**The Influence of Solder Void on IGBT Temperature**

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**Abstract.** The void in solder layer is the main factor that causes bad heat dissipation of IGBT (Insulated Gate Bipolar Transistor) module. Based on the seven-layer structure of IGBT, this article established a three-dimensional finite element model of IGBT module packaging structure and carried out its thermal analysis, then had a study on the effect of welding layer void on the temperature of IGBT chip. The overall distribution of IGBT module with or without solder hole is compared, meanwhile the article analyzed the effects of void type, size, shape, number and distribution on the temperature distribution of IGBT chips. The results show that the void in the solder layer of the chip has a great influence on the temperature of the chip. The influence of penetrating voids on chip temperature is greater than that of non-penetrating voids, the bigger the single hole is, the higher the temperature of IGBT chip. Voids of the same shape have greater influence on chip temperature at edge and corner positions than those inside the welding layer. The more concentrated the distribution of multiple holes, the higher the chip’s temperature. Therefore, in order to improve the reliability of IGBT, it is necessary to avoid voids in the chip welding layer during the packaging process.

**Introduction**

Insulated Gate Bipolar Transistor (IGBT) is a composite fully controlled voltage-driven power semiconductor device composed of bipolar triode (BJT) and insulated gate field effect transistor (MOS), which has been widely used in various fields, such as high-speed rail, smart grid, new energy vehicles, solar energy and so on[1]. It has the advantages of both MOSFET and BJT, high input impedance and low conduction voltage drop. Since its birth, it has rapidly become the focus of industry development[2].

**IGBT Finite Element Model and Related Parameters**

The solid model of IGBT is a seven-layer structure after removing plastic shell and silica gel[3]. The order from top to bottom is chip, chip welding layer, front copper layer, liner, back copper layer, liner welding layer and substrate, as shown in Figure 1.

![Figure 1. Schematic diagram of IGBT module.](image)

Taking the IGBT module of 1200V/100A, this paper establishes a finite element model for analysis.

Semiconductor material properties vary significantly with temperature and the variation of thermal conductivity $\lambda_{si}(W/(cm \cdot K))$ with absolute temperature $T$ is:
\[ \lambda_s(T) = A/(T - B) \]  
(1)

where \( A = 320, B = 80 \). Compared with semiconductor materials, the thermal conductivity of metal materials changes little with temperature, so we can focus only on the change of thermal conductivity with temperature\(^4\). In the working state, IGBT chip is the main source of module heating. Therefore, this paper only considers IGBT chip heating. The heating rate of IGBT chip is as follows:

\[ H_{gen} = P/V \]  
(2)

\( H_{gen} \) is the heat generation rate, \( P \) is power and \( V \) is volume. In this paper, the power applied to IGBT chip is selected as 120W\(^5\). The heat generation rate calculated by Eq. 2 is \( 1.98 \times 10^9 W/m^3 \). The bottom of the substrate is installed on the radiator for forced convection heat transfer, and the convection heat transfer coefficient is set to \( 4000 W/(m^2 \cdot ^\circ C) \)\(^6\); natural convection heat transfer between the four sides of the substrate and the air, the coefficient of convective heat transfer is \( 10 W/(m^2 \cdot ^\circ C) \), the ambient temperature is \( 25 ^\circ C \)\(^7\).

Analysis and Discussion of Calculation Results

Effect of Single Solder Void on Maximum Temperature of Chip

In this paper, the shape of the cavity is circular, and the center of the cavity is in the position 1 to 6. Positions 1, 2, 4 are inside the weld layer, 3, 5, 6 are in the corner. When the radius of the void is equal, the void rate on position 3 and 5 is half that of the void inside the weld layer, and the void rate is 1/4 that of the void inside the weld layer when the void is on position 6. That is to say, when the voids in the weld layer have the same void rate in position 1 to 6, the radius corresponding to the voids in the edge corner and the inner voids in the weld layer are also different. Therefore, the voids in the weld layer and the voids in the edge corner are discussed separately.

Figure 2. a) shows the effect of voids of different sizes on the maximum temperature of the chip when they are inside the welding layer.
It can be seen from the figure that when the void is small, the effect of the weld layer void on the chip maximum temperature is not significant. However, with the increase of voids, the maximum temperature of the chip almost rises in a straight line. The voids have the greatest influence on the temperature of the chip at position 1, and the smallest influence on the temperature of the chip at position 4. When the void ratio reaches 10%, the temperature difference between them is the largest, about 6 °C. When the cavity is large, the influence of the cavity position on the maximum temperature of the chip is not obvious. The maximum temperature of the chip on positions 1, 2 and 4 is almost the same, nearly 121 °C, while the chip temperature is 82.5 °C when there is no cavity in the welding layer, and the temperature rises nearly 39 °C, which seriously affects the normal operation of the IGBT module.

Figure 2. b) and Figure 2. c) are the effects of different size of edge voids and fillet voids on the maximum temperature of the chip. As can be seen from the figure, the maximum temperature of the chip increases parabolically with the increase of the voids. When the voids are small, the maximum temperature of the chip does not change much. When the voids are on the edge of the welding layer, the influence of position 3 and 5 on chip temperature is not significant. With the increase of voids, the maximum temperature of the chip rises sharply, especially the effect of fillet on the maximum temperature of the chip is particularly serious.

The maximum temperature of the chip reaches 116.7 °C at 5% void rate. Compared with the case without voids, the temperature of the chip rises sharply, which seriously affects the working characteristics of IGBT module. Contrast Figure 2. a) shows that at the same void rate, the effect of edge and corner voids on chip temperature is greater than that of inner voids on chip temperature.

In the above analysis, the shape of the voids in the weld layer is different from that in the corner. The voids in the weld layer are circular, the voids in the weld layer are semi-circular, and the corner voids in the weld layer are 1/4 circles.

Therefore, taking position 1 as an example, the voids in the shape of semi-circle and 1/4 circle are selected for thermal analysis. The results are shown in Figure 3.
Effect of Multiple Welding Layer Voids on the Maximum Temperature of Chip

The influence of single void on the maximum temperature of the chip is analyzed, and then we consider the influence of multiple solder voids on the maximum temperature of the chip. Sixteen voids were selected in the chip welding layer, and the radius of each void was 0.62 mm (void rate was 1%). Three regular void distribution models are introduced below: uniform distribution, centralized distribution and edge distribution, as shown in Figure 4.

![Figure 4. Three-population distribution of voids in chip weld layer.](image)

The highest temperature of the chip is shown in Figure 5 under the three groups of void distribution.

![Figure 5. Maximum chip temperature of three populations with voids distribution.](image)

It can be seen from the figure that when the voids are concentrated, the temperature of the chip is the highest; when the void edge is distributed, the temperature of the chip is the lowest. Compared with Figure a, it is found that the effect of 16 voids which have the 1% void rate on the maximum temperature of the chip is much smaller than that of one single 16% void which has the 16% void rate. Therefore, in the process of chip welding, attention should be paid to the formation of large voids in the welding layer.

Conclusion

In this paper, we focused on the temperature dependence of thermal conductivity of semiconductor materials. A three-dimensional finite element model of IGBT module packaging structure is established. Then we calculated and analyzed the effects of void type, size, shape, number and distribution on the maximum temperature of IGBT chip\textsuperscript{8}. The results show that:

The influence of penetrating voids on chip temperature is greater than that of non-penetrating voids. For non-penetrating voids, the closer the voids to the chip, the greater the influence on chip temperature.

When the voids are small, the influence on the maximum temperature of the chip is small. With the increase of voids, the maximum temperature of the chip increases gradually. Under the same conditions, the effect of voids in the corner on chip temperature is greater than that in the solder layer. Especially the corner voids in the welding layer have the greatest influence on the chip temperature. Therefore, the formation of corner voids in the welding layer should be avoided in the manufacturing process. The appearance of voids makes the highest temperature of the chip appear above the voids, which is easy to form hot spots, leading to the failure of IGBT chips.

At the same void rate, the effect of single solder void on chip temperature is greater than that of multiple small voids. When multiple voids exist, the closer the voids are to the center of welding layer, the greater the influence on chip temperature.
The temperature of IGBT chip increases exponentially with the increase of weld gap. Although the effect of weld gap on chip temperature is less than that of void. However, with the increase of weld gap, the influence on the temperature of IGBT chip cannot be ignored. Therefore, more attention should be paid to the generation of cracks in the production process.

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