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Influence of Surface Morphology of Press-Pack IGBT on Temperature and Thermal Resistance

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Abstract

The main work of this paper is to use the finite element method to establish a two-dimensional finite element model of press-pack IGBT power device, and calculate the temperature change of each material layer and the contact thermal resistance between each material layer through the thermo-electric coupling algorithm. Since the thermal contact resistance between the Al metallization layer and the emitter Mo plate increases more dramatically during the power cycle of the press-packed IGBT device, the two-dimensional surface morphology of the contact interface between the Al metallization layer and the emitter Mo plate is established by the W-M fractal function, and the influence of the two-dimensional surface morphology under different roughness on the junction temperature of the press-packed IGBT chip and the thermal contact resistance between the Al metallization layer and the emitter Mo plate during the power cycle is analyzed. The results show that with the change of the contact interface roughness between the Al metallization layer and the emitter Mo plate in the press pack IGBT device, the contact thermal resistance between the chip junction temperature and the material layer during the power cycle is also changing. Therefore, the two-dimensional contact interface equivalent model with different roughness established in this paper can simulate the surface morphology of the contact interface with different power cycles.

1 Introduction

Press-packed insulated gate bipolar transistor (PP-IGBT) module has the advantages of high power density, double-sided heat dissipation and short-circuit failure, and has been widely used in high-power conversion systems. In order to maximize the reliability performance, the thermal behavior of the PP-IGBT device is a very important design consideration, especially in the high power range, because about 60 % of the power semiconductor device failure is caused by heat[1]. Thermal resistance is one of the key factors determining the thermal behavior of PP-IGBT device. In the PP-IGBT device, the IGBT chip is directly connected to two Mo plates, and both sides of the Mo plate are connected to the Cu electrode. In the working process of the PP-IGBT device, in order to maintain the thermal contact and electrical contact of these components, a clamp is used to provide clamping force. Compared with the fully bonded interface of the solder device, the total thermal resistance of the PP-IGBT module consists of two parts: the material layer thermal resistance and the contact interface contact thermal resistance, which is introduced by the multi-layer structure of the PP-IGBT device. Therefore, it is of great significance to study the degradation of contact thermal resistance during the operation of PP-IGBT device.

One of the main factors affecting the contact thermal resistance of the internal contact interface of the PP-IGBT device is the surface roughness characteristics of the contact interface [2]. For example, the Al metallization layer is not flat, but is characterized by folds [3]. In the current research, scholars have fully observed the surface morphology of the contact interface, but the research on the change degree of the surface morphology of the contact interface is not sufficient, and the relationship between the surface morphology change of the contact interface and the contact thermal resistance has not been established. The real mechanical contact between rough surfaces does not occur on the whole surface, but is limited to a part of the top of the surface asperity. In order to consider the influence of surface roughness characteristics, a model for calculating contact thermal resistance is proposed in this paper. The finite element model of equivalent surface morphology between Al metallization layer and emitter Mo plate is established by W-M fractal function. The surface morphology parameters of Al metallization layer and emitter Mo plate are calculated, and then the contact thermal resistance on the contact interface between Al metallization layer and emitter Mo plate of PP-IGBT module is calculated according to the analytical model for calculating contact thermal resistance. Finally, the effects of different parameters on the surface morphology and contact thermal resistance of Al metallized layer and emitter Mo plate were analyzed.

2 Thermo-electric coupling of press-pack IGBT

Press-pack packaging is a special form of packaging. Each layer inside the module must be in close contact. In the press-pack IGBT module, the Al metallization layer of the IGBT chip will contact with the emitter Mo plate. The temperature distribution and heat dissipation process of IGBT chip cannot be observed intuitively through experiments. Therefore, the finite element method can be used to perform thermal-electric coupling on the press-pack IGBT module, and the material layers of the module can be calculated during the power cycle.

The construction modules of the finite element model of press pack IGBT are collector Cu, collector Mo plate, IGBT chip, Ag plate, emitter Mo plate and emitter Cu from top to bottom, as shown in Fig.1. There is an Al metallization layer on the surface of IGBT chip. Table 1 shows the two-dimensional structure size of each layer of the finite element model.

The unit type used in this paper is DC2D3E. The material parameters of each layer in the finite element model are shown in Table 2 and Table 3. The boundary conditions and loads of the whole model are as follows:

(1) Boundary conditions: set the emitter surface to 0 potential surface; set the ambient temperature to 23 °C; set the bottom surface of the model completely fixed.

(2) Thermal load: The heat dissipation temperature of collector and emitter surface is set to 45 °C.

(3) Electrical load: The DC current load is set to flow from the collector surface at the upper end of the model, and the emitter surface at the lower end of the model flows out. The DC current load is 50 A. In a single power cycle, the model conduction time is 2 s and the cooling time is 2 s.

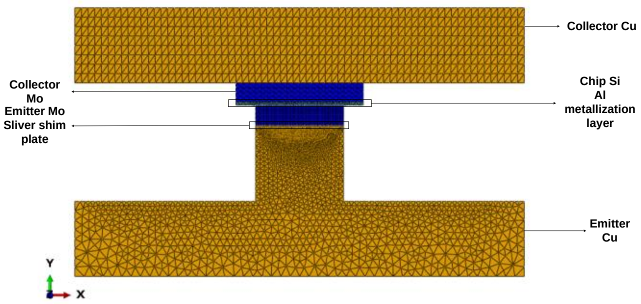


Fig.1. Finite element model of the press-pack IGBT module

TABLE1. Dimensions of the finite element model

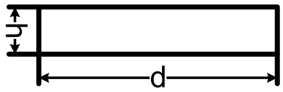
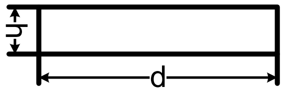
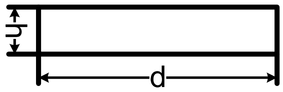
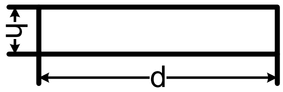
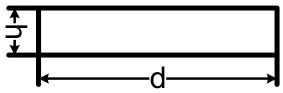
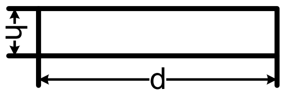
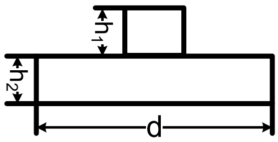
Parts	Size/mm	Graphics
Collector electrode	d=48 h=8	
Collector Mo plate	d=9.4 h=2	
IGBT chip	d=13.6 h=0.37	
Al metallization layer	d=10 h=0.2	
Ag plate	d=9.4 h=0.2	
Emitter Mo plate	d=9.4 h=2	
Emitter electrode	d=48 h_1=8;h_2=8	

TABLE2. Material parameters

Material	Thermal conductively W/(m*k)	Conductivity S/mm	Thermal expansion coefficient 1/℃
Si	150	0.01	3.00×10^{-6}
Cu	400	58.82	1.70×10^{-5}
Al	235	37.73	2.45×10^{-5}
Mo	138	19.23	5.10×10^{-6}
Ag	429	68.027	1.96×10^{-5}

TABLE3. Material parameters

Material	Young's modulus(GPa)	Poisson ratio	Density (kg/m3)	Specific heat10^{-6} （kg*K)
Si	170	0.28	2329	7.00×10^{8}
Cu	110	0.35	8930	3.80×10^{8}
Al	70	0.33	2700	9.00×10^{8}
Mo	312	0.30	1020	2.50×10^{8}
Ag	83	0.37	1050	2.35×10^{8}

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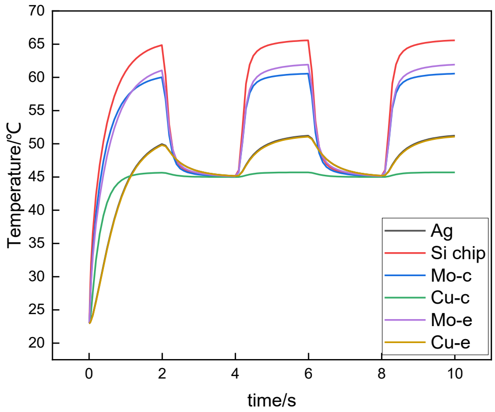
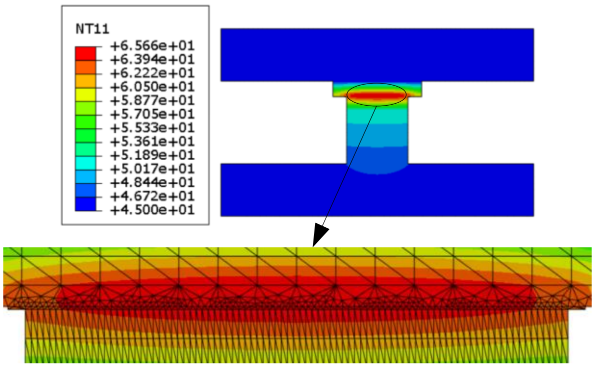
Fig.2 shows the temperature distribution of the IGBT module during the power cycle. With the continuous conduction of the current, the temperature of each material layer of the IGBT module continues to increase until the current stops flowing in, and the temperature of each material layer begins to continue to decrease due to the effect of water-cooled heat dissipation. The temperature of each material layer reciprocates with the conduction and shutdown cycles. The highest temperature shows an increasing trend from the collector and emitter to the chip. The temperature at the position of the Si chip is the highest, which is 65 °C, and the temperature at the emitter is the lowest, which is the same as the water cooling temperature, which is 45 °C. The highest temperature difference reaches 20 °C. The highest temperature of collector Mo plate and emitter Mo plate is almost the same, which is 60 °C. The highest temperature of Ag plate and collector is 50 °C.



(a)



(b)

Fig.2. The temperature distribution of the IGBT

(a) Temperature change curve of each material layer

(b) The temperature distribution of the IGBT at the last time of conduction

3 Influence of surface morphology on junction temperature and contact thermal resistance of press-pack IGBT

During the power cycle process, due to the increase of the contact thermal resistance, especially the significant increase of the contact thermal resistance between the Al metallization layer and the emitter Mo plate, the total thermal resistance of the press pack IGBT device increases, which reduces the thermal performance of the device. Therefore, aiming at the change of the surface roughness of the contact interface between the Al metallization layer and the emitter Mo plate, the influence of the roughness change on the junction temperature and the contact thermal resistance is studied.

3.1 W-M fractal function characterizes the 2D surface morphology

Fractal was originally proposed by the mathematician Benoit Mandelbrot, and gave an explanation for fractal: part and whole have a similar shape. This definition emphasizes the self-similarity of fractals. Later, more scholars have studied fractal, emphasizing the self-similarity and scale-free characteristics of fractal [4].

The W-M fractal function model can accurately reflect the morphological characteristics of rough surfaces determined by fractal dimension and scale index. At all points, they are continuous and non-differentiable, and satisfy the self-affine fractal characteristics of surface morphology. Its function expression is:

$$z(x) = G^{D-1} \sum_{n=n_{\min}}^{\infty} \frac{\cos(2\pi\gamma^{n} x)}{\gamma^{(2-D)n}} (1 < D < 2, \gamma > 1) \quad (1)$$

where z(x) is the height of the surface profile at x, and x is the independent variable, which represents the horizontal position coordinates of the profile;G represents the height size parameter (μm) of the contour, and its value represents the contour height of the two-dimensional rough surface; D is the fractal dimension of two-dimensional contour, which reflects the irregularity of z(x) at all scales, and 1 < D < 2 ; n is the frequency exponent of the surface; n_{min} is the lowest cut-off frequency of all asperities ; L is the actual sampling length of the wear surface ; γ is a frequency density factor, and the value is constant and $\gamma > 1$. In practical engineering problems, the value of γ is usually 1.5; γ_n is the discrete frequency of the two-dimensional surface profile, which satisfies$\gamma^{n_{min}} = 1/L$.

In order to establish a finite element model of surface morphology under different roughness, the surface morphology of the contact interface between the Al metallization layer and the emitter Mo plate is simulated according to the W-M fractal function, and the instructions are written in python script. The two rough surfaces are

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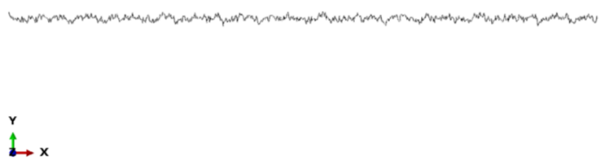
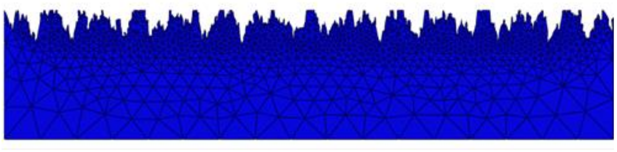
equivalent to a smooth Al metallization layer surface and a rough emitter Mo plate surface. The surface morphology of the emitter Mo plate is shown in the Fig.3.



(a)



(b)

Fig.3. Equivalent contact interface of emitter Mo plate(D=1.4,G=0.01)

(a) Equivalent contact interface of emitter Mo plate

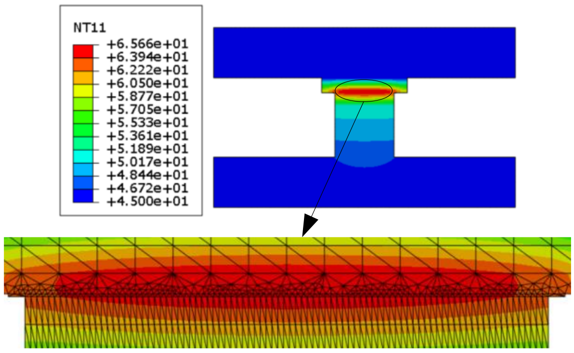
(b) Equivalent surface morphology of emitter Mo plate

In order to establish the relationship between the change of surface morphology and the junction temperature and contact thermal resistance of the press-packed IGBT module, the variable parameters are set as the characteristic scale parameter *G* and the two-dimensional contour fractal dimension *D*, taking *G*= 0.01,0.001,0.0001; taking D=1.4,1.6,1.8; the finite element model of equivalent surface morphology of different emitter Mo plates is established.

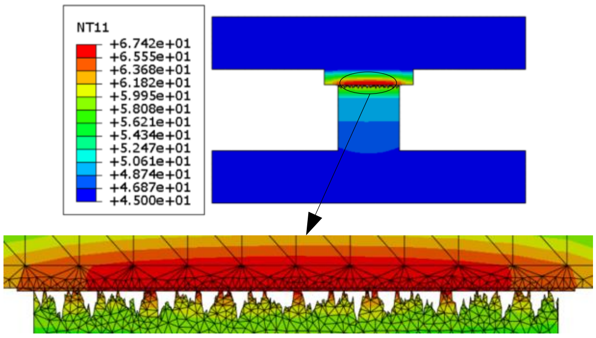
3.2 Influence of surface morphology on junction temperature

The original smooth emitter Mo plate is replaced by emitter Mo plate with different surface topography, which is consistent with the working condition of the thermo-electric coupling finite element model in the second section, and the same load and boundary conditions are set. The junction temperature of the pressed IGBT module under smooth contact surface and different fractal parameters is analyzed and compared.

Fig.4 shows the temperature distribution around the IGBT chip with different surface morphology emitter Mo plates under the condition of load current of 50 A and period of 4 s. Fig.4(a) shows that the junction temperature of the chip with smooth contact surface is 65.7 °C, and the temperature decreases from the center of the chip to the outside. Figs.4(b)-(c) give a similar rule. As the contact surface morphology changes, the chip junction temperature gradually increases. When D = 1.4, G = 0.01, the junction temperature of the chip is 67.4 °C; when D = 1.6, G = 0.01, the junction temperature of the chip is 68.9 °C. When the surface morphology changes from Fig.4(a) to Fig.4(c), the contact area between the Al metallization layer and the emitter Mo gradually decreases, resulting in a continuous increase in the chip junction temperature.



(a)



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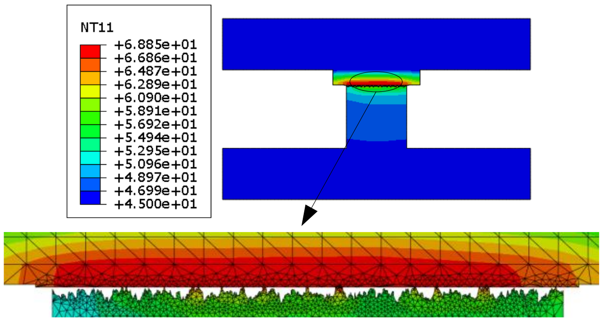

(c)

Fig.4. Different surface morphology chip junction temperature

(a)smooth surface

(b)D=1.4,G=0.01(c)D=1.6,G=0.01

3.3 Influence of surface morphology on contact thermal resistance

The microstructure diagram of the two contact interfaces is shown in Fig.5.Each contact point is called micro-contact, and the other uncontacted gaps are occupied by gas. The heat flow is mainly transmitted through micro-contact. This contact condition causes the heat flow to shrink, resulting in contact thermal resistance at the contact interface[5]. The contact thermal conductance h_c between the contact interfaces can only consider the shrinkage/diffusion thermal conductance h_s caused by micro-contact and the void thermal conductance h_g caused by void heat conduction. Then the

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contact thermal resistance R_c between the contact interfaces can be expressed as

$$R_c = 1/(A_{nom}h_c) = 1/\left[A_{nom}(h_s + h_g)\right] \tag{2}$$

where A_{nom} is the nominal contact area of the two contact surfaces.

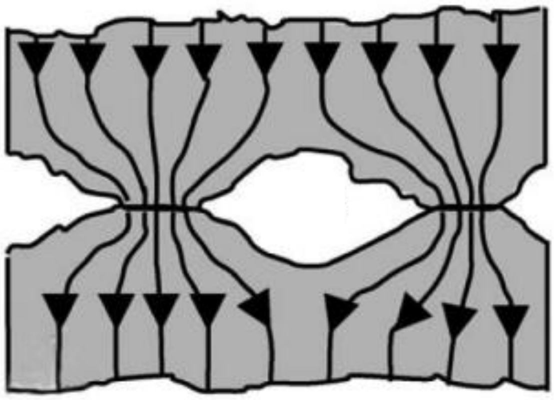

Fig.5. Microscopic schematic diagram of contact interface

The equivalent root mean square surface roughness σ of the equivalent rough surface shown in Fig.3(a) can be expressed as

$$\sigma = \sqrt{\frac{1}{l}\int_0^l Z^2(x)dx} \tag{3}$$

where l is the length of the equivalent contact interface, and z(x) is the height of the surface profile at x.

Since the roughness of the contact surface between the Al metallization layer and the emitter Mo is less than 0.8 μm, the equivalent surface slope of the contact interface is expressed as [6]

$$m = 0.124\sigma^{0.743}, \sigma \le 1.6\mu m \tag{4}$$

According to Bahrami 's plastic contact thermal resistance model, the thermal conductivity of a single micro contact is calculated, and the h_s is characterized by the empirical formula[7]

$$h_s = 1.25k_s(m/\sigma)(p/H_c)^{0.95} \tag{5}$$

where p is the contact pressure, and the contact pressure of the press-pack IGBT device is usually 1100N;k_s is the harmonic mean of the thermal conductivity of the contact interface, $k_s = 2k_1k_2/(k1+k2)$, k_1 and k_2 are the thermal conductivity of the two contact materials, respectively. H_c is the microhardness of softer materials [8]

$$p/H_c = \left\{p/\left\{c_1\left[1.62\sigma/(m\sigma_0)\right]^{c_2}\right\}\right\}^{1/(1+0.071c_2)} \tag{6}$$

where c_1 is the Vickers hardness coefficient and c_2 is the Vickers hardness size factor, which can be calculated by the Sridhar empirical formula

$$c_1 = H_{BGM}\left(4 - 5.77\kappa + 4\kappa^2 - 0.61\kappa^3\right) \tag{7}$$

$$c_2 = -0.57 + \kappa/1.22 - \kappa^2/2.42 + \kappa^3/16.58 \tag{8}$$

$$\kappa = H_B / H_{BGM} \tag{9}$$

where H_B is the Brinell hardness of softer material, H_{BGM}=3.178GPa ; σ_0 is the reference value, taking 1 μm.

H_g was calculated using Yovanovich 's theoretical model [9]

$$h_g = k_g/(Y + M) \tag{10}$$

$$Y = 1.53\sigma\left(p/H_c\right)^{-0.097} \tag{11}$$

where k_g is the thermal conductivity of filled gas;Y is the effective void thickness, and M is the gas parameter.

After extracting the data coordinates of each point of the equivalent surface topography model, the root mean square surface roughness and surface slope of the equivalent contact surface are calculated, and finally the contact thermal conductance of the contact surface can be obtained. By changing the parameters D and G of the W-M fractal function, the contact thermal conductivity of different surface roughness models can be calculated, and the change rule of contact thermal resistance is studied as shown in table 4.

TABLE4. Contact thermal conductance of different equivalent surface topography

Fractal dimension *D*	Height scale parameters *G*	Surface RMS roughness *σ*/μm	Surface slope *m*	Thermal contact resistance/ K·W
D=1.2	*G*=0.01	0.293	0.050	0.029
D=1.4	*G*=0.01	0.141	0.029	0.025
D=1.6	*G*=0.01	0.071	0.017	0.021
D=1.8	*G*=0.01	0.040	0.011	0.017
D=1.4	*G*=0.1	0.660	0.091	0.037
D=1.4	*G*=0.001	0.053	0.014	0.019
D=1.4	*G*=0.0001	0.021	0.007	0.014

Fig.5(a) gives the relationship between the fractal dimension D of the two-dimensional profile and the contact interface morphology parameters and contact

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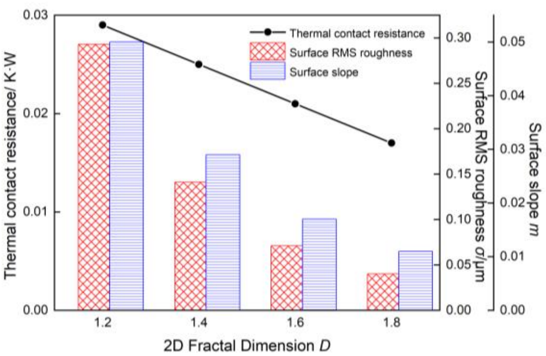
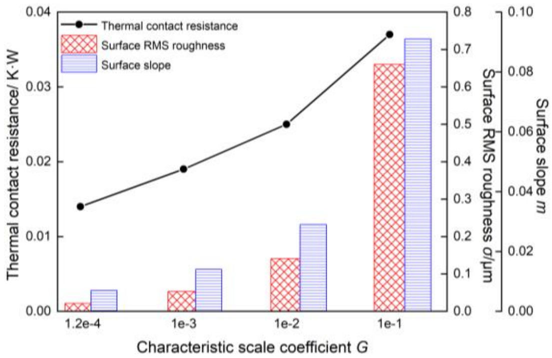
thermal resistance of the Al metallization layer and emitter Mo plate. For the equivalent contact surface of the Al metallization layer and the emitter Mo plate established by the W-M fractal function, when the characteristic scale parameter *G*=0.01 remains unchanged and the two-dimensional profile fractal dimension *D*=1.2, the root mean square surface roughness of the two-dimensional profile of the contact surface is 0.293 μm. When *D*=1.8, the root mean square surface roughness of the two-dimensional contour surface is reduced to 0.04μm;with the decrease of the fractal dimension of the two-dimensional profile, the amplitude fluctuation range of the two-dimensional profile curve is larger, that is, the gap space between the two materials is larger, which is not conducive to the conduction of heat flow during the power cycle of the press pack IGBT module. Therefore, the contact thermal resistance between the Al metallization layer and the emitter Mo plate increases from 0.017 K·W to 0.029 K·W.

Fig.5(b) gives the relationship between the characteristic scale parameter *G* and the contact interface morphology parameters and contact thermal resistance of the Al metallization layer and emitter Mo plate. When the fractal dimension *D*=1.4 of the two-dimensional profile remains unchanged and the characteristic scale parameter *G*=0.0001, the root mean square surface roughness of the two-dimensional profile of the contact surface is 0.021 μm. When *G* = 0.1, the root mean square surface roughness of the two-dimensional contour surface increases to 0.66μm;with the decrease of the height scale of the two-dimensional profile, the fluctuation range of the amplitude of the two-dimensional profile curve decreases, that is, the area of the micro-contact between the two materials increases, and the degree of heat flow shrinkage increases when passing through the micro-contact point, so the contact thermal resistance between the Al metallization layer and the emitter Mo plate decreases from 0.037 K·W to 0.014 K·W.



(a)



(b)

Fig.6. Relationship between the thermal contact resistance and the morphology parameters of the Al metallization/Mo contact interface.

(a) Different 2D contour fractal dimension

(b) Different characteristic scale parameters

4 Conclusions

In this paper, the two-dimensional electro-thermal coupling simulation analysis of the press-pack IGBT device is carried out by the finite element method. The temperature distribution of the press-pack IGBT module during the power cycle and the temperature change of each material layer are studied. The two-dimensional equivalent surface topography finite element model of Al metallization layer and emitter Mo plate is established by W-M fractal function. Different two-dimensional equivalent contact surfaces are established according to different parameters and electro-thermal coupling simulation analysis is carried out to observe the change of chip junction temperature, and compared with the chip junction temperature obtained by smooth contact surface finite element results. It is found that when the actual contact area of the contact interface becomes smaller, the heat flow will shrink sharply when passing through the micro-contact. The shrinkage of the micro-contact to the heat flow reduces the heat conduction volume, thereby reducing the heat dissipation and increasing the junction temperature of the pressed IGBT device chip. When the fractal dimension *D* of the two-dimensional profile increases, the micro-contact points of the contact interface decrease, resulting in an increase in the junction temperature of the chip during the power cycle.

The equivalent root mean square roughness and the equivalent slope of the contact interface of different two-dimensional equivalent surface topography are calculated by theoretical method. It is found that when the fractal dimension *D* of the two-dimensional profile increases and the characteristic scale parameter *G* remains unchanged, the two-dimensional surface profile curve gradually becomes complicated, but the amplitude of the curve decreases. Therefore, the

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equivalent root mean square roughness of the two-dimensional surface profile curve and the equivalent slope of the contact interface decrease. Therefore, the two-dimensional surface profile curve established by changing the fractal dimension *D* of the two-dimensional profile can simulate the equivalent surface topography between the material layers of the press-pack IGBT module under different cycles. Similarly, when the fractal dimension *D* of the two-dimensional profile is constant and the characteristic scale parameter *G* increases, the shape of the two-dimensional surface profile curve does not change significantly, but the fluctuation range of the curve increases. Therefore, the equivalent root mean square roughness of the two-dimensional surface profile curve and the equivalent slope of the contact interface increase. Therefore, the two-dimensional surface profile curve established by changing the characteristic scale parameter G can simulate the equivalent surface morphology between the material layers of the press-pack IGBT device under different cycles. The thermal resistance of different contact surface topography models is calculated by theoretical formula. It is further verified that the established two-dimensional surface profile finite element model can simulate the surface topography of each material layer of the press-pack IGBT device at different stages.

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