

Selection Method of Test Pulse Width and Amplitude to Avoid Self-heating Effect of Power Devices

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Abstract. The objective of this study was to address the deviation of electrical parameters, which is caused by the self-temperature rise effect of power devices in electrical testing processes. The pulse width and amplitude of the device test were considered as the research object. The three-dimensional variation of the power, junction temperature, and pulse width of semiconductor power devices were investigated using the principle of electrical temperature measurement, and the three-dimensional variation surfaces of the power, junction temperature, and pulse width were established. A method for selecting the pulse width and amplitude of the test to avoid the self-temperature rise of the power device is proposed. This method uses cutting projection to obtain the characteristic curve of the pulse width and power change, and selects an appropriate two-dimensional region of the pulse width and power to avoid the self-temperature rise of the power device. Moreover, the proposed method can be used as a reference when selecting a pulse test method.

1.Introduction

The electrical characteristic parameters of a semiconductor power device are measured to investigate the characteristics of the device, through which the measured parameters can be obtained under the established conditions and environment. However, the device generates thermal power under the specified test conditions, which causes additional temperature rise in the device chip. Moreover, the additional temperature rise is typically as high as ten or even several tens of degrees, because the temperature rise curve of the chip is steep and the heating rate is faster in the initial stage [1]. On one hand, the temperature rise of the device causes the test environment temperature (particularly in the low temperature test) to be destroyed. On the other hand, the measured characteristic electrical parameters also have large errors and cannot be practically applied. Therefore, the temperature rise requirements are more stringent in the reliability detection of semiconductor power devices, wherein measurements must be repeated multiple times. To reduce the influence of additional temperature rise, the method of shortening the test time is typically adopted to ensure that the additional temperature rise of the chip is negligible. In other words, the pulse test method is adopted to address the deviation of the electrical parameters, which is caused by the self-temperature rise resulting from the heating power consumption of the device.

With regard to measuring the electrical characteristic parameters of a device, the pulse test method was first proposed in the US military, MIL-STD-750D experimental method semiconductor test standard



[3], and subsequently implemented in the Chinese national military, GJB128A-97 semiconductor discrete device standard [4]. Therein, it is stipulated that the pulse time does not exceed 10 ms and the duty cycle is up to 2% during the pulse test. Subsequently, a test pulse of 300 μ s [5-6] is specified in GB/T 4587-94 and GB/T 6218-1996 to ensure that the temperature rise of most device chips is negligible. However, in all standards, only the maximum pulse width limit or the reference pulse width is provided. The rule of pulse width variation with the device junction temperature, and a method of selecting an appropriate pulse width are not specified. Additionally, in studies using pulse testing as the test method, the application of electrical pulse testing has not been investigated in a detailed and systematic manner [7-13]. For example, in 2008, Yuqin from NIST Laboratories in the United States proposed a new method of pulse temperature measurement for measuring the junction temperature [7] by changing the continuous signal to a test pulse and shortening the test time to weaken the phenomenon of device self-temperature rise caused by a high current. Huaijiang et al. used the pulse method to measure the junction temperature and heat capacity of LEDs [8]; Eriksson used the pulse method to measure the junction temperature and thermal resistance of 4H-SiC power bipolar transistors [9]. Nguyen used a short electrical pulse measurement to check the spontaneous thermal effect of thin film transistors [10]. The abovementioned studies directly used pulse testing to reduce the influence of device self-temperature rise. However, these studies have not discussed a method of selecting an appropriate test pulse width to avoid self-temperature rise.

With the continuous development of semiconductor power devices, the device package size is gradually improving, and the power density has been increasing. The test specifications provided by existing standards are increasingly failing to meet the requirements of new power devices. Moreover, a detailed study on a method for selecting a device such that the rise of self-temperature can be avoided has not been reported in existing electrical pulse testing literature. In this paper, the pulse width and amplitude of the device test were considered as the research object. The three-dimensional variation of the power, junction temperature, and pulse width of semiconductor power devices were investigated using the principle of electrical temperature measurement, and the three-dimensional variation surfaces of the power, junction temperature, and pulse width were established. A method for selecting the pulse width and amplitude of the test to avoid the self-temperature rise of the power device is proposed. This method uses cutting projection to obtain the characteristic curve of the pulse width and power change, and selects an appropriate two-dimensional region of the pulse width and power to avoid the self-temperature rise of the power device. Moreover, the proposed method can be used as a reference when selecting a pulse test method.

2. Variation of Power, Junction Temperature, and Pulse Width

The junction temperature rise of power devices is related to the power, duration, and heat dissipation conditions. Under short pulse test conditions (within 1 ms in this study), the heat generated by the device is not transmitted from the interior of the device to the device case or the external environment. Therefore, the influence of the external heat dissipation conditions is not considered (It has been proved by later experiments.). Under these conditions, the device obeys the three-dimensional relationship of the pulse width, junction temperature, and power during pulse testing. The amount of power carried by the device, and the working time of the device, jointly affect the device's junction temperature variation. However, the actual relationship of temperature variation with time and power is complex and related to many device properties such as the thickness, length, other geometric dimensions, thermal conductivity of the material, thermal diffusivity, and so on. Therefore, it is difficult to determine the specific expressions of power, junction temperature, and pulse width. The relationship between the temperature and heating time and power can be obtained by qualitative analysis, as follows:

$$T = T(t, P) + T_0 \quad (1)$$

where T_0 is the initial temperature of the device, t is the heating time, and P is the actual thermal power consumption.

2.1 Design Experiment Principle and Process

To investigate the relationship between the power, pulse width, and junction temperature, it is necessary to accurately measure the junction temperature at any time during the pulse test. There are many methods of measuring the junction temperature, such as the physical contact method, optical non-contact method, impedance model prediction method, and electrical method [14-15]. Amongst them, the electrical temperature measurement method can realize non-destructive measurement without changing the packaging structure, and the fast measurement of the junction temperature at the μs level. Additionally, it can realize real-time on-line measurement. Therefore, this study used the electrical method to measure the junction temperature of the device.

Electrical temperature measurement is based on the one-to-one relationship between the physical parameters of semiconductor devices and temperature, and the junction temperature of the device can be measured by detecting the variation of the sensitive electrical parameters with temperature.

In the experiment, this study considered the power VDMOS device (model IRFP250NPBF, package model TO-247) as the research object using B1505A to apply pulse voltage, combined with the changes of current, voltage, and resistance under different power (10-200 W) and different pulse width (0-1 ms) to investigate and analyze the relationship between the power of the test pulse, pulse width, and junction temperature.

2.2 Junction Temperature Measurement under Different Power and Pulse width Conditions

2.2.1 Establishment of Temperature Calibration Curve by Electrical Method. The junction temperature measurement is key for studying the change of the power, pulse width, and junction temperature. Additionally, the basis of ensuring the accuracy of the temperature measurement result is the establishment of an accurate temperature calibration curve. The junction temperature of the device can be measured at any time during the testing process using the temperature calibration curve established beforehand. The test method consists of setting different temperatures (30-150 °C) by placing the tested device into the thermostat, and waiting for the device heat to stabilize. At this time, the temperature of the thermostat is the junction temperature of the device being tested. Then, the voltage and current of the device are measured at different temperatures, respectively, and the temperature calibration curve and corresponding temperature-sensitive electrical parameters can be established. To ensure that the test conditions will not cause the self-heating of the device when setting up the temperature calibration curve, the maximum margin test method was adopted in this study. According to the maximum power requirement, the test pulse width is long for the functional characteristics of the device to be stable, and short for the test parameters to remain unchanged. As can be seen in Fig. 1, the 100- μs amplification before the 1-ms pulse width interception shows that, under the 200-W power condition, the device current was in the ascending stage within 70 μs of the test pulse width, and there was no obvious change within 70 to 100 μs . After 100 μs , the current in the pulse width of 1 ms significantly decreased owing to the influence of the device junction temperature rise. Therefore, a 100- μs test pulse width was selected to establish the temperature calibration curve.

In the selection of the actual test pulse width, owing to the influence of the circuit parasitic capacitance inductance, and to ensure the stable operation of the device under different power, it was necessary to select a longer test pulse width while considering the cost of the testing device, without causing an increase in the junction temperature. In other words, as the test pulse width became shorter, the pulse equipment with higher amplitude became more expensive. Therefore, it was necessary to select an appropriate pulse width for different powers; that is, establish a power and pulse width characteristic curve to avoid the rise of self-temperature.

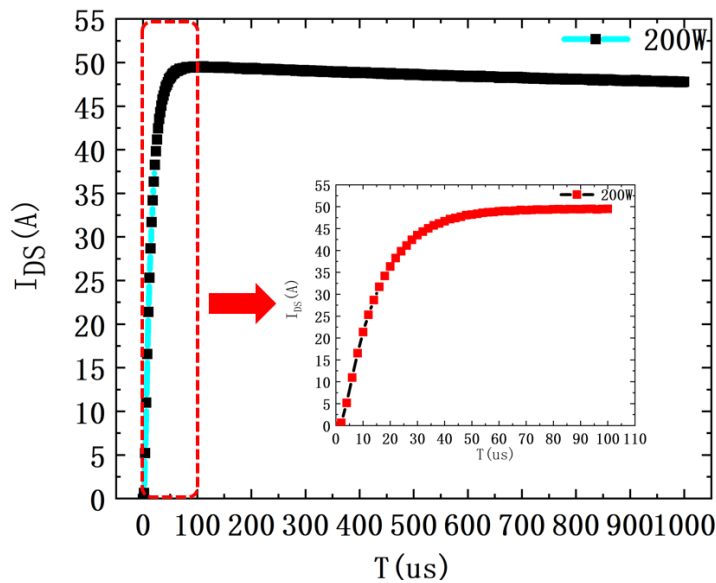


Figure 1. Relationship between current and time in 1 ms.

Using the abovementioned 100- μ s test pulse voltage, the device current and voltage changes were measured at 20-120 $^{\circ}$ C. The current-voltage curves at different temperatures were obtained using the source-drain current I_{DS} and forward voltage V_{DS} as the sensitive electrical parameters. The data were mapped to a three-dimensional coordinate system using the biharmonic interpolation algorithm in the MATLAB software. The discrete data were interpolated into continuous functions, and surface reconstruction was carried out. Additionally, the three-dimensional temperature calibration surface [16] was established as shown in Figure 2.

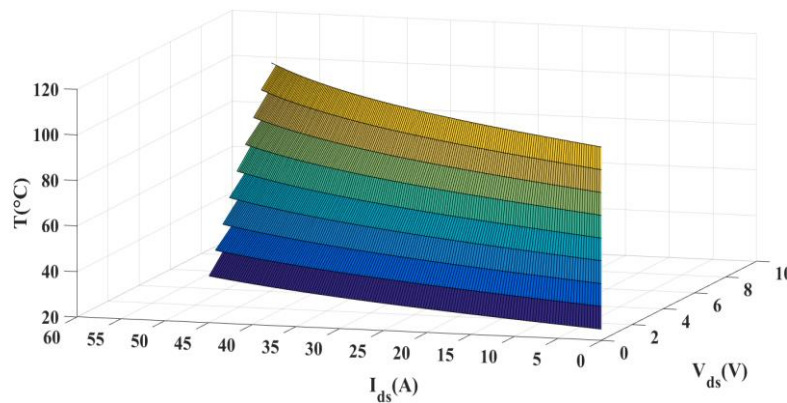


Figure 2. V_{DS} - I_{DS} - T three-dimensional temperature calibration surface.

2.2.2 Verification of Temperature Measurement Results. Using B1505A to measure the current-voltage relationship between the tested devices at different powers (10-200 W) and different pulse widths (0-1 ms), and by comparing the current-voltage variation results with the abovementioned calibration temperature curve, the actual junction temperature was obtained at different powers and different pulse widths. Additionally, the temperature measurement results were compared with the test results obtained by the TTE-800 thermal resistance tester, as presented in Table 1. The results revealed that the self-temperature rise of the two apparatus was close within 1 ms of testing time, which proves that the temperature measurement results obtained by the proposed method are accurate.

Table 1. Comparison of temperature measurement results for different test instruments with test pulse width of 1 ms.

Power (W)	Temperature difference: ΔT ($^{\circ}\text{C}$)	
	B1505A	TTE-800
70	7.05	5.92
60	5.72	5.46
50	4.76	4.44
40	3.83	3.57
30	2.87	2.77

2.3 Relationship between Power, Junction Temperature and Pulse Width

Temperature changes with time and power; that is, the temperature thermal response curves are often complex and related to many device properties such as the thickness, length, other geometric device dimensions, thermal conductivity, thermal diffusivity of materials, and so on. The complex variations in the heating response curve are typically caused by the heat transfer through different device materials. However, for the short pulse test device, the generated heat was not transmitted from the interior of the device to the device shell or the external environment because the test time was short. Therefore, owing to the heat conduction in a limited number of materials, the temperature changes tended to evolve in a simple linear manner. By installing a constant temperature platform and adjusting the temperature of the platform (30-80 $^{\circ}\text{C}$), the pulse test results were obtained as presented in Fig. 3.

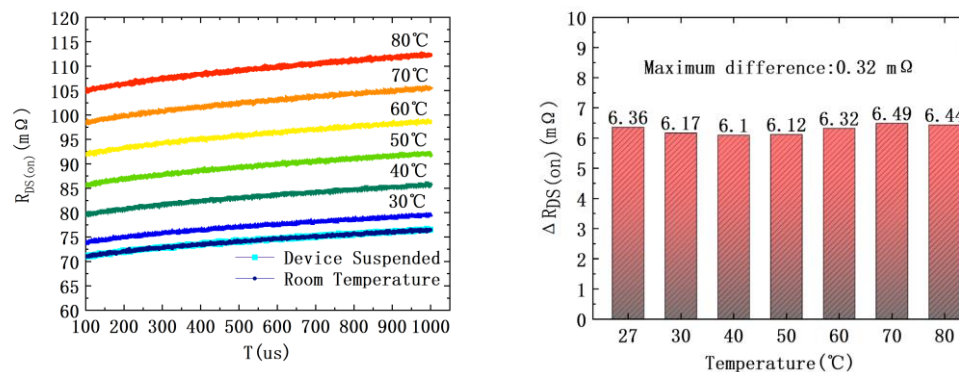


Figure 3. (a) Comparison of on-off resistance change for single pulse with time at different temperatures without additional radiator and with external lower radiator; (b) comparison diagram of resistance difference at different platform temperatures.

As can be seen in Fig. 3, when the same pulse was applied at different temperatures with the 1-ms test pulse width, the on-resistance change of the device was the same. In other words, the on-resistance difference was small at different platform temperatures, and the difference of the device's self-temperature rise produced by the pulse test was less than 1 $^{\circ}\text{C}$, which indicates that the external heat dissipation conditions did not cause the device's self-temperature rise during the pulse test period.

The test temperature measurement results were processed, and the temperature and power, and temperature and time variation diagrams were obtained under the conditions of constant power and constant pulse width, respectively, as shown in Fig. 4.

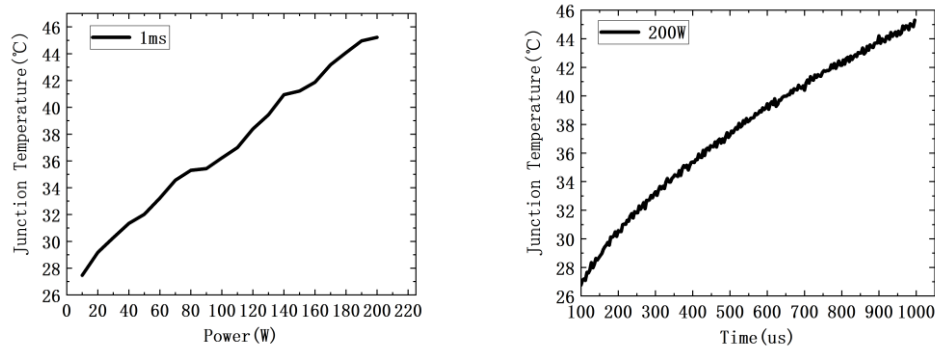


Figure 4. (a) Device temperature versus power change; (b) device temperature versus test time.

As can be seen in Fig. 4, the power and temperature, and the time and temperature, underwent approximately simple linear positive correlation changes under short-term pulses. From the experiments, it was inferred that the heat generated under short-term pulses was transmitted in a limited number of materials. Additionally, for a single homogeneous material, the temperature, power, and heating time undergo simple linear changes. Therefore, the relationship between the temperature, pulse width, and power can simply evolve in a linear manner, as follows:

$$\begin{aligned}
 T &= T(t, P) + T_0 \\
 &= k (P_{total} - P_E) \cdot t + T_0 \\
 k &= C(t) \cdot M(t)
 \end{aligned} \tag{2}$$

where k is the product of the specific heat capacity and mass of the device within a certain range of the device at different times, C is the specific heat capacity, M is the mass, P_{total} is the total power consumption of the device, and P_E is the non-thermal power consumption of the device.

Then, the actual temperature measurement results, and the power and time data, were mapped to the three-dimensional coordinate system, and the temperature-power-time three-dimensional pulse width and temperature rise were plotted using MATLAB, as shown in Fig. 5.

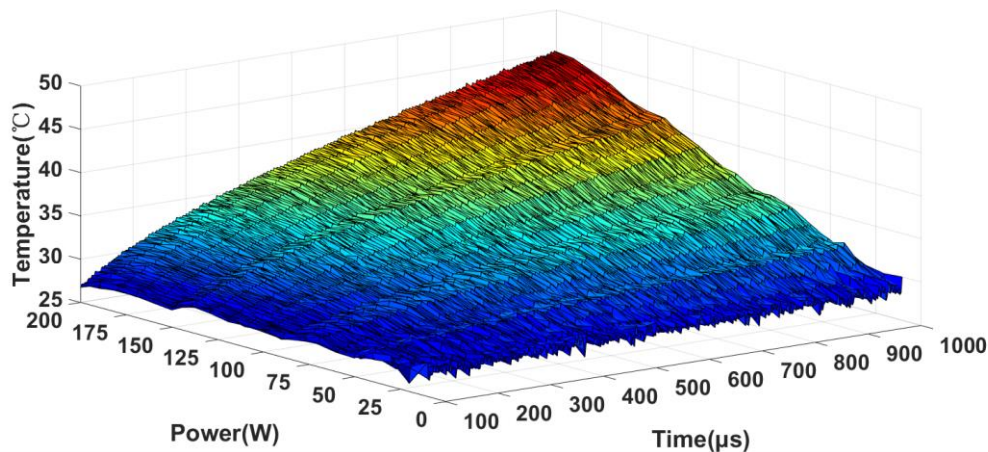


Figure 5. Temperature-power-pulse width relationship change surface.

According to the formula deduced above and Fig. 5, it can be seen that the junction temperature of the device has a one-to-one relationship with the measured pulse width and power. Hence, as the test pulse width and power become larger, the device's self-temperature rise becomes higher. When the test pulse width or power is less than a certain range, the small fluctuation of the junction temperature can be ignored. Generally, when measuring the electrical characteristic parameters using a pulse, the device's

self-temperature rise can be reduced by reducing the measurement pulse width, because the measurement current and voltage cannot be changed.

3. Selection of Device Pulse for Avoiding Self-heating

Because the actual power consumption of the device is inevitable, there is no ideal test condition without additional thermal power consumption. In this study, according to the three-dimensional curve of the power, temperature, and test pulse width, combined with the minimum acceptable device self-temperature rise required by the actual experiment, the reasonable non-temperature rise pulse selection region satisfying the experimental requirements was obtained.

In the national standards of measuring the electrical characteristic parameters, the selection of the pulse width for pulse testing is typically only a general standard. On one hand, owing to the different device structures and thermal resistances of different devices, the heating time constants of the devices themselves are different, which leads to the general conditions being unable to satisfy the test pulse requirements. On the other hand, even for the same device, the test pulse width requirements under different test currents and voltage levels must also be changed to satisfy the requirement of controlling the device's self-temperature rise within the acceptable range. Therefore, when choosing the test pulse width, the temperature rise of the device should be controlled within a reasonable range, instead of only limiting the power or pulse width range. The derivation of the formula is described below.

According to the actual needs, the temperature change should not exceed m , as follows:

$$\Delta T = T - T_0 \leq m \quad (3)$$

By substituting Equation (3) into the Equation (2) relating the temperature, pulse width, and power, we can obtain the following relationships:

$$k (P_{total} - P_E) \cdot t \leq m$$

$$P_{total} \leq \frac{m}{kt} + P_E \quad (4)$$

If P_E is negligible relative to the heating power, then the following relationship holds:

$$P \leq \frac{a}{t} \quad (5)$$

where $a = \frac{m}{k}$ is the variable coefficient.

It can be concluded that the pulse width and power range of the selected test pulse obey the approximate inverse proportional function under variable coefficients when the temperature increase does not exceed m °C. Using the three-dimensional temperature-power-pulse width relationship variation map, which was obtained as described above, for the selected device, combined with cutting projection wherein the junction temperature change $\Delta T = 1^\circ\text{C}/2^\circ\text{C}/3^\circ\text{C}$ is the boundary projection, we can obtain a device temperature rise of less than $1^\circ\text{C}/2^\circ\text{C}/3^\circ\text{C}$. The power and pulse width change curve is shown in Fig. 6.

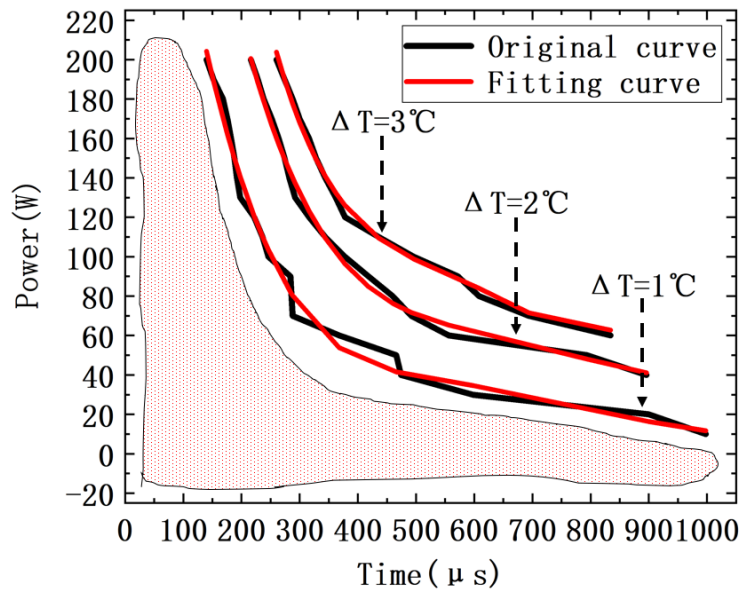


Figure 6. Characteristic curves of power and pulse width.

The experimental results presented in Figure 6 were fitted to meet the general trend of the abovementioned inference formula (Equation (5)). The red region surrounded by the fitting curve and the horizontal and vertical coordinate axis indicate the reasonable pulse width of the device and the selected power region when the temperature increase does not exceed 1 °C with different power.

From Fig. 6, the maximum pulse width of the power VDMOS device for a temperature increase not exceeding 1 °C was selected as presented in Table 2.

Table 2. Selection table of partial power and test pulse width with temperature increase difference within 1 °C.

Power(W)	Pulse width(us)
20	850
50	380
100	250
150	180
200	150

4. Conclusion

The pulse width and amplitude of semiconductor power devices were investigated with regard to the self-temperature rise effect of the power devices, which is caused by electrical tests. The principle of temperature measurement using the electrical method was used to investigate the three-dimensional variation relationship of the power, junction temperature, and pulse width of the power devices, and the three-dimensional variation relationship surface of the power, junction temperature, and pulse width was established. Additionally, a method is proposed to obtain the pulse width and amplitude of the device. The proposed method avoids the self-temperature rise of the power device, and the characteristic diagram of the curve of the pulse width and power change can be obtained by the cutting projection method, which is used to select an appropriate pulse and two-dimensional power region that avoid the self-temperature rise of the power device. The pulse width of the power VDMOS device used in this study was selected when the temperature rise difference of the device was within 1 °C under varying power. In this study, only the test pulse width characteristics within a single pulse width were investigated, while the complete pulse width sequence was not considered. The task of future work will

be to investigate the sequence of multiple test pulse widths, the pulse characteristics at different duty cycles, and the selection of the duty cycle of a multi-pulse width sequence to avoid the self-temperature rise of the device.

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