UBM opening.

Both the crowding ratio and the radius of passivation opening increases when the radius of passivation opening is larger than 30μm. However, this phenomenon goes against the common sense. The larger the radius of passivation opening is, the lager the contact area will be. Therefore, most of the studies infer that the current density would spread more uniformly due to the larger contact area.

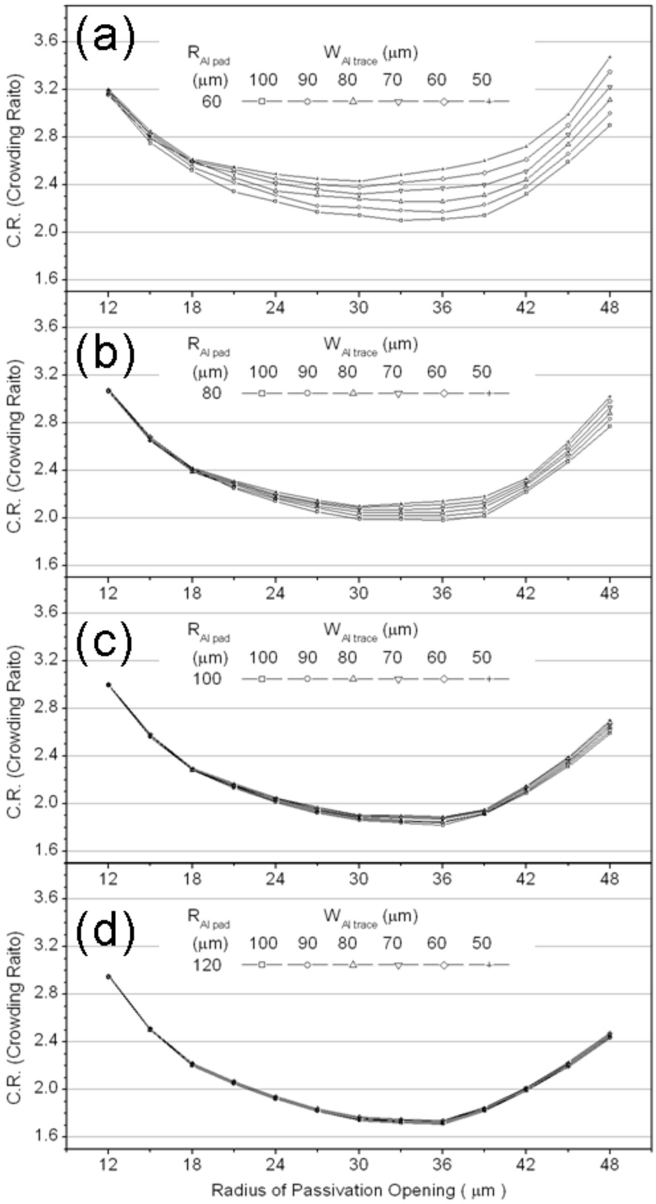

Fig. 3. Crowding ratio of models with different radius of passivation opening and radius of Al pad: (a) 60μm (b) 80μm (c) 100μm (d) 120μm

This phenomenon results from the limitation of UBM opening area. As shown in Fig. 5(c), the current density fully spread across the total area of UBM opening. The limitation effect of passivation opening area is observed in Fig.5 (a) and (b); the small area of passivation opening limits the spreading range for the current density. Therefore, the crowding ratio shows opposite trend to radius of passivation opening when the radius of passivation opening is less than 30μm. None the less, the limitation effect of UBM opening area is observed in Fig. 5 (d) and (e), especially in Fig. 5 (e). The arrows represent the spreading directions of electron flow. It can be observed in Fig. 5 (e) that the first arrow (leftward) exceeds the edge of UBM opening. In other words, the area of UBM opening limits the spreading range for current density. As a result, the crowding ratio increases as the radius of passivation opening close to the radius of UBM opening.

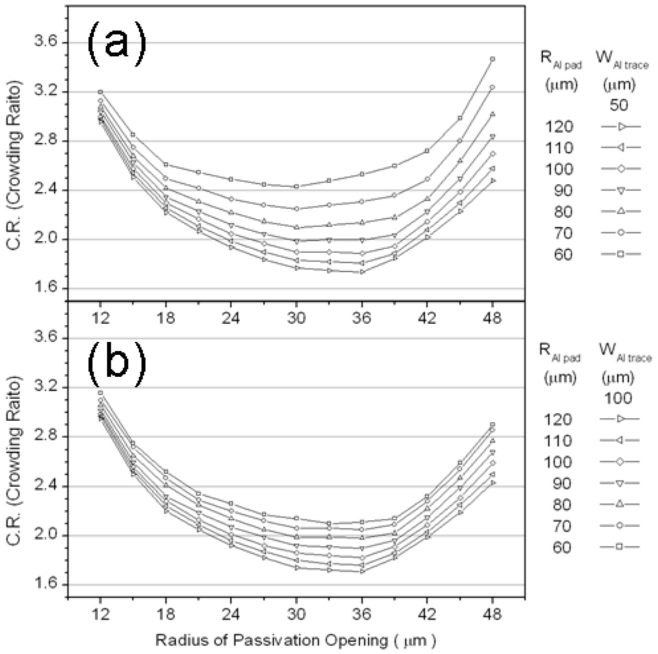

Fig. 4. Crowding ratio of models with different radius of Al pad and radius of passivation opening: (a) 50μm (b) 100μm

The limitation effect of passivation opening area can be described as a simplified model. The average current density of passivation opening and UBM opening are as the following equations:

$$J_{avg,pass} = \frac{I}{\pi r_{pass}^2} \quad (1)$$

$$J_{avg,UBM} = \frac{I}{\pi r_{UBM}^2} \quad (2)$$

Where I is the total applied current and r_{pass}, r_{UBM} are radius of passivation opening and UBM opening. From eqn. (1) and eqn. (2), C.R is obtained.

$$C.R._{<30} = \alpha \cdot \frac{J_{avg,pass}}{J_{avg,UBM}} = \alpha r_{UBM}^2 \cdot \frac{1}{r_{pass}^2} \quad (3)$$

Where α is a crowding factor to represent the current crowding because the current density does not distribute uniformly. Nevertheless, the average current density of Al trace is

$$J_{avg,trace} = \frac{I}{T_{Al} w_{trace}} \quad (4)$$

Where T_{Al} is the thickness of Al trace and w_{trace} is the width of Al trace. Therefore, the limitation effect of UBM opening area can be written as

$$C.R._{>30} = \frac{\beta}{r_{UBM} - r_{pass}} \cdot \frac{J_{avg,trace}}{J_{avg,UBM}}$$

$$C.R._{>30} = \frac{\pi r_{UBM}^2}{T_{Al}} \cdot \frac{1}{w_{trace}} \cdot \frac{\beta}{r_{UBM} - r_{pass}} \quad (5)$$

Where β is a spread factor to represent the ability of spreading current density of Al pad and UBM. From the results of Fig. 4, radius of Al pad also makes a small influence on crowding ratio when width of Al trace is narrow enough, 50μm for example, so β is the function of radius of Al pad.

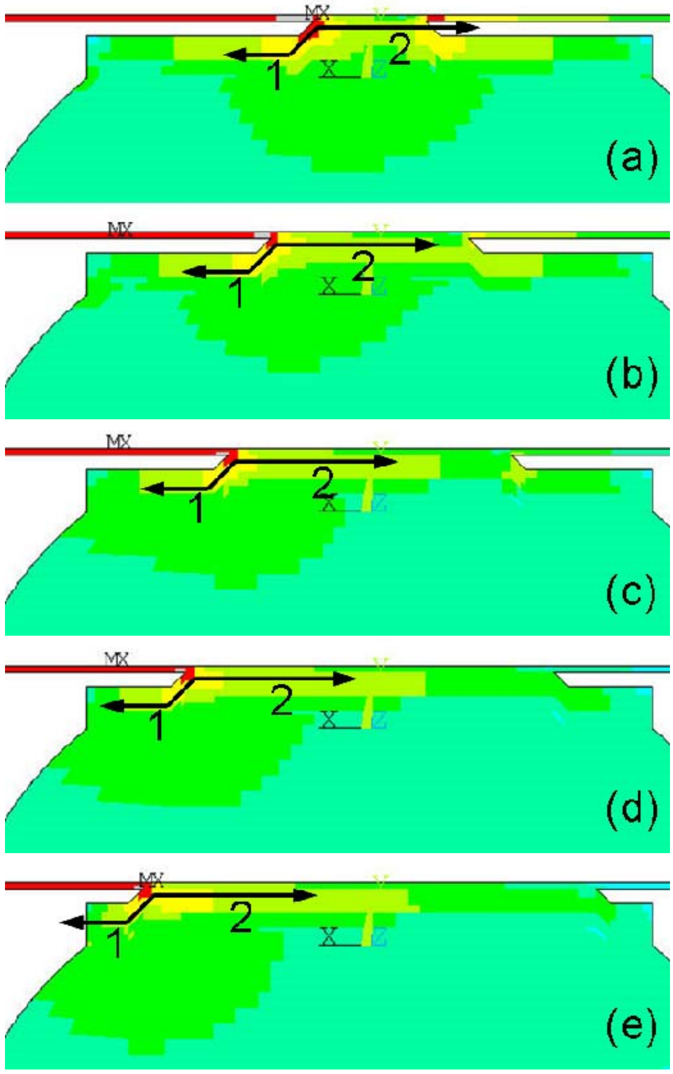

Fig. 3. Cross-sectional current density distribution of models with radius of passivation opening: (a) 12μm (b) 21μm (c) 30μm (d) 39μm (d) 48μm

$$\beta = \beta(r_{pad}) \quad (6)$$

Where r_{pad} is the radius of Al pad and the eqn. (6) transforms into

$$C.R._{>30} = \frac{\pi r_{UBM}^2}{T_{Al}} \cdot \frac{1}{w_{trace}} \cdot \frac{\beta(r_{pad})}{r_{UBM} - r_{pass}} \quad (7)$$

From eqn. (3) and (7), the crowding ratio is finally described as the following equation.

$$C.R. = \alpha r_{UBM}^2 \cdot \frac{1}{r_{pass}^2} + \frac{\pi r_{UBM}^2}{T_{Al}} \cdot \frac{1}{w_{trace}} \cdot \frac{\beta(r_{pad})}{r_{UBM} - r_{pass}} \quad (8)$$

By fitting the factors, α and β, and the dimensions of the simulation models, eqn. (8) shows the same trend as the simulation results.

From the results shown in Fig. 3 and Fig. 4, the crowding ratio is relative to the width of Al trace and the radius of Al pad. The ratio of radius of passivation opening and UBM opening is close to 0.6 with a larger radius of Al pad. Since the larger Al pad spread the current density more uniformly in advanced before the current flow into the solder joint. That means the larger Al pad reduces the limitation effect of UBM opening area.

On one hand, the ability of relieving current crowding effect is only related to the radius of passivation opening when the ratio of radius of passivation opening and UBM opening is less than 0.3. The limitation comes from the small area of passivation opening. Although the current spreads uniformly at the whole contact area of passivation opening, the current density still increases rapidly as the radius of passivation opening decreases. Even if the larger Al pad and wider Al trace spread the current more uniformly, the small area of passivation opening dominates the behavior of crowding ratio.

The ability of relieving current crowding effect is also limited by the radius of the Al pad. The wider the Al trace is, the lower the current crowding will be. But the change of Al trace width shows no influence on relieving current crowding effect when the radius of Al pad is larger than 100μm, which is shown in Fig. 3 (c) and (d). The width of Al trace defines the initial current density which flows into the solder joint. However, larger Al pad spreads the current more uniformly so the effect of Al trace width on initial current density is reduced. The influence of these dimensions, width of Al trace and radius of Al pad and passivation opening shows saturate condition.

This approach facilitates the systemic study of optimized design to relieve the current crowding effect and thus increase the EM resistance of solder joints. In addition, the results provide a guideline for optimal design for solder joints with a specific UBM structure. The wider the Al trace is, the lower the crowding ratio will be, but the effect is limited by the radius of Al pad. The width of Al trace has little influence on crowding ratio when the radius of Al pad is lager than 100μm. In other point of view, the larger is the radius of Al pad, the lower the crowding ratio is but the effect is also limited by the width of Al pad. The radius of Al pad shows little influence on crowding ratio when the width of Al trace is wider than 90μm. No matter in what kind of conditions, the best ability to reduce the current crowding effect is obtained when the ratio of radius of passivation opening and UBM opening is between 0.5 to 0.6.

Conclusions

The current crowding effect takes place at the corner near the traces and the local high current density causes the failure such as void formation and UBM consumption to occur much earlier than expected in the current-crowding region in solder bump. As a result, to relieve the current crowding effect can significantly increase the MTTF of solder bump, since the MTTF may be doubled when the local current density is reduced to half of its original value. In order to obtain more precise observation, a three-dimensional finite element model (3D-FEM) was performed to simulate the current density distribution in solder bump.

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