Shape Effect of Passivation Opening on the Electric Behavior in Flip-chip SnAg Solder Joints under Electromigration

Hsin-Ying Peng and Chih Chen
Department of Materials Science and Engineering, National Chiao Tung University, Hsin-chu 30010 Taiwan, ROC

Abstract

Flip-chip solder joints have become the most important technology for high-density packaging in the microelectronic industry. As the size of the joints progressively shrinks, the carried current density increases. The octagonal passivation opening is now used in packaging industry. The shape effect of passivation opening on its electric behavior during electromigration is clear. This study investigates current density and temperature distribution in eutectic SnAg solder joints with various dimensions on different shapes of passivation opening, including circles, semicircle, squares, octagons, and D-shapes. Three-dimensional electric simulation was carried out to simulate the current and distribution of different passivation opening. According to the results, the maximum current density in the solder joints with square, D-shaped, semicircular passivation opening are lower than that with circular passivation opening under the same contact area. Because the electric current is dispersed along one edge near to the entrance of the Al trace, the current crowding effect is relieved to some extent. The linear measure of the edge near to the entrance of the Al trace is defined as contact length. The contact length dominates the dispersion of current. The semicircular passivation opening has the longest contact length which makes current spread uniformly before entering the solder joint, so the crowding ratio is lowest. However, the D-shaped and square passivation opening also possess higher capability to reduce current crowding effect. Furthermore, the D-shaped passivation opening has two advantages which include longer contact length and larger contact area. The contact area make current travel further before entering the solder joints and offers more space for the depletion of voids. It also enhance the life time. The sequence of cutting circular from one side near the current entrance to the center of the circular passivation opening is also studied by electric simulation. Even though the contact area decreases, the smaller distance from the center of circular passivation opening to the cur edge has better ability to reduce the crowding effect due to the longer contact length. Finally, the current density that is obtained from the simulation can be used to estimate mean-time-to-failure (MTTF) of the joints. Through changing the shape of passivation opening from circle to semicircle, the MTTF can be enhanced to 3.84 times. This study provides the guideline of an optimal design rule for the shape of the contact opening flip-chip solder joints.

Introduction

As the electronic technology progresses rapidly, the size of entire die reduces and the density of input/output (I/O) increases so the flip-chip technology has been adopted in microelectronic technology recently. Flip-chip has excellent electrical characteristic and superior heat dissipation capability [1]. To date, the dimension of each bump shrinks to 100 μm or less. The design rule of packaging dictates is likely to carry current of 0.2 to 0.4A, and therefore the current density in the solder bump may increase over 1×10^4 A/cm^2. The electromigration becomes an important reliability issue. Besides, serious current crowding happens because of the line-to-bump structure [3, 4, 5. 6]. Due to current crowding effect, the non-uniform current density distribution in a solder joint causes non-uniform drift velocity. The drift velocity is proportional to the current density and non-uniform temperature distribution inside a solder joint [7]. Thus, reduction in current crowding renders a longer electromigration time.

Current density is affected by many factors such as the under bump metallization (UBM) material, the design of Al trace, the thickness of UBM, the size of contact opening, and so on [8,9]. According to 3-D simulation results, the current crowding effect decreases when the thickness of UBM increases [10]. The shape effect of passivaton on its electric behavior during electromigration is unclear. In this study, 3-D finite element simulation is used to investigate the current density distribution in eutectic SnAg solder joints with different shapes of passivation opening under current stressing and to figure out the optimal design of passivation opening for relieving the current crowding in solder joints. In 1969, James R. Black delineated the equation that explained the mean-time-to-failure (MTTF) in the presence of electromigration [11]. The relationship between the MTTF and the shape effect of passivation opening is also estimated by simulation in this study. Furthermore, the larger contact area provides more space for migration of voids and enhances longer depletion time of voids [12]. It also increases the reliability of solder joints.

Simulation

The basic cross-sectional schematic model for the solder joints and the definition of contact length used in this study is shown in Fig. 1.

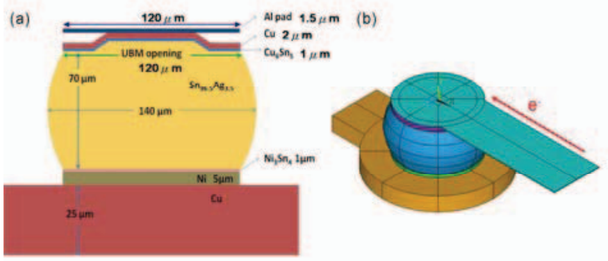

Fig. 1. (a)The cross-sectional schematic models for the solder joints. (b) Schematic drawing with the direction of current in simulation model

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The thickness of UBM is 2-μm Cu and the diameter of UBM opening is 120 μm. The diameter of Al pad is 120 μm. The dimension of the Al trace is 1.5 μm thick, 250 μm long, and 80 μm wide, whereas the Cu line on the substrate side is 25μm thick, 150 μm long, and 80 μm wide. The diameter of Cu pad is 200 μm. Besides, the intermetallic compounds (IMCs) of Cu_6Sn_5 are formed at the interfacial of the UBM and the solder. The thickness of the IMCs is 1 μm. The eutectic SnAg is adopted in this study. The bump height is 70 μm and the diameter of bump is 140 μm. On the substrate side, Ni_3Sn_4 IMCs of 1 μm was adopted for the Ni metallization. Furthermore, the resistivities of the materials used in simulation are reported by S. W. Liang et al [8, 13]. The finite-element method is used to obtain the current density distribution in the flip-chip solder joints.

The various shapes of the passivation opening that are used in this study are circular, octagonal, square, D-shaped and semicircular shown in Figure 2(a), 2(b), 2(c) 2(d) and 2(e). The contact length is defined as the linear measure of the edge near the current entrance as shown in Fig.2. For the circular passivation opening, the diameters are 40, 60, 80, 100, and 110 μm. The contact lengths of the octagonal passivation opening are 15, 23, 31, 38, and 42μm. The dimensions of the square passivation opening are 24×24, 36×36, 42×42, 48×48, 60×60, and 72×72 μm^2. The diameters of the original D-shaped passivation opening are 40 μm, 60 μm, 80 μm, 100 μm, and 110 μm. The contact lengths of the semicircular passivation opening are 42, 60, 72, 80, and 100 μm. All sets of solder joints are stressed by 0.8 A.

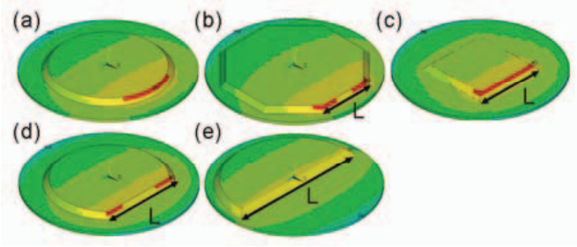

Fig. 2. Various shapes of passivation opening and definition of the contact length(L): (a) circle (b) octagon (c) square (d) D-shape (e) semicircle

3. Results and Discussion

According to the simulation result, the maximum current densities in solder joints are 5.1×10^4, 4.4×10^4, 4.1×10^4, 4.1×10^4, and 4.4×10^4 A/cm^2 for the circular passivation opening with diameter of 40, 60, 80, 100, and 110 μm, respectively. The corresponding crowding ratios are 7.1, 6.2, 5.8, 5.8, and 6.2. The crowding ratio is obtained by dividing the maximum current density by the average current density. As the diameter of circular passivation opening increases, the maximum current density in solder joint decreases, but it has a minimum value around 100 μm. When the diameter of circular passivation opening surpasses 100 μm and is close to the diameter of UBM opening, the maximum current density in solder joint increases slightly. Figure 3(a) through 3(e) show the current density distribution in the solder joints with circular passivation opening model with diameters of 40, 60, 80, 100, and 110μm, respectively. For the solder bumps with circular passivation openings, current crowding effect takes place in a small contact area near the entrance point of electron flow. When the diameter increases, the enlarged contact area helps the dispersion of current and relieves the current crowding effect. However, when the diameter of circular passivation opening is close to the UBM opening, the current directly enters UBM without dispersing and accumulates at the point of contact area.

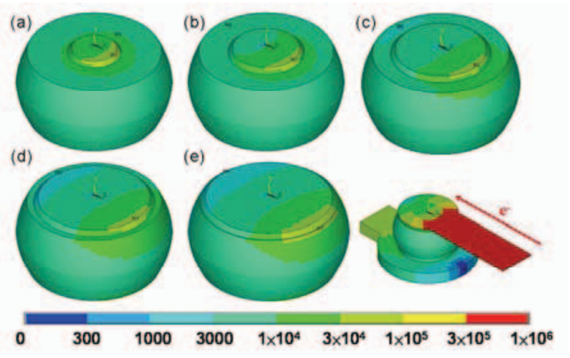

Fig. 3. The current density distribution in solder joints with different diameters of circular passivation opening (a) 40 μm (b) 60 μm (c) 80 μm (d) 100 μm (e) 110 μm

In some company, the octagonal passivation opening is in use due to restriction of manufacture. The maximum current densities in solder joints are 5.3×10^4, 4.6×10^4, 4.2×10^4, 4.1×10^4, and 4.2×10^4 A/cm^2 for the octagonal passivation opening with the contact length of 15, 23, 31, 38, and 42 μm, respectively. The corresponding crowding ratios are 7.5, 6.5, 5.9, 5.8, and 5.9. It cannot decrease current crowding effectively. Because the octagonal passivation opening confines the contact length to the UBM opening, the contact lengths are lower than other designs. Without long contact length, current also concentrated on the small edge near the entrance of electron flow which is shown in Fig. 4. Just as the circular passivation opening, when the contact area increases to approach to the UBM opening, the current cannot disperse with effect and the crowding ratio increase slightly.

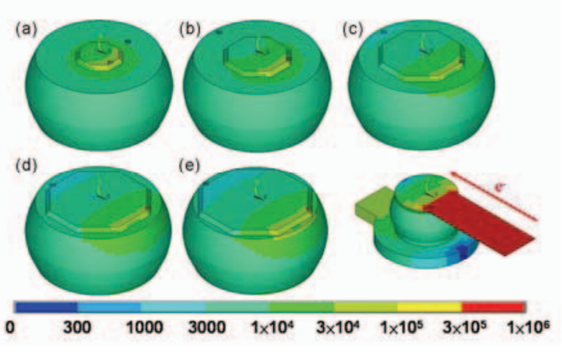

Fig. 4. The current density distribution in solder joints with different contact lengths of octagonal passivation opening (a) 15 μm (b) 23 μm (c) 31 μm (d) 38 μm (e) 42 μm

For the square passivation opening, the maximum current densities in solder joints are 6.1×10^4, 4.9×10^4, 4.5×10^4, 4.2×10^4, 3.6×10^4, and 3.1×10^4 A/cm^2 for the square passivation opening with the contact area of 24×24, 36×36, 42×42, 48×48, 60×60, and 72×72 μm^2, respectively; moreover, the corresponding crowding ratios are 8.7, 7.0, 6.4, 6.0, 5.2, and 4.4. The current density distributions of square passivation opening are shown in Fig. 5. Unlike the circular passivation opening models, the square passivation opening spreads the current crowding point into a region along the edge near the entrance point of electron flow. Therefore, the current crowding effect for the solder joints with circlular passivation openings is more serious than those with square passivation openings. However, when the square of passivation opening shrinks too much, the maximum current density increases rapidly due to the relatively smaller contact area. In the Figure 5(a), the current concentrated on the entire contact window so a smaller square passivation opening renders higher maximum current density. Furthermore, the UBM opening area imposes a restriction on enlarging the contact area of square passivation opening. So the area of the square opening cannot extend lager than 72×72 μm^2

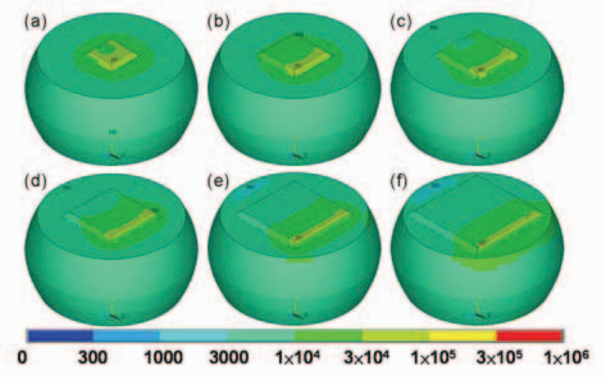

Fig. 5. The current density distribution in solder joints with different dimensions of square passivation opening (a) 24×24 μm^2 (b) 36×36 μm^2 (c)42×42μm^2 (d)48×48μm^2 (e)60×60μm^2 (f)72×72 μm^2

In terms of D-shaped passivation opening, the maximum current densities in solder joints are 5.2×10^4, 4.2×10^4, 3.6×10^4, 3.2×10^4, and 3.2×10^4 A/cm^2 for the solder joint with a diameter of 40, 60, 80, 100, and 110 μm original circular passivation opening, respectively. In addition, the corresponding crowding ratios are 7.3, 6.0, 5.1, 4.5, and 4.5. The current density distributions in solder joints with D-shaped passivation opening are shown in Figure 6. The D-shaped passivation opening combines two advantages. Not only can current be dispersed over wider contact length at the current entrance but also a greater amount of current can travel further before flowing down into a solder joint due to the larger area of contact opening. Furthermore, the D-shaped passivation opening also provides larger area for depletion of voids. It enhances the reliability of devices.

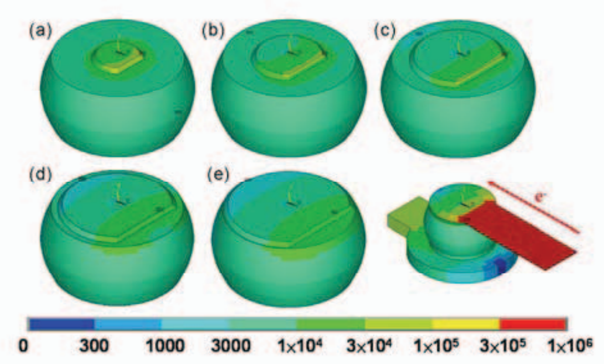

Fig. 6. The current density distribution in solder joints with different diameters of D-shaped passivation opening (a) 40 μm (b) 60 μm (c) 80 μm (d) 100 μm (e) 110 μm

The semicircular passivation opening can provides largest contact length as shown in Fig.7 (e), so the maximum current density in solder joints can reduce considerably. The maximum current densities in solder joints are 5.4×10^4, 4.1×10^4, 3.6×10^4, 3.2×10^4, and 2.6×10^4 A/cm^2 for the semicircular passivation opening with the contact length of 42, 60, 72, 80, and 100 μm respectively. The corresponding crowding ratios are 7.6, 5.8, 5.0, 4.6, and 3.6. Along the edge of the entrance of electron flow, the current spread uniformly and the current crowding effect reduces quite substantially.

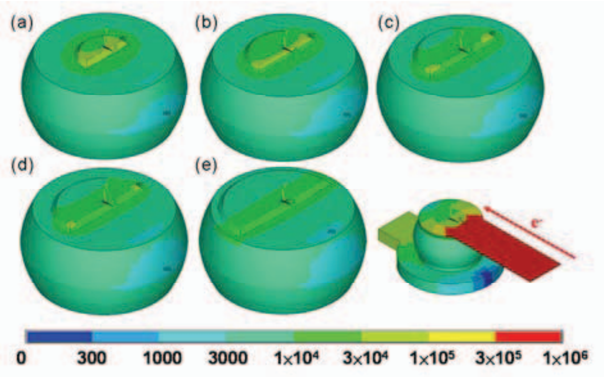

Fig. 7. The current density distribution in solder joints with different contact lengths of semicircular passivation opening (a) 42 μm (b) 60 μm (c) 72 μm (d) 80 μm (e) 100μm

When different designs of passivation opening have same contact length, the semicircular passivation opening has the longest contact length and reduces crowding ratio remarkably. The relationship between contact length and contact area are list in Table. 1, which is arranged in descendant order. In terms of the same contact area, the ability of dispersing current and reducing crowding effect from excellent to weak is semicircular, square, D-shaped, and octagonal passivation opening as the order of contact length.

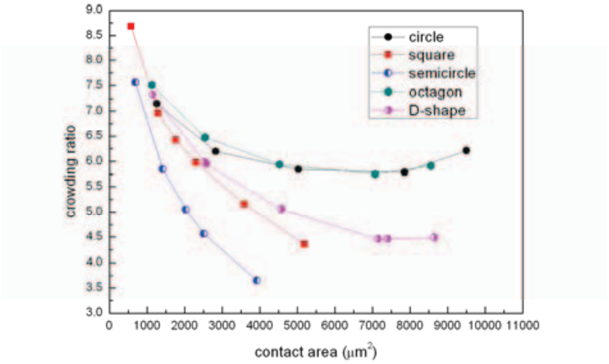

Fig. 8. Crowding ratio as a function of contact opening area for the five designs of passivation opening

Table 1. The contact area (A) denotes the contact length (L) of different designs of passivation opening.

Passivation opening	Semicircle	square	D-shape	octagon
Contact length(L)	$1.6A^{\frac{1}{2}}$	$A^{\frac{1}{2}}$	$0.84A^{\frac{1}{2}}$	$0.46A^{\frac{1}{2}}$

Conversely, the octagonal passivation opening has the largest contact area of other designs which have the same contact length according to Table 1. If the contact lengths are equivalent, the larger contact areas make current spread further in UBM before entering solder joints and decrease the crowding ratio. This is shown in Fig. 9.

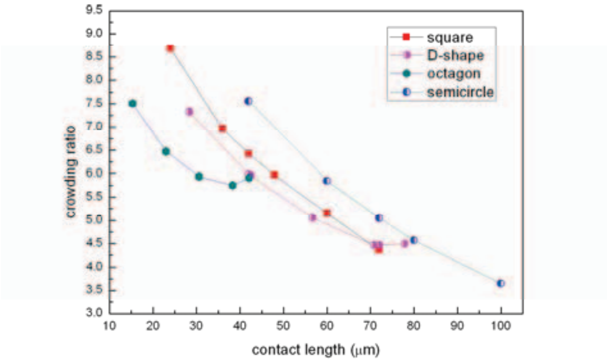

Fig. 9. Crowding ratio as a function of contact length for the four designs of passivation opening

The electric simulation results of cutting circular passivation opening from one side that current flow into to the center of circular passivation opening are shown in Fig. 10 and 11. The distance between the center of circular passivation opening and the cut edge is defined as d. As d is 50μm, Fig. 10(f) is circular passivation opening. As d is 0 μm Fig. 10(a) is semicircular passivation opening cut from circular passivation opening. As d becomes smaller, the contact length becomes longer. Owing to the longer contact length, the crowding ratio decreases obviously. Although the contact area is also smaller, the longer contact length is major factor that relieves current crowding.

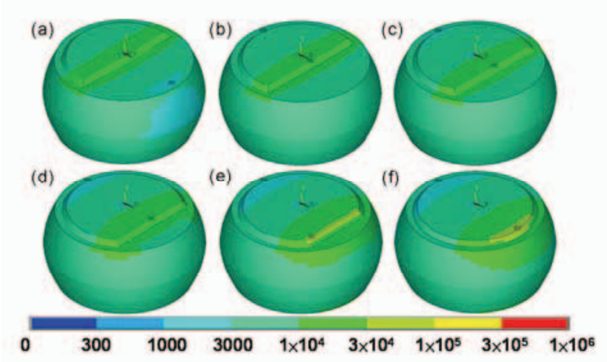

Fig. 10. The current density distribution in solder joints with different distance between the center of circular passivation opening and the cut edge (a) 0 μm (b) 10 μm (c) 20 μm (d) 30 μm (e) 40 μm (f)50 μm

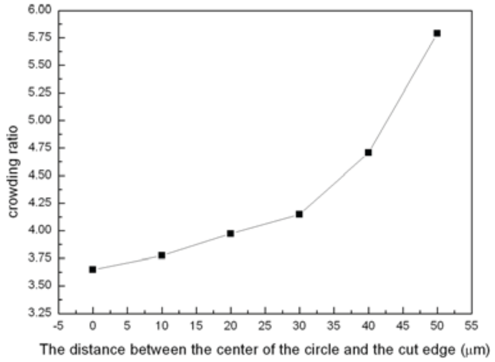

Fig. 11. Crowding ratio as a function of the distance between the center of circular passivation opening and the cut edge

Furthermore, the effect of the shape of passivation opening on the MTTF can be estimated by the equation that is delineated by James R. Black [11]. The equation express as

$$MTTF = A\frac{1}{j^n}\exp\left(\frac{\mathrm{Q}}{\mathrm{kT}}\right)$$

where A is a constant, J is current density, n is model parameter, Q is activation energy, k is Boltzmann's constant, and T is average bump temperature in degrees Kelvin. If we take n=2, compared with the MTTF of the circular passivation opening whose diameter is 40 μm, the MTTF of the D-shaped passivaton opening with the diameter 100 μm is increased to 2.6 times; the MTTF of the square passivation opening with contact length 72 μm is increased to 2.7 times and the MTTF of semicircular passivation opening with the contact length 100μm is even enhanced to 3.84 times. By modifying the shape of passivation opening, the electromigration lifetime can be enhanced remarkably.

Conclusions

In summary, the shape of the passivation opening plays a crucial role in the current crowding effect and the MTTF. Both increasing contact lengths and contact areas will reduce the crowding effect. The contact lengths dominate the dispersion of current. The semicircular passivation opening has best capability for relieving current crowding among the five designs due to the longest contact length. However, the properties of square and D-shaped passivation opening still have lower maximum current density than that of circular passivation opening. By changing circular passivation opening to semicircular passivation opening, the mean time to failure MTTF would increase about 3.84 times due to lower maximum current density. Besides, the D-shaped passivation opening not only possesses long contact length that reduces the crowding effect but also provides more space for depletion of voids. That also enhances the life time. This study provides a guideline for optimal design rule of passivation opening for prolonging MTTF and enhancing the reliability.

Acknowledgments

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