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Research on IGBT Limit Current Based on Heat Balance Analysis

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Abstract. Insulated Gate Bipolar Transistor(IGBT) is the most widely used fully-controlled power electronic device at present, and the rated DC current and maximum pulse current given in the manual can't reflect the working limit current. In this paper, considering the influence of temperature, the electrical model of IGBT is extended to electro-thermal model, and the stable point, unstable point and critical point of junction temperature are obtained by combining IGBT power consumption-temperature curve and heat transfer curve, thus the limit power consumption at the critical point is obtained, and the limit current is designed. Finally, experimental verification is carried out.

1. Introduction

Insulated Gate Bipolar Transistor (IGBT) is a composite device which combines the structure of field effect transistor (MOSFET) and bipolar transistor (BJT), and absorbs the advantages of both. Widely used in various green energy fields such as wind energy and solar energy, it is the most widely used fully-controlled power electronic device at present[1].

IGBT simulation model is an important tool for device structure design, performance analysis and parameter optimization, and has always been a research hot spot. According to different application objectives, the modeling method, simulation accuracy and operation complexity are also different. The mathematical model is based on the internal physical structure and actual working mechanism of IGBT, and is established by semiconductor physics method[2-3]. According to the requirements of simulation accuracy, by reasonably simplifying and approximating the actual working process of IGBT, a good compromise is achieved between simulation accuracy and calculation amount, which is easy to be realized by electrical simulation software. The characteristics of semiconductor materials and internal parameters are affected by temperature, which will cause the working characteristics of IGBT to change greatly with the change of temperature[4]. Therefore, the mathematical model of IGBT is extended to an electro-thermal model which can reflect the working characteristics of devices at different temperatures.

In this paper, considering the influence of temperature, the electrical model of IGBT is extended to electro-thermal model, and then the thermal balance analysis is carried out by combining the power consumption curve and heat transfer curve of IGBT, and the stable point, unstable point and critical point of junction temperature are obtained, thus the limit power consumption of IGBT at critical junction temperature is obtained, and then the limit current design is carried out. Finally, experimental verification is carried out.

2. Theoretical analysis

2.1. IGBT electric heating model

The working states of IGBT include turn-on transient, on state, turn-off transient and blocking state. Because different types of IGBT (NPT type, PT type and FS type) have different physical structures and manufacturing processes, the assumptions and boundary conditions adopted in the modeling process are also different, so the on-off voltage drop, switching voltage and current of devices are also different.

As the physical constants and internal parameters of semiconductor power IGBT devices, including carrier mobility, intrinsic carrier concentration, diffusion coefficient, excess carrier life, emitter electron saturation current, gate threshold voltage and trans-conductance, etc., will change with temperature, resulting in the on-state voltage drop, switching speed, collector leakage current and other performance indicators of IGBT, so the operating characteristics of IGBT are greatly affected by temperature.

According to the internal simulation parameters of IGBT mathematical model, the temperature-related parameters can be divided into two categories. The first category is the internal parameters of the device, including excess carrier life, gate threshold voltage, trans-conductance and emitter electron saturation current, etc. References [5-6] gives empirical formulas of these parameters changing with temperature.

The other is the semiconductor physical constants of materials, including intrinsic carrier concentration, carrier mobility and diffusion coefficient. Among them, the relationship between intrinsic carrier concentration and temperature can be expressed as:

$$n_i(T) = C(\frac{T}{300})^{1.5}\sqrt{\exp(-\frac{1.206}{kT})} \tag{1}$$

Where: $k = 8.62\times10^{-5} eV/K$ is Boltzmann constant; $C = 8.324\times10^{19} cm^{-3}K^{-1.5}$ is the scale factor.

Off-state power consumption of IGBT is the product of blocking voltage V_{CE} and leakage current I_{leak}, and multiplied by duty cycle D, which is expressed as:

$$P_{off}(T) = V_{CE}\times I_{leak}(T)\times(1-D) \tag{2}$$

IGBT conduction power consumption is the product of conduction current I and conduction voltage drop $V_{ce(on)}$, and multiplied by duty cycle, which can be expressed

$$P_{on}(T) = V_{ce(on)}(T)\times I\times D \tag{3}$$

IGBT switching power consumption is the energy of single switching times the switching frequency, which is expressed as:

$$P_{sw}(T) = [E_{on}(T) + E_{off}(T)]f \tag{4}$$

IGBT power consumption-temperature relation is obtained:

$$P_{heat}(T) = P_{on}(T) + P_{sw}(T) + P_{off}(T) \tag{5}$$

2.2. Heat balance analysis of IGBT

IGBT is a multi-layer structure composed of different materials. As shown in Figure 1, the internal silicon chip is equivalent to a heat source, and the heat is transferred to the bottom plate through the direct copper-clad layer. In order to increase the heat dissipation area, the bottom plate is usually connected with a heat dissipation device. A layer of silicone grease with good heat dissipation is coated between the bottom plate and the heat dissipation device, which can reduce the contact air gap and thus the contact thermal resistance. The bottom plate transfers heat to the surrounding environment through the heat dissipation device.

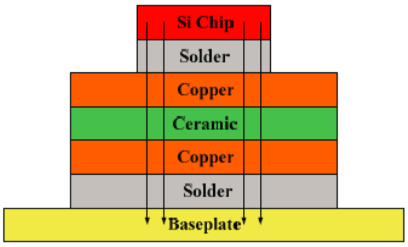

Figure 1. IGBT module structure plane

When the dissipated heat is equal to the heat generated by the chip, the system reaches the heat balance state, and the temperature of each part remains stable. For a certain combination composed of IGBT module, heat sink and cooling medium, its steady-state heat transfer power consumption can be expressed as[7]:

$$P_{cool}=\frac{T_j-T_A}{R_{thJA}}=\frac{T_j-T_c}{R_{thJC}} \tag{6}$$

Where: R_{thJA} is the steady-state thermal resistance between junction and environment; R_{thJC} is the steady-state thermal resistance of junction-shell; T_j is junction temperature; T_A is the ambient temperature; T_c is the shell temperature; P_{cool} is the power consumption conducted for the heat sink which equal to the power consumption generated by IGBT.

Equation (6) relates the power consumption of the device to the ambient temperature and cooling method, but the applicable situation is that the system has entered the heat balance state, and the steady temperature distribution of each part has been established. The IGBT power consumption curve and heat transfer power consumption curve are plotted in the same coordinate system, with junction temperature as abscissa and power consumption as ordinate. The thermal breakdown failure mechanism can be shown in Figure 2.

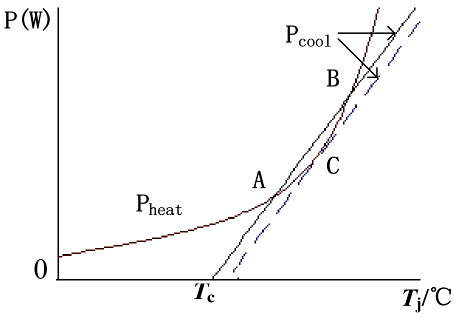

Figure 2. Chart of thermal equivalent analysis

Among them, P_{heat} is the power consumption curve of IGBT, and t P_{cool} is the junction-shell heat transfer power consumption curve of IGBT. It can be seen that the relationship between the two curves and the temperature is not the same. If the curves intersect at A and B, there are:

(1) Below the first intersection point A, there is $P_{heat} > P_{cool}$, which means that the generated power consumption is greater than the power consumption taken away by the heat sink. The IGBT chip will reach the thermal balance and keep the temperature stable.

(2) Between the point A and B, there is $P_{cool} > P_{heat}$, which means that the generated power consumption is less than the power consumption taken away by the heat sink, and T_j will fall back to the equilibrium point A.

(3) Above the point B, there is $P_{heat} > P_{cool}$, which means that the generated power consumption is greater than that taken away by the heat sink, and IGBT can no longer reach balance.

As the increase of T_j will lead to further increase of power consumption, the junction temperature and power consumption will enter a continuously rising positive feedback state, the junction temperature will rise continuously and the collector leakage current will increase sharply, the chip temperature will rise rapidly to the intrinsic temperature and short circuit will occur, and then the junction temperature will continue to rise until thermal breakdown failure occurs. Therefore, this point is also called thermal unstable temperature point, that is, at a certain shell temperature.

2.3. Limit current design of IGBT

The thermal balance simulation method based on IGBT electro-thermal model can not only obtain the shell temperature of IGBT when thermal breakdown occurs, but also be used to design the IGBT parameters for maximum use under certain shell temperature conditions. The IGBT parameter limit use design method, which uses IGBT electro-thermal model simulation as a means to analyze the heat balance, can be used to design the current limit of IGBT under a given switching frequency and analyze the influence of voltage and shell temperature on the current and switching frequency limit. The design steps are as follows:

(1) according to IGBT device types, different modeling methods are selected to obtain the conduction voltage drop, transient voltage and current and collector leakage current of IGBT, and the models of conduction power consumption, switching power consumption and off-state power consumption are obtained by circuit conditions, and the total power consumption model of IGBT is obtained by adding them.

(2) extracting the internal parameters needed for simulation of IGBT total power consumption model, considering the relationship between semiconductor physical constants and internal parameters and temperature, expanding the IGBT total power consumption model into an electro-thermal model reflecting temperature characteristics, and obtaining the temperature curve of IGBT power consumption;

(3) Based on the steady-state thermal resistance of the junction-shell, the heat transfer equation of the junction-shell at a given shell temperature is obtained, and then the heat transfer and power consumption curve of the junction-shell is obtained.

(4)Heat balance analysis is carried out by combining the IGBT power consumption-temperature curve and the heat transfer curve, and the IGBT power consumption-temperature curve is moved by changing the IGBT current until tangent to the heat transfer curve.

(5)The current when the two curves are tangent is the limit current under this application condition.

3. Experimental verification

The IGBT module with GD50HFL120C1S is selected in the experiment, which is a soft punch-through two-unit half-bridge module. The experimental conditions are as follows: DC voltage is 600V, switching frequency is 5kHz, and initial duty cycle is 0.5.

The IGBT module is fixed on a cooling base plate which can adjust the water flow speed in a large range, and the thermo-couple for measuring the shell temperature is arranged right under the test chip. Initially, a larger water flow velocity is adopted, and when the IGBT reaches the thermal equilibrium state, the water flow velocity is reduced and the shell temperature is slowly increased to 80°C. Increase the current by slowly adjusting the resistance value of variable load until failure occurs. The current value at this time is recorded, which is the limit current corresponding to the working state. Then, by changing the duty cycle, the failure current values under different duty cycles are obtained by the same experimental method. Duty cycle and limit current are shown in Table 1.

Table 1. Limit current under different duty cycles

Duty	0.2	0.3	0.4	0.5	0.6	0.7	0.8
Limit current(A)	117	102	92	84	79	75	72

The data in Table 1 are processed by MathCad software, and the curve shown in Figure 3 is simulated. It can be seen that with the increase of duty cycle, the corresponding current application limit decreases, and the change rate of current with duty cycle gradually slows down. This shows that the current limit level can be significantly increased by reducing the duty cycle.The heat balance curves of three groups of different duty cycles in simulation analysis are shown in Figure 4.

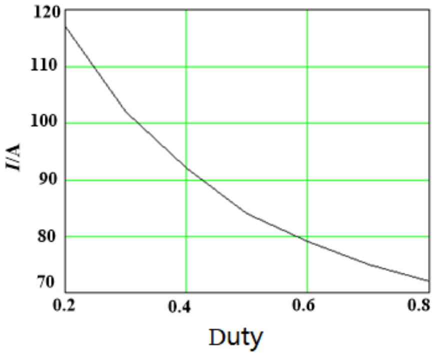

Figure 3. Curve of limited current

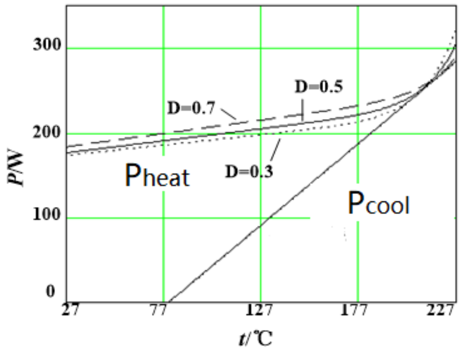

Figure 4. Thermal equivalent curve

4. Summary

Based on the heat balance analysis of the power-temperature curve and heat transfer curve of the simultaneous IGBT, the maximum power consumption when the two curves are tangent is obtained, and the limit current is designed by the maximum power consumption. Finally, experimental verification is carried out.

Acknowledgments

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