Detection of Transient Junction Temperature Characteristics of High Power IGBT

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Abstract. In this paper, Insulated Gate Bipolar Transistor (IGBT), which is the most widely used full-control power electronic device, is taken as the research object. Under the special working mode of short-time intermittent pulse, with the increase of conduction current, the chip junction temperature of high-power IGBT will rise sharply and fluctuate greatly, causing the operating characteristics of the device to be greatly affected by temperature. The commonly used method of measuring the bottom plate shell temperature with thermocouples and then estimating the steady junction temperature can no longer meet the demand. Firstly, the fluctuation characteristics of junction temperature of high-power IGBT are analyzed. Then, a high-speed infrared thermal imaging device is used to carry out real-time junction temperature detection. The distribution and rising process of instantaneous junction temperature on the chip surface are obtained, which further verifies the correctness of theoretical analysis. The research has important guiding significance for IGBT application design under short-time intermittent pulse operation mode, and also has certain reference value for general operation mode.

1. Introduction
In the conventional heat dissipation design of power electronic devices, the general concern is the steady junction temperature of the devices after long-term operation. The commonly used method is to monitor the temperature of the bottom plate of the device and calculate the internal chip junction temperature through the thermal impedance parameters from the bottom plate to the chip. At the same time, air cooling, water cooling and other heat dissipation methods are used to control the chip temperature within the safe working range [1]-[2].

However, in some large-capacity special high-performance power electronic devices, the voltage and current levels of power electronic devices are very high, resulting in large power loss. Especially in some military special devices, such as aircraft electromagnetic ejection, electromagnetic gun and laser weapon, the short-time intermittent pulse working mode is adopted[3]. Power electronic devices conduct great current in a very short time, generally close to its repeatable turn-off peak current, which generates great power consumption in a very short time, causing the junction temperature of the devices to rise sharply and fluctuate greatly.

The characteristics of semiconductor materials are greatly affected by temperature, which results in the operating characteristics of semiconductor electronic devices changing greatly with temperature. As the main power device in the electric energy conversion device, the on-state current and blocking voltage during operation are very large, and the on-state loss and switching loss generated during stable on-state and switching transient process are much larger than those of general microelectronic...
devices, so the temperature rise degree and fluctuation range during operation of power electronic devices are more significant, thus causing great influence on the operation characteristics of power electronic devices[4]-[5].

Therefore, temperature is an important consideration in power electronic device application, especially in heat dissipation design. Therefore, for these power electronic devices, the conventional temperature estimation method has been difficult to accurately calculate the real-time operating temperature of the chip inside the module, and an accurate equivalent heat transfer model must be established to analyze the instantaneous temperature distribution[6]-[7]. On the other hand, the conventional method of using thermocouples to detect the steady-state shell temperature at the bottom plate of the device currently used cannot accurately reflect the instantaneous junction temperature change of the internal chip, and high-speed detection equipment must be used to detect the junction temperature of the chip in real time[8]-[9].

In this paper, Insulated Gate Bipolar Transistor (IGBT), the most widely used full-control power electronic device, is taken as the research object[10]-[11]. Firstly, the working junction temperature variation and fluctuation principle of high-power IGBT are analyzed, and then a high-speed infrared thermal imaging device is used to carry out real-time junction temperature detection[12]-[13], further verifying the correctness of theoretical analysis.

2. Analysis of IGBT Junction Temperature Fluctuation Principle

The general commercial high-power IGBT at present adopts the packaging form of a module, the chip is packaged inside the module, and the surface is covered with a layer of silica gel. Due to the heat blocking effect of silica gel, most of the heat generated by chip operation is transmitted downwards along the direction perpendicular to the bottom plate, passes through various layer structures such as the substrate, solder layer, bottom plate, and finally is dissipated by the heat dissipation device. Since the injection position of electron current through the MOSFET conductive channel is near the gate on the upper surface of IGBT chip, which is the main part generating power loss and the main heat source, and because the chip is very thin relative to other layers of the module, the upper surface temperature of IGBT chip is generally analyzed as the IGBT working junction temperature. The rise of IGBT junction temperature is caused by power loss during operation. when rectangular single pulse with amplitude or continuous pulse with long enough interval time acts on IGBT chip, the change of IGBT junction temperature from the initial temperature is shown in figure 1.

![Figure 1. Temperature movement caused by power pulse](image)

As can be seen from figure 1, when a rectangular power pulse with width \( t_p \) acts on the IGBT chip, the junction temperature of the IGBT \( T_j \) will rise from the initial temperature \( T_0 \), and the rising rule can be expressed as[10]-[11]:

\[
\Delta T_j(t) = P_0 \sum_{i=1}^{n} R_i (1 - e^{-\frac{t}{\tau_i}})
\]  

(1)
Where, \( n \) is the number of heat transfer network nodes; \( R_i \) is the thermal resistance value at the node \( i \); \( C_i \) is the heat capacity value at the node \( i \), \( \tau_i = R_i C_i \). \( T_j \) rising to the maximum value \( T_{j\text{max}} \) at the moment \( t_p \) can be expressed as:

\[
T_{j\text{max}} = T_j(t_p) + T_0
\]  

(2)

Since then, due to the disappearance of the power pulse, \( T_j \) starts to gradually decrease according to the exponential law. The decrease process can be expressed as follows:

\[
T_j(t) = P_0 \sum_{i=1}^{n} R_i e^{-\frac{t}{\tau_i}}
\]  

(3)

It will return to the initial temperature after a long enough time. However, generally speaking, IGBT is in the PWM mode of continuously conducting a series of pulses, and the interval time of continuous pulses is not sufficient to restore the junction temperature to the initial temperature. at this time, the rise and fluctuation process of IGBT junction temperature will be shown in figure 2.

Figure 2. Raise process of temperature cumulation

As can be seen from figure 2, under the action of a series of continuous pulses, the junction temperature rises when the IGBT conducts current, and the junction temperature starts to fall after the IGBT is turned off. however, before the junction temperature returns to the initial value in the falling phase, it enters another rising process, thus cumulatively rising under the repeated action of continuous pulses. After a gradual rise, the junction temperature enters a periodic constant amplitude fluctuation state, which is approximately constant amplitude fluctuation around a constant temperature \( T_{j\text{avg}} \). The highest temperature is \( T_{j\text{max}} \), the heat generation and dissipation reach a dynamic balance.

The rising process of IGBT junction temperature is related to device power consumption, heat dissipation conditions, operating frequency, duty cycle, etc. The magnitude of fluctuation is directly related to power consumption. Under short-time intermittent pulse operation, IGBT instantaneous conduction current is extremely large, resulting in great power consumption and heat generation. Therefore, the amplitude and fluctuation range of junction temperature rise is much larger than that under general normal operation conditions. When IGBT works, the junction temperature cannot exceed its maximum safe working junction temperature. In general continuous working power electronic devices, the working current is relatively small, and the amplitude of IGBT junction temperature fluctuation is not very large. Therefore, the average temperature fluctuation is generally analyzed as the working junction temperature. However, under short-time intermittent pulse operation, the operating current is close to the repeatable turn-off peak current of the device, the operating current of IGBT is much larger, and the fluctuation amplitude of junction temperature is more severe. Therefore, the highest temperature of junction temperature fluctuation must be taken into account when the device is applied and the heat dissipation design is carried out.
3. IGBT Transient Junction Temperature Detection

At present, the commonly used temperature detection methods mainly include thermocouple method, infrared thermal imaging detection method and electrical parameter method. These three methods have their own characteristics[12], but they are not all suitable for real-time detection of IGBT instantaneous operating junction temperature. The specific analysis is as follows:

First, thermocouple temperature measurement method is not feasible. On the one hand, the thermocouple temperature measurement method is relatively slow in detection speed, and the test speed is also related to specific measurement conditions, which cannot meet the requirements of IGBT junction temperature real-time detection. On the other hand, when thermocouple is used to measure temperature, it needs to be in full contact with the object to be measured. When high-power IGBT is in operation, the voltage and current on the chip are very large. At the same time, there is also a connection key wire to connect with the external port and the substrate. Considering factors such as insulation and avoiding short circuit, only the thermocouple part can be placed around the chip, thus leading to large measurement errors.

Second, the electrical parameter temperature measurement method can estimate the operating junction temperature of IGBT, but the test accuracy and speed of this method are not very high. The electrical parameter method is an indirect method to measure temperature through temperature-sensitive IGBT electrical parameters. Firstly, the method needs to select appropriate temperature parameters and calibrate them. During the temperature measurement process, it needs to switch from the working state to the testing state. The testing steps are complicated, which is easy to cause large errors in the operation process. Switching between the two states requires a certain time, thus limiting the improvement of temperature measurement speed of the electrical parameter method. Therefore, the method can only make rough estimation of IGBT junction temperature.

Third, as a temperature measurement method that does not directly contact the measured object, the infrared temperature measurement method has high accuracy and very fast detection speed, and can meet the requirements of IGBT real-time junction temperature measurement. Two problems need to be solved when using this method to detect IGBT real-time junction temperature: first, the general commercial IGBT modules are all packaged finished products with a shell, and the surface of the internal chip is also covered with a layer of silica gel, which must be opened and removed before measurement can be carried out. In this paper, a module specially made for IGBT packaging factory in China is used for testing. The module is GD50HEL120C1S, rated voltage 1200V, rated DC continuous working current 50A. The structure is shown in figure 3.

High-speed infrared thermal imaging temperature measuring equipment must be used. In this paper, a high-speed infrared temperature measuring device named InfraScopeⅡII is used. The device has the function of high-speed continuous shooting. It can continuously shoot 100 pictures at a speed of 0.1 second/picture. It can be used to detect the real-time operating junction temperature of IGBT. Its appearance is shown in figure 4.

![Figure 3. IGBT for test](image1)
![Figure 4. InfraScopeⅡ](image2)

In the junction temperature detection experiment, the load uses a variable resistor to adjust the on-current by changing the resistance value, and the turn-on and turn-off of the IGBT under test are realized by DSP controlling the drive circuit. Set the working frequency of IGBT to be tested to 1kHz, pulse width to 1mS, duty ratio to 0.5, DC bus voltage to 530V, peak voltage to 740V during shutdown, conduction current to 100A, reaching repeatable shutdown peak current, twice its rated DC working
current, working time to 1 second, continuous conduction of 1,000 pulses, intermission of 10 minutes after one operation, and chip surface temperature returning to the initial state.

The temperature on the surface of the IGBT chip was observed by InfraScopeII infrared thermal imager, and the temperature distribution on the surface of the IGBT chip as shown in figure 5(a) was obtained. In the figure, different color indicate different temperatures, and the deeper the color, the higher the temperature. The temperature value of each test area can be conveniently obtained through the color temperature scale as shown in figure 5(b) in the thermal imaging processing software.

![Temperature distribution and Color thermometer](image)

(a) Temperature distribution (b) Color thermometer

**Figure 5.** Temperature distributing of IGBT chip

From the test results shown in figure 5, it can be seen that the surface temperature of IGBT chips is not completely consistent, but the difference is not big in most areas, basically within. The highest temperature occurs at the edge of the chip, i.e. the junction between the chip and the copper substrate. At the same time, the connection position between the chip center and the bonding wire also has some high temperature areas, and the temperature distribution in other areas is relatively uniform. Therefore, the average temperature on the chip surface is generally analyzed as the IGBT junction temperature in the literature. The junction temperature rise process of IGBT was tested by using the high-speed continuous shooting function of InfraScopeII infrared thermal imager. In the IGBT chip surface temperature distribution map obtained by continuous shooting, when the shooting time is 0.2 seconds, 0.4 seconds, 0.6 seconds and 0.8 seconds, the measured images are shown in figure 6 (a), (b), (c) and (d), respectively.

![Continuous shooting images](image)

(a) 0.2s (b) 0.4s (c) 0.6s (d) 0.8s

**Figure 6.** Chip temperature distributing on different moment

As can be seen from figure 6, under the set short-time intermittent pulse operation mode, the IGBT chip surface temperature rises very high, and the average temperature of the whole chip surface at different times is shown in table 1.

| t(s) | t=0.2s | t=0.4s | t=0.6s | t=0.8s |
|------|--------|--------|--------|--------|
| T(°C) | 20     | 33     | 45     | 45     |

**Table 1.** On-state current sharing at different temperature

As can be seen from table 1, the junction temperature rose from near room temperature to the highest temperature around 0.6 seconds and remained basically stable. At this time, the IGBT junction
temperature entered a constant amplitude fluctuation state. Since the maximum testing speed of the InfraScopeII temperature measuring equipment is only 0.1 seconds/amplitude, and the average temperature within 0.1 seconds is measured, the junction temperature rise process is detected, and the obvious temperature fluctuation process cannot be measured, so higher speed instruments are needed to capture.

4. Conclusion
In this paper, the instantaneous junction temperature of IGBT under short-time intermittent pulse operation mode is analyzed, and then a high-speed infrared thermal imaging device is used to carry out real-time junction temperature detection, and the distribution and rising process of the instantaneous junction temperature on the chip surface are obtained, which has important guiding significance for IGBT application design under short-time intermittent pulse operation mode and certain reference value for general operation mode.

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