Research on Thermal Characteristics of IGCT Based on Structure Function

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Abstract: According to the principle of heat conduction during the operation of semiconductor devices, a GCT package model of IGCT devices is established. Perform transient simulation and use structure function analysis software for analysis. Based on the thermal resistance and heat capacity curve obtained by the structure function analysis method, the factors that may affect the thermal characteristics of the device are analyzed from the two angles of the thickness of the molybdenum disk and the thickness of the copper cathode. Thermal analysis of the 1μm micro-gap on the surface of the molybdenum disk and suggestions for improvement were put forward. The research results show that the structure function method is a non-destructive analysis method that can obtain the thermal resistance and heat capacity of each layer inside the device with high accuracy. The application of this method can analyze the internal microstructure changes of the device, and provide convenience for the research and evaluation of the thermal characteristics of the device.

1. Introduction

After years of development, high-power semiconductor devices have become one of the cores of power electronics technology. Integrated gate commutated thyristor (IGCT) has the advantages of high power level, high switching frequency, compact structure, low conduction loss, etc., and has broad application prospects. But the high power loss during use will cause the device to heat up, affect the reliability of the device, and then affect the stability of the entire system.

Among the common thermal resistance testing methods, Electrical methods and infrared methods each have their limitations[1-2]. And neither can know the heat distribution inside the device. The structure function method is based on the electrical method to obtain the transient response curve of the device, and mathematical analysis is carried out to analyze the internal thermal resistance and heat capacity of the device. It is a non-destructive method for thermal analysis of the device.

In recent years, people have made some improvements in the structure function to make the results more accurate[3], and some scholars have applied this method to the research of the thermal characteristics of IGBT or MOSFET[4-6]. But now it is rarely applied on IGCT. On this basis, this paper independently develops structural function software. A three-dimensional thermal simulation model of the IGCT device is established, and the thickness of the molybdenum disk and the thickness of the copper cathode in the device are respectively changed to simulate the model and then analyze by the structure function. The thermal analysis of the device is carried out through the obtained structure function curve. Finally, a micro-contact layer was added to the surface of the molybdenum disk. The structure function software was used to analyze it. Finally put forward suggestions for improvement.
2. Structure function theory

If the thermal conduction path of the device is one-dimensional, the device can be regarded as a series thermal resistance and heat capacity network composed of chips, solder, and copper substrates. And the structure function method can be used to extract the thermal resistance and heat capacity of each part of the device from transient response curve.

Figure 1(a) is a heat conduction model where constant power (P) is applied directly above, the bottom surface is constant temperature. Each layer is made of different materials. The total thermal resistance of the model is the sum of the thermal resistance of each layer. Figure 1(b) is the transient response curve of the model, which can be expressed as:

$$a(t) = \sum_{i} r_i [1 - \exp(-t / \tau_i)]$$  \hspace{1cm} (1)

where $a(t)$ is the transient response curve; $r_i$ is the thermal resistance component of each stage; $t$ is the response time; $\tau_i$ is the time constant of each stage. Let $z = \ln t$ and take the derivative of $z$ to get:

$$\frac{da(z)}{dz} = r(z) \mathcal{O} \sigma_i(z)$$  \hspace{1cm} (2)

$$\sigma_i = \exp[z - \exp(z)].$$  \hspace{1cm} (3)

Deconvolve the curve to get $r(z)$, see Figure 1(c). It contains the time constant information of the heat conduction path[7]. For $r(z)$ discretization, each unit can be equivalent to a stage in the Foster model, see Figure1(d). Since the Foster model has no clear physical meaning, this network model is converted to a Cauer model, as shown in Figure 1(e), which can reflect the thermal resistance and heat capacity of the actual physical structure. According to the solved Cauer model, the integral structure function curve is obtained by superposing the thermal resistance and heat capacity of each order, and the differential structure function curve is obtained by deriving the integral structure function.

3. Finite element model

The finite element model refers to the 5SHY45L4520 type IGCT device of ABB, and the model refers to the GCT part. The device is mainly composed of tube cover, anode molybdenum, chip, cathode molybdenum, gate assembly, copper cathode. As shown in Figure 2(a). Since the GCT part is a dual-sided heat sink device, the superposition of the heat dissipation paths on both sides will make the structure function curve unable to show the layering according to the device structure. Some scholars have proposed the use of anode insulation to measure the thermal resistance. Therefore, this paper adopts this method and establishing only the cathode side model to analysis structure function.
The finite element model established in this paper is shown in Figure 2(b) after removing the structure irrelevant to heat dissipation. The corresponding material of each part are shown in Table 1.

| Material            | Density kg/m³ | Conductivity W/(m·K) | Specific heat J/(kg·K) |
|---------------------|---------------|----------------------|------------------------|
| Chip (Si)           | 2340          | 148                  | 750                    |
| Molybdenum Disk (Mo)| 10280         | 138                  | 250                    |
| Gate (Al)           | 2700          | 237                  | 880                    |
| Cathode (Cu)        | 8900          | 401                  | 385                    |

4. Simulation and result analysis

The device manual calculates the power is about 4234W. After applying power and heat transfer coefficient, the heat conduction from chip to cathode. The maximum junction temperature transient response curve used for structure function analysis, and the structure function curve is shown in Figure 3. It can be seen that the curve is divided into three sections: chip, molybdenum disk and copper cathode. The R_th of the device is 0.025K/W, equal to the sum of three partial thermal resistances.

4.1. The influence of different molybdenum disk thickness on thermal characteristics

The molybdenum disk is a part for fixing the chip. The thickness of the molybdenum disk directly affects the thermal reliability of the device. Change the thickness of the molybdenum disk, and the thermal load was applied. The simulation results are shown in Figure 4.

The four lines in Figure 4 represent the structure function curves of the molybdenum disk with thicknesses of 1-4mm. It can be seen that when the area of the molybdenum disk is constant, the greater the thickness, the higher the thermal resistance. And the increase in the thermal resistance of the molybdenum disk leads to an increase in the overall thermal resistance of the device. This is because the increase of the thickness of the molybdenum disk will make the vertical conduction path longer, which increases the temperature and the thermal resistance.
Figure 4. Differential structure function curves corresponding to different molybdenum disk thicknesses.

From the figure, when the thickness of the molybdenum disk is 1mm, there is one peak loss in the curve. This is because when the thermal diffusivity of the material is similar, the thermal resistance peak will be submerged in the adjacent peak, that is to say it happened when a thin layer with low heat capacity and high thermal resistance is beside a material with high heat capacity. As the molybdenum disk becomes thicker and thicker, the missing "peaks" will gradually separate.

4.2. The influence of different cathode thickness on the thermal characteristics of the device

According to the original model, the thickness of the copper cathode was changed, and the differential structure function curve obtained after the simulation result was analyzed is shown in Figure 5.

Figure 5. Differential structure function curves of different copper cathode thicknesses.

Through the differential structure function curve, we can see that under the condition of changing the thickness of the copper cathode, the thermal resistance of the copper cathode has changed. As the thickness of the copper increases, the heat conduction path becomes longer. The thermal resistance of the copper cathode increases, resulting in an increase in the overall thermal resistance of the device. Through the structure function, we can see that the thermal resistance of each part inside the device changes very obviously.

4.3. The effect of the surface of the molybdenum disk of the device and its improvement

The surface of the molybdenum is rough due to the process problem. The surface roughness of the molybdenum disk without coating is shown in Figure 6. It is considered that the contact area is composed of many uniformly distributed discrete micro contact areas and related micro gaps, which are filled with air. These micro gaps hinder the heat transfer of the device, change the temperature distribution of the device, cause excessive heat concentration in the chip, and severely burn the device.

On the basis of the original model, a 1μm micro-contact air layer was added to simulate the contact surface between the molybdenum disk and the chip. Table 2 shows the material properties of air.
(a) Molybdenum disk. (b) Surface roughness of the molybdenum contact. [9]

Figure 6. Molybdenum disk and its surface roughness.

Table 2. Material properties of air.

| Material | Density $\text{kg/m}^3$ | Conductivity $\text{W/(m} \cdot \text{K)}$ | Specific heat $\text{J/(kg} \cdot \text{K)}$ |
|----------|------------------------|------------------|------------------|
| Air      | 1.177                  | 0.026            | 1006.4           |

The simulation result is shown in Figure 7. It can be seen that, due to the existence of the micro-gap layer, a large amount of heat is concentrated on the chip, and the temperature is increased 28.5K and 6.85% compared with the original model.

Figure 7. Model simulation results of adding a thin layer of micro-contact.

In response to this situation, we consider applying thermal grease between the molybdenum disk and the chip to enhance the heat dissipation of the device. In addition, other treatment method is to plate metals such as silver and rhodium on the surface of the molybdenum disk. The required material properties are shown in Table 3. The simulation results are shown in Table 4. And the integral structure function is shown in Figure 8.

Table 3. Material properties of thermal grease, silver and rhodium.

| Material | Density $\text{kg/m}^3$ | Conductivity $\text{W/(m} \cdot \text{K)}$ | Specific heat $\text{J/(kg} \cdot \text{K)}$ |
|----------|------------------------|------------------|------------------|
| Grease   | 2000                   | 4                | 932              |
| Ag       | 10490                  | 429              | 235              |
| Rh       | 12410                  | 150              | 242.7            |

Table 4. Simulation results of thin layers of different materials.

| Material | Temperature rise $\Delta K$ | Thermal resistance K/W |
|----------|-----------------------------|------------------------|
| Grease   | 114.831                     | 0.0271                 |
| Ag       | 111.126                     | 0.0262                 |
| Rh       | 111.320                     | 0.0263                 |
| Air      | 144.718                     | 0.0341                 |

It can be seen from Table 4 that these micro gaps will seriously affect the heat dissipation of the device. The temperature of the chip surface has reached 444.7K, which seriously exceeds the safe working temperature. However, whether applying thermal grease or metal plating on the surface of the molybdenum disk, it can effectively reduce the temperature rise.
Figure 8. Comparison of the curves of the micro gap layer with different filling materials.

From Figure 8 we can see that the thermal resistance of the model with the air layer is significantly higher than others. The thermal resistance of the chip and the molybdenum disk in the model with the air layer is 0.0154K/W, the thermal resistance of the filled model is 0.0097K/W. Therefore, the treatment of the micro-contact layer can reduce the overall thermal resistance by 37%. It can be clearly seen from the curve shape that there are obvious effects of fillers. The red circle in the figure represents the difference between the application of thermal grease and metal plating. The effect of reducing thermal resistance by metal plating is better than thermal grease. Therefore, the structure function method is suitable for lateral comparison of devices for thermal analysis.

5. Conclusion

According to the 5SHY45L4520 IGCT device, build a three-dimensional model, and simulation is performed to obtain the transient response curve of the maximum junction temperature. Analyze the structure function of the transient response curve. When the thickness of the molybdenum disk increases, the molybdenum disk part of the structure function curve moves toward the trend of increasing thermal resistance; when the thickness of the copper increases, the structure function curve separates at the copper cathode and the curve of the layer moves toward the thermal resistance increases tends to move. Finally, the structure function method is used to analyze the micro-gap with a thickness of 1 μm on the surface of the molybdenum disk. When air is contained in the micro-gap, the structure function curve obviously expands in the direction of large thermal resistance. When the surface is coated with thermal grease, silver or rhodium, the structure function curve clearly show that the molybdenum-chip part of the curve is significantly shortened, and due to the different filling materials in the micro gap, the curve will also be separated accordingly. It is concluded that the structure function method can not only obtain the overall thermal resistance value of the device, but also obtain the internal thermal resistance and heat capacity composition of the device without damage, and accurately analyze the internal structure changes of the device. Therefore, in further research, the structure function method can be used to analyze the thermal characteristics of the IGCT device to improve the subtle parts of the device.

References
[1] Dong, S.H., Liu, Y.K., Feng, B., et al. (2007) The technology of extracting die S parameters through TRL calibration. J. Semiconductor Technology. 02:96-99.
[2] Wood, A., Brakensick, W., Dragon, C., et al. (1998) 120 Watt, 2 GHz, Si LDMOS RF power transistor for PCS base station applications. J. IEEE Mtt S International Microwave Symposium Digest IEEE Mtt S International Microwave Symposium. 2:707 - 710.
[3] Szekely, V., et al. (1997) A new evaluation method of thermal transient measurement results. J. Microelectronics Journal. 28(3): 277-292.
[4] Kim, T., Funaki, T. (2016) Thermal measurement and analysis of packaged SiC MOSFETs.
[5] Gao, W., Yin, P., Li, Z., Zhang, J. (2018) Analysis of package thermal resistance and thermal conduction process of power VDMOS devices. J. Electronic Components and Materials. 37(07): 29-34.

[6] Deng, E., Zhao, Z., Zhang, P., et al. (2018) Study on the Method to Measure the Thermal Contact Resistance within Press pack IGBTs. J. IEEE Transactions on Power Electronics. PP(99):1-1.

[7] Yu, D. (2012) Fatigue life assessment and prediction of ball grid array package under environmental conditions. D. State University of New York at Binghamton.

[8] Zhang, G. C. (2008) Research on non-destructive testing technology for thermal characteristics of semiconductor devices. D. Beijing University of Technology.

[9] Gonzalez, J. O., Aliyu, A. M., Alatise, O., et al. (2016) Development and characterisation of pressed packaging solutions for high-temperature high-reliability SiC power modules. J. Microelectronics Reliability. 434-439.

[10] Bahrami, M., Culham, J. R., Yovanovich, M. M., et al. (2004) Thermal Contact Resistance of Nonconforming Rough Surfaces, Part 1: Contact Mechanics Model. J. Journal of Thermophysics and Heat Transfer. 18(2):p.209-217.