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Research on Temperature Monitoring and Control Technology for SiC MOSFET

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Abstract:

This paper focuses on the reliability issues of silicon carbide (SiC) MOSFETs under harsh working conditions and conducts a detailed study on their junction temperature monitoring technology. The article reviews the two main methods for monitoring the junction temperature of current SiC MOSFETs: the physical contact method (such as infrared thermal imaging, direct measurement using thermocouples, fiber optic grating temperature measurement, etc.) and the electrical method based on thermosensitive electrical parameters (TSEP). The article thoroughly analyzes and compares the key characteristics of various TSEP parameters (such as threshold voltage, on-state voltage drops, body diode voltage, switching delay time, etc.), including their principles, temperature sensitivity, linearity, feasibility of online monitoring, and anti-aging ability. Through comparative analysis, the advantages and disadvantages of different TSEP methods in different application scenarios are clarified, and the future development direction of SiC MOSFET junction temperature monitoring technology is proposed. This article provides guiding recommendations for the selection and optimization of junction temperature detection methods for SiC MOSFETs.

Keywords: SiC MOSFET; temperature monitoring; Temperature sensitive electrical parameters (TSEP); Thermal model; Reliability

1. Introduction

With the development of automobiles, power electronic systems are widely used in speed control drives, new energy systems, and electric vehicles. However, the operating conditions are rather harsh. The ambient temperature of electric vehicle engines is very high, and many electronic systems will malfunction and have their lifespan shortened in such high-temperature environments. For example, IGBT which is the full name of Insulated Gate Bipolar transistor, is one of the power semiconductor devices as a large power converter in the electronic powered automobile. But, failure of IGBT is instability and heat intolerance, which may lead to a reduction in the reliability of the electronic powered automobile

[1]. Furthermore Silicon Carbide (SiC) is a third-generation wide bandgap semiconductor material, featuring high temperature resistance, high voltage tolerance, excellent high-frequency performance, and low energy loss. As a medium and small power converter, its application scope is just as extensive as that of IGBT, and the market size is increasing year by year. According to QY Research, it is predicted that the global market size of SiC wafers will reach 21.45 billion yuan in 2031. The average annual compound growth rate from 2025 to 2031 will be 14.8%. This clearly shows the huge demand and scale for SiC in the future market. But 31% of the industry respondents believe that this component is the most prone to failure in power electronic systems, and 55% of the failures are caused by temperature-related damage. So real-time monitoring of junction temperature (Ti) is of great importance [2]. This essay mainly combines the current research status of SiC MOSFET junction temperature monitoring technology and the principles and characteristics of the thermal model method. Based on the comparison and analysis of SiC MOSFET junction temperature monitoring methods using TSEP, it finally reaches a conclusion and puts forward expectations for future research on SIC MOSFET.

2. Research Status of Junction Temperature Monitoring Technology for SiC MOSFET

According to the current research status, there are two methods for measuring the junction temperature of silicon carbide MOSFETs [1]. The first method is the physical method - directly contacting the semiconductor chip and using physical contact methods such as therrmistors and thermocouples to measure the junction temperature of power semiconductor devices. The spatial resolution depends on the coating particles of the thermal probe, and the response time depends on the thermal capacity of the thermal probe. This method has high accuracy and good resolution, but due to the influence of power module packaging, it is usually not possible to directly contact the device, and the thermal capacity of the thermal probe leads to a response time of less than 5 milliseconds. The second method is favored in power module junction temperature measurement than the physical method, namely the electrical method (thermal sensitive electric parameter, TSEP) [3]. It achieves monitoring by utilizing the electrical parameters (such as saturation current and threshold voltage) of power devices (such as silicon carbide MOSFETs) that are strongly related to the junction temperature. First, an offline calibration model between parameters and junction temperature is established, and then the parameters are measured online in real time and substituted into the model to infer the junction temperature. This method does not require external physical sensors, has a rapid response and is non-destructive, but its accuracy depends on the temperature sensitivity of the parameters.

2.1 Overview of Non-TSEP Detection Methods

2.1.1 Infrared Thermal Imaging Method

Based on the blackbody radiation law, the infrared thermal imager collects the infrared radiation emitted by the device surface through the optical system, and converts it into electrical signals by the detector to generate a temperature field image [4]. Advantages: It can directly display the overall temperature distribution, quickly locate hotspots, does not require contact with the device, and is suitable for thermal characteristic analysis and failure location in laboratory conditions. Disadvantages: It cannot directly measure the junction temperature due to the limitation of the packaging structure. The resolution is affected by the lens and the measurement distance, and it has high requirements for the measurement environment.

2.1.2 Direct Measurement Method Using Thermocouples

By utilizing the Seebeck effect, a thermocouple probe composed of two different metals is directly brought into contact with the surface or pad of the device. The temperature can be calculated by measuring the generated thermoelectric potential. Advantages: High measurement accuracy and fast response speed; Temperature data close to the junction can be obtained when arranged inside the package, suitable for scenarios requiring precise local temperatures. Disadvantages: It requires damaging the package or pre-implanting during manufacturing, which may affect the reliability of the device; High maintenance cost, and insulation safety issues exist in high-voltage environments.

2.1.3 Fiber Bragg Grating Temperature Sensing Method

The Bragg reflection wavelength of the optical fiber grating shifts with temperature. By measuring this wavelength change through optical demodulation technology, the temperature can be obtained [4]. Advantages: Strong anti-electromagnetic interference capability, suitable for high-voltage and large-current environments; capable of multi-point distributed measurement, small in size, light in weight, and easy to integrate into device packaging. Disadvantages: Complex installation process, high requirements for packaging space; the measurement points are at a certain distance from the junction area, and the accuracy

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is affected by the installation position and packaging material.

2.1.4 Finite Element Method (FEM) Temperature Field Analysis

Based on the three-dimensional heat conduction equation, the device structure is discretized into tiny grid units using the finite element method. The temperature values of each unit are calculated to obtain the complete temperature field distribution [5, 6]. Advantages: It can accurately capture local hotspots in the junction area, such as the high-temperature regions at the edge of a SiC MOSFET chip due to current concentration; it is suitable for optimizing the design of heat dissipation structures, such as choosing appropriate substrate materials and thicknesses. Disadvantages: The computational load is large. High-power SiC module models often contain millions of grid units, and a single simulation may take several minutes or even several hours, making it difficult to meet the requirements of high-frequency online monitoring.

2.1.5 Infrared Microscopic Temperature Measurement Technology

Principle: By combining high-resolution infrared imaging with microscopic technology, the device surface is magnified for imaging, enabling temperature measurement at the microscopic scale. Advantages: It allows for observing the temperature distribution in the microscopic area of the device, which is helpful for studying local thermal effects and failure mechanisms; the resolution can reach the micrometer level, enabling the detection of tiny hotspots that are difficult to identify with conventional thermal imagers. Disadvantages: The equipment is expensive and requires strict environmental conditions; special sample preparation or transparent encapsulation is necessary, which limits its practical application scenarios.

2.1.6 Combined Measurement Using Thermal Imager and Thermocouple

Principle: The infrared thermal imager is used to obtain the overall temperature distribution, while thermocouples are employed to measure the precise temperature at key locations, achieving complementary measurements. Advantages: It combines the observation of the overall distribution with precise local measurements, enhancing the reliability and comprehensiveness of temperature measurement, and is suitable for in-depth research on the thermal characteristics of devices. Disadvantages: The system is complex, requiring the collaboration of multiple devices, the calibration process is cumbersome, and the measurement cost is high.

2.1.7 Infrared Thermography Combined with Finite Element Method

Principle: Infrared thermal imaging is used to obtain the surface temperature distribution, which serves as the boundary condition for the finite element model, and the internal junction temperature is inversely calculated. Advantages: It combines the advantages of experimental measurement and numerical calculation, enabling more accurate internal temperature estimation. It is particularly suitable for studying the thermal distribution within the package. Disadvantages: A complex calibration process is required, strict requirements for the measurement environment, high computational cost, and it is difficult to achieve real-time online monitoring.

2.1.8 Heat Flow Meter Measurement Method

By measuring the heat flux density on the surface of the device, the internal temperature distribution can be calculated using the thermal resistance network model [4]. It enables direct acquisition of heat flux information, which is beneficial for optimizing thermal management design, such as improving the heat dissipation structure and selecting thermal interface materials. Measuring accuracy is affected by the installation position and contact quality of the sensor, and requires a supporting thermal resistance model. It also has high requirements for the measurement environment.

2.2 The core principle of the TSEP method

Temperature-Sensitive Electrical Parameter (abbreviated as TSEP) is a core technology that enables non-invasive temperature extraction by leveraging the inherent physical correlation between the electrical parameters of power semiconductor devices and their junction temperature. This method does not require the destruction of the power device's packaging and also takes into account response speed and measurement flexibility .

The essence of the TSEP method is based on the thermoelectric coupling physical mechanism of power semiconductor devices [7]. That is, changes in junction temperature will affect the carrier transport characteristics within the device, the PN junction barrier characteristics, or the charging and discharging process of capacitance, thereby causing specific electrical parameters to exhibit quantifiable temperature sensitivity. Its core principle can be summarized into three categories:

· Carrier mobility and concentration regulation: An increase in temperature alters the intrinsic carrier concentration and carrier mobility of semiconductor materials. For instance, the threshold voltage of SiC MOSFET decreases with rising temperature, due to the reduction in the threshold of the surface inversion layer formed as a result of the increase in n_i; while the temperature characteristics of the conduction resistance are dominated by the competitive effect between the channel resistance (negative temperature coefficient, NTC) and the drift region resistance (positive temperature coefficient, PTC).

· Thermal electric characteristics of PN junction: The PN junctions built into the device (such as the emitter-base junction of IGBT, the body diode of SiC MOSFET) have a forward voltage drop that conforms to the Schottky equation. Its value decreases linearly with increasing temperature, and the temperature coefficient is typically. This characteristic is the core principle of TSEP parameters such as low current conduction voltage.

· Dynamic regulation of the switching process: Changes in junction temperature will affect the charging and discharging speed of the gate capacitance and the carrier transit time, resulting in temperature sensitivity of dynamic parameters such as switching delay time and current change rate. For example, the turn-on delay time of IGBT increases with temperature rise, due to the decrease in carrier mobility, which slows down the channel conduction speed.

2.2.1 Analysis of Characteristics of Typical TSEP Parameters

Different TSEP parameters vary greatly due to the different physical mechanisms they rely on. There are significant differences in terms of sensitivity, linearity, parameter dependence, and applicable scenarios. The following will conduct an analysis based on the core TSEP parameters of SiC MOSFET and IGBT [8,9].

Static class parameters need to be measured under the condition where the device is in a stable conducting or off state. The core includes threshold voltage, on-state voltage, body diode voltage, etc. Their characteristics focus on linearity and parameter cross-sensitivity:

Threshold Voltage

The Vth of both SiC MOSFET and IGBT exhibits a negative temperature coefficient, with good linearity (the fitting degree is usually > 0.98). Low parameter dependence, no need for additional load current, and can be measured simply by scanning the gate voltage. Susceptible to bias temperature instability (BTI), PBTI of SiC devices will cause positive drift of Vth, requiring regular calibration; measurement requires synchronous capture of the gate-current threshold point, and errors are prone to occur in high electromagnetic interference environments.

Conduction Voltage

Temperature Characteristics: At low currents (such as the conduction voltage of IGBT (low), current ranging from 1mA to 100mA), it is dominated by the PN junction, showing an NTC (-1.5 to -2mV/°C); at high currents (such as the conduction voltage (high), rated current ranging from 10% to 100%), it is dominated by the drift region resistance, showing a PTC (+2 to +3mV/°C). Both have excellent linearity. The low current mode is relatively simple for measurement and is suitable for offline calibration; the high current mode can simultaneously measure during the normal operation of the device, and supports online monitoring . At high currents, the voltage drop caused by parasitic resistances in the package (such as bonding wires and solder layer resistances) will introduce errors (for IGBT modules, the typical error is ±30°C), and correction factors need to be updated as the power device ages; in the low current mode, the load current needs to be interrupted, and it cannot be applied in real time.

Diode voltage

The forward voltage drop of the SiC MOSFET body diode is an NTC (Negative Temperature Coefficient), with a typical value of -2 to -2.5 mV/°C. A negative gate voltage (e.g. -10V) needs to be applied to turn off the main channel to avoid interference. The linearity is greater than 0.97 within the temperature range of 25 to 150°C. Less affected by packaging aging (the parasitic voltage drop can be ignored during low-current measurement), suitable for junction temperature monitoring in power cycle tests. Negative gate voltage may affect the reliability of the gate oxide layer, and the measurement needs to avoid the transient state of the device switching, and the timing control is complex.

Dynamic class parameters need to be measured at the moment of power device switching. The core includes switching delay time, current change rate, peak gate current, etc. Their characteristics focus on response speed and engineering feasibility.

Switch delay time :

The switching delay times of both IGBT and SiC MOSFET exhibit PTC, with typical sensitivities ranging from +1 to +2 ns/°C. The linearity is affected by the gate resistance, the higher the gate resistance, the better the linearity. It can be measured during the normal switching cycle of the SiC MOSFET device without the need for additional test signals and can be monitored in real time online. It requires a high-bandwidth oscilloscope with a frequency greater than or equal to 100 MHz and needs to be triggered in a precise time sequence. It is susceptible to electromagnetic interference, which can cause time measurement errors. The switching speed of SiC devices is usually less than 100 ns, which places extremely high demands on the resolution of the measurement equipment.

Peak Gate Current:

Due to the PTC characteristic of the internal gate resistance (the temperature coefficient of the gate resistance is approximately +3 mΩ/°C), Peak gate current decreases

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with increasing temperature, with a sensitivity of approximately -0.1 mA/°C and good linearity. The measurement circuit is simple, requiring only the monitoring of the gate loop voltage. It can be integrated into the gate drive board, with low engineering costs. It is greatly affected by the aging of the external gate resistor, and the correlation between the gate resistor and the current needs to be calibrated regularly.

2.2.3 Key Characteristics of the Application of the TSEP Method

The practical application of the TSEP method should focus on three key characteristics: measurement accuracy, online feasibility, and anti-aging ability. Its core performance is as follows:

· Measurement accuracy: For static parameters, the accuracy can reach ±2°C in offline calibration scenarios. The online measurement accuracy for dynamic parameters is typically ±5°C. The main sources of error include parasitic parameters of the package, electromagnetic interference, and deviations in the calibration model [4].

· Online feasibility: Dynamic class parameters and high current conduction voltage can be monitored online without interrupting the operation of power devices; low current conduction voltage requires offline calibration and cannot be applied anytime and anywhere.

· Anti-aging capability: The body diode voltage of the device is least affected by the aging of the package (such as voids in the solder layer and bond wire detachment) when the temperature rises, making it suitable for long-term monitoring; parameters such as threshold voltage and channel resistance are easily influenced by BTI (Bias Temperature Instability) and hot carrier injection, thus requiring the introduction of aging compensation algorithms (such as drift models based on stress time) to maintain accuracy.

3. Comparative Analysis of Temperature Monitoring Methods for SiC MOSFET Based on TSEP

Table 1 clearly shows different type of TSEP methods and compare them to figure out which is the most suitable in some scene.

Table 1. The Comparison Among the Different TSEPs

TSEP Method Type	Linearity Temperature Sensitivity	Advantage	Disadvantage	Typical Application Scenarios
On-state Voltage (High Current)	Good linearity, PTC, sensitivity -+ 2~+3mV/ °C	No interruption, supports high-frequency	Interfered by parasitic resistances	SiC on-board inverters for new energy vehicles, online protection for industrial inverters
On-state Voltage (Low Current)	Good linearity, NTC, sensitivity ~ -1.5~ -2mV/ °C	Low dependence, high offline accuracy	Load current interruption needed	Junction temperature calibration of SiC power modules, thermal characteristic testing
Threshold Voltage (Vth)	Fairly good linearity, NTC, sensitivity ~-5--8mV/°C	No additional load current needed	Susceptible to BTI/ PBTI drift	Offline thermal characteristic analysis of SiC MOSFET modules, temperature monitoring of industrial control equipment
Body Diode Voltage	Fairly good linearity, NTC, sensitivity --2~-2.5mV/°C	Minimal impact from packaging aging	Negative gate bias may affect reliability	Power cycle life testing of Sic power modules, junction temperature decay monitoring
Switching Delay Time	Moderate linearity, PTC, sensitivity ~+1~+2ns/°C	Measurable during normal switching cycles	Relies on high-bandwidth oscilloscope	High-frequency SiC RF power devices, transient junction temperature monitoring of on-board Sic inverters
Current Change Rate (di/dt)	Moderate linearity, PTC/ NTC, sensitivity +3A/ micro°C	Ultra-fast response, captures nanosecond-level changes	High dependence on multiple parameters	Ultra-high-frequency SiC power converters, nanosecond-level switching speed device monitoring

4.Conclusion

This paper explores the junction temperature monitoring technology of SiC MOSFETs, reviewing the physical contact method and the electrical method based on temperature-sensitive electrical parameters (TSEP). The thermal modeling method builds a network through „thermal-electrical analogy“, analogizing thermal resistance to resistance and thermal capacitance to capacitance for junction temperature estimation. It is divided into lumped parameter models (such as Foster and Cauer models) and distributed parameter models. Lumped models have low computational complexity and are suitable for steady-state and low-frequency transient scenarios (such as <1 kHz industrial inverters), and can be implemented in DSP/FPGA, with a single estimation time of <1 ms. Distributed models are based on three-dimensional heat conduction equations and the finite element method, capable of detecting local hotspots at the edge of ICs (such as the edge junction temperature of 650 V SiC trench MOSFETs being 12–15°C higher than the midpoint during high-frequency switching), but due to fine grids and long simulations, they are more suitable for offline design. The TSEP method utilizes the temperature sensitivity of internal electrical parameters of the device for non-invasive monitoring. Static parameters (threshold voltage, on-voltage) have good linearity at small currents but require load interruption; at large currents, they can be online but are susceptible to parasitic resistance interference. Dynamic parameters (switching delay, current change rate) can be real-time but require high-bandwidth oscilloscopes or frequent calibration. Different parameters are applicable in different scenarios and need to be combined with aging compensation algorithms.

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