Simulation Research on Transient Junction Temperature Characteristics of High Power IGBT

Tang Yong¹, Wang Bo¹ and Chen Yong Hong ¹
¹College of Mechanical and Electronic Engineering, Wuhan Donghu University, Wuhan 430000, Hubei Province, China.

Email address of corresponding author: tangyong_tt@163.com

Abstract. Because the characteristics of semiconductor materials are greatly affected by temperature, the working characteristics of semiconductor electronic devices also change greatly with the change of temperature. High-power power electronic devices will bear larger conduction current and blocking voltage when working, and the temperature rise and fluctuation range will be more significant when working. Especially in the special working mode of short-time rest pulse, the junction temperature inside the chip will rise sharply and fluctuate greatly. The commonly used method of detecting the bottom plate shell temperature by thermocouple and then calculating the steady-state junction temperature can no longer meet the demand. According to this situation, this paper first analyzes the principle of junction temperature fluctuation of high-power power electronic devices, and then establishes the equivalent heat transfer model from the device bottom plate to the internal chip by using the multi-node heat transfer network method. Finally, the transient change and fluctuation process of the chip junction temperature during short-time intermittent pulse operation are obtained through simulation analysis, and the accuracy of the model is also verified.

1. Introduction

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 common microelectronic devices. Therefore, the temperature rise degree and fluctuation range during operation of power electronic devices are more significant, thus causing great influence on the operating characteristics of power electronic devices[1]-[2]. Therefore, temperature is an important consideration in power electronic device application, especially in heat dissipation design.

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[3]-[4]. 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 [5] is adopted. 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. 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, the principle of junction temperature variation and fluctuation in high-power power electronic devices is analyzed, and the equivalent heat transfer model from the device bottom plate to the internal chip is established. Through simulation analysis, the transient variation and fluctuation process of chip junction temperature under short-time intermittent pulse operation are obtained.

2. Analysis of Junction Temperature Fluctuation Principle
Taking Insulated Gate Bipolar Transistor (IGBT) as an example, which is the most widely used full-control power electronic device at present[10]-[11], 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]:

$$
\Delta T_j(t) = P_0 \sum_{i=1}^{n_i} R_i (1 - e^{-\frac{t}{\tau_i}})
$$

(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 $i$. $\tau_i = R_iC_i$. $T_j$ 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](image-url)

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. Simulation of Transient Junction Temperature Characteristics

In order to analyze the rise and fluctuation process of IGBT junction temperature under different operating conditions and obtain its instantaneous change process, this paper uses commercial electrical simulation software Saber and uses IGBT model and equivalent heat transfer model in its model base to construct chopping operation simulation circuit and equivalent heat transfer simulation circuit as shown in figure 3 [2].

![Simulation circuit structure](image)

**Figure 3. Simulation circuit structure**

As shown in the figure 3, the simulation circuit adopts a chopper circuit consisting of IGBT, freewheeling diode, load resistor and load inductor, wherein the IGBT model is an ideal original with a thermal interface in Saber model base and can be connected with an external heat transfer network model. The heat transfer model consists of chip components, package components and radiator components in Saber model library. These heat transfer components are an equivalent heat transfer model based on RC network, and each component is composed of many single heat nodes connected as shown in figure 4.

![Single node of thermal net](image)

**Figure 4. Single node of thermal net**

As can be seen from figure 4, the RC heat transfer network is actually equivalent to the heat transfer process as the current flow process in the circuit, in which the temperature $T$ of each node is equivalent to voltage, the heat flowing into the node is equivalent to current, the thermal resistance $R$ and the heat capacity $C$ are equivalent to the resistance and capacitance in the circuit respectively, and the direction indicated by arrows in the figure is the heat transfer direction. According to Kirchhoff's circuit equation, the current (heat) flowing into node $i$ is conserved, so equation (4) can be obtained, and the series connection of multiple nodes can more closely approximate the real transfer process.

\[
\frac{T_{i+1} - T_i}{R_{i+1}} = C_i \frac{dT_i}{dt} + \frac{T_i - T_{i-1}}{R_{i-1}}
\]

(4)

Using the simulation circuit shown in figure 3, the operating voltage is set to 530V, the gate driving voltage is set to 15V, the load inductance is 1mH, the load resistance is 5.3 ohms, the ambient temperature is room temperature, $T = 25^\circ C$, the switching frequency is 1kHz, and the duty ratio is 0.5. the simulation results show the junction temperature waveform, the operating voltage waveform and the current waveform after entering the constant amplitude fluctuation as shown in figure 5 [4].
As can be seen from figure 5, since power loss will occur in both the on-state and off-state of IGBT during the on-state transient, the junction temperature will rise accordingly. After entering the constant amplitude fluctuation state, the junction temperature fluctuates with constant amplitude $T_{j\text{max}} - T_{j\text{min}}$ around the average temperature $T_{jav}$. When the IGBT enters the on state, the junction temperature starts to rise and keeps rising throughout the on state, the on state and the off state. When the IGBT exits the off state, the junction temperature starts to fall until the next on state starts. The rising and falling amplitudes of the junction temperature are equal. When the duty ratio is 0.5, the rising and falling times are also equal. It can also be seen from the figure that during the switching transient, the switching loss will cause a sharp rise in temperature and a temperature spike will appear, especially during the off transient. This is mainly due to the commutation between IGBT and diode during the turn-off transient. IGBT voltage first rises to bus voltage, and then current begins to drop. At the same time, current will not disappear immediately when IGBT is turned off, and there will be a tailing phase when the voltage has risen, thus resulting in larger power consumption and sharp rise in junction temperature.

![Figure 5. Simulation wave of IGBT chip temperature](image)

Using the simulation circuit shown in figure 3, the load resistance is changed to 5.3 ohms and 10.6 ohms respectively, and the corresponding IGBT maximum conduction current is 100A and 50A respectively, the simulation results show that the junction temperature rises and fluctuates as shown in figure 6 [2].

![Figure 6. Temperature wave under different current](image)

As can be seen from figure 6, under certain heat dissipation conditions, the larger the conduction current, the more intense the junction temperature rise, and the higher the average temperature of the fluctuation central temperature after entering the constant amplitude fluctuation state, the greater the fluctuation amplitude. When the conduction current is 50A, the IGBT junction temperature enters the constant amplitude fluctuation state in about 0.4 seconds, and the constant amplitude fluctuation and
the highest temperature $T_{\text{max}} = 20^\circ C$ with the amplitude $3^\circ C$ as the central temperature $T_{\text{ave}} = 17^\circ C$. However, when the conduction current is 100A, the IGBT junction temperature enters an equal amplitude fluctuation state in about 0.6 seconds, with the central temperature $T_{\text{ave}} = 45^\circ C$ and the amplitude $9^\circ C$ as the equal amplitude fluctuation and the highest temperature $T_{\text{max}} = 54^\circ C$.

From the simulation results, it can be seen that for large-capacity special high-performance power electronic systems, especially for short-time intermittent pulse operation with instantaneous conduction of great current, the junction temperature fluctuation of IGBT will be very severe, and the difference between the maximum junction temperature and the average junction temperature in the fluctuation will be large, which will have a great impact on the normal operation, lifetime and reliability of devices. Therefore, the maximum junction temperature in the fluctuation process must also be considered as an important factor in the design phase.

4. Conclusion
In this paper, the transient junction temperature of IGBT under short-time intermittent pulse operation mode is simulated and analyzed. It is found that with the increase of operating current, the rise range and fluctuation range of the junction temperature of IGBT internal chip are also larger. It 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.

Acknowledgments
Project supported by Youth Foundation of Wuhan Donghu University(2018dhzk004), science and Technology Research Project of Hubei Education Department(B2019273).

References
[1] Benbahouche L, Merabe A, Zegad A. An Improved Understanding of IGBT Behavior under Thermal Stress[C]. Proceedings of MIEL,2008:11-14.
[2] Tang Yong, Wang Bo, Chen Ming. Temperature Characteristic and Electric-thermal Model of IGBT Switching Transient[J]. Transactions of China Electrotechnical Society, 2012,27(12):146-153.
[3] Lim D J, Pulko S H. Characterisation of Heat Spreader Materials for Pulsed IGBT Operation[J]. IET Circuits Devices Syst, 2007,1(2):126-136.
[4] Tang Yong, Wang Bo. Reliability and on-line Evaluation of IGBT Modules under High Temperature [J]. Transactions of China Electrotechnical Society, 2014,31(30):54-60.
[5] Clemente S. Transient Thermal Response of Power Semiconductors to Short Power Pulses[J]. IEEE Trans. on Power Electronics,1993,8(4):337-341.
[6] Palmer P R, Santi E. Circuit Simulator Models for the Diode and IGBT with Full Temperature Dependent Features[J]. IEEE Trans. on Power Electronics,2003,18(5):1220-1229.
[7] Chan S Y, Malberti P, Ciappa M. Thermal Component Model for Electro-thermal Analysis of IGBT Module Systems[J]. IEEE Trans. on Advanced Packing,2001,24(3):401-405.
[8] Hefner A R, Beming D, Blackbum D. A High-speed Thermal Imaging System For Semiconductor Device Analysis[C]. Proceedings of 17th Annual IEEE Semiconductor, Thermal Measurement and Management Symposium,2001:43-49.
[9] Afridi M, Beming D, Hefner A R. Transient Heating Study of Micro-hotplates by Using a High-speed Thermal Imaging system[C]. Proceedings of 18th IEEE SEMI-THERM Symposium,2002:92-98.
[10] Zhou WenDing, Kang BaoWei. The Summary on Continuous Development of IGBT Technology[J]. Power Electronics, 2008, 41(9):115-118.
[11] Majumdar G, Minato T. Recent and future IGBT evolution[C]/ Power Conversion Conference, Nagoya, Japan, 2007: 355-359.