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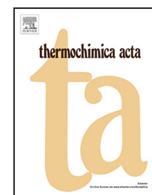

Thermal measurement and analysis of packaged SiC MOSFETs

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ABSTRACT

This paper reports an approach for transient thermal resistance measurement and thermal analysis of packaged SiC MOSFETs. A relationship of gate-source voltage (V_{GS}) and temperature of a SiC MOSFET measured using constant current pulses of 2 A that have width of 200 μs is employed to measure junction temperature. The transient thermal resistance of the packaged SiC MOSFET is measured with constant current injection of 2 A in heating condition. A modified thermal resistance analysis by an induced transient (TRAIT) method is introduced. The measured transient thermal resistance is characterized with a discrete time constant spectrum, and analysed using structure functions based on a Cauer equivalent thermal model. The partial thermal resistances of the packaged SiC MOSFET were extracted and compared to the results from the thermal model based on finite difference method (FDM), and comparison shows good agreement between both results.

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1. Introduction

Due to the capability of low loss, high temperature and high speed switching operation, silicon carbide (SiC) devices are mentioned as one of the alternatives for silicon (Si) devices. Among the SiC devices, SiC MOSFETs have received attention as a promising device to replace Si IGBTs used for power electronics applications in an industrial, consumer and automotive system prevalently. Several research results of the SiC MOSFETs have been reported in [1–3].

The power loss in the SiC MOSFETs operation increases junction temperature of the device that affects electrical characteristics, reliability and life time. Thermal management that controls the junction temperature in appropriate ranges is essential in operation of the system with the SiC MOSFETs. The thermal characteristics of the packaged SiC MOSFETs, transient or static thermal resistance, can be very useful in design of the thermal management system by providing information on the structural evaluation inside the assembled package as well as estimation of the junction temperature in operation of the device [4–6].

There are several research results for measurement and characterization of power semiconductors [7–9]. The junction temperature measurement should be carried out in these works. Temperature measurement equipment such as an infrared camera and an optical fiber after encapsulation of the package can be utilized [10–12]. The junction temperature measurement using temperature sensitive electrical parameters (TSEPs) such as a parasitic *p-n* junction, on-state resistance and etc. is generally used method [13–15]. This method allows measurement of the accurate junction temperature with a high time resolution without the external measurement system. It is observed that SiC devices have different temperature characteristics compared to Si devices through several research results [16,17]. In measurement of the transient thermal characteristics of the packaged SiC MOSFETs, it is required to select and characterize the TSEPs for the junction temperature measurement.

The measured thermal results should be characterized and modelled to analyse thermal performance of the packaged devices or to simulate junction temperature of the devices, and there are several methods for these works [18–21]. The thermal-resistance analysis by induced transient (TRAIT) method is suggested in [22], to analyse the thermal resistance of semiconductor packages. The TRAIT method characterizes the thermal behavior of the semiconductor packages using the finite terms of series of exponential time constants. The TRAIT method enables the thermal analysis inside the semiconductor packages. However, the number of the time constant should be increased to characterize the thermal behavior including heat spreading inside the package with the complex structure in the TRAIT method, and the help of numerically simulated thermal data is required for the accurate thermal analysis. To carry out the accurate thermal analysis of the packaged device without numerically simulated work, a modified method for the TRAIT is introduced in this paper. The modified TRAIT

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method extracted the discrete time constant spectrum from the transient thermal resistance measured in heating condition and analyses thermal performance of the packaged SiC MOSFET using the structure functions transformed from the time constant spectrum through the Foster-Cauer conversion.

Currently, high temperature packaging technologies have been introduced, and the package performance has been demonstrated with high temperature operation of the SiC devices through several research results [23,24]. In this paper, we study a procedure for measurement and analysis of the transient thermal characteristics of a packaged SiC MOSFET for high temperature operation. In this work, the relationship between the gate-source voltage and temperature of the SiC MOSFET was used as the TSEP to measure the junction temperature, and the theoretical background, experiment setup and calibration process were described. The transient thermal resistance of the packaged SiC MOSFET was measured and characterized using a modified TRAIT method. Finally, the extracted thermal partial resistances of the packaged SiC MOSFET were compared with the results from thermal model based on the finite difference method (FDM).

2. Devices and measurement

The output characteristics of the SiC MOSFETs in the saturation region under supplied constant drain-source voltage (V_{DS}) can be modelled by the equation as follows:

$$I_D = \frac{1}{2}\mu_n(T)C_{OX}\frac{W}{L}[V_{GS} - V_{TH}(T)]^2 \quad (1)$$

where, I_D is the drain current, μ_n is the electron mobility, C_{OX} is the intrinsic gate channel oxide capacitance, W/L is the gate width/length ratio, V_{GS} is the gate-source voltage, V_{TH} is the threshold voltage and T is the temperature. In Eq. (1), μ_n, and V_{TH} has the temperature dependence characteristics [25]. The electron mobility is limited by several scattering process, and decreases with temperature. The temperature dependence of the electron mobility can be empirically modelled by given Eq. (2),

$$\mu_n = \mu_n(T_0)\left(T/T_0\right)^{\alpha} \quad (2)$$

where T_0 is the reference temperature. In case of the 4-H silicon carbide, α is about −2.7. V_{TH} decreases with temperature due to the temperature dependence of the Fermi level in a channel region, and it is described by Eq. (3),

$$V_{TH} = V_{FB}(T) + 2\Psi_B(T) + \frac{\sqrt{4\varepsilon_{sic}qN_A\Psi_B(T)}}{C_{OX}} \quad (3)$$

where ε_{sic} is the dielectric constant of the silicon carbide, q is the electron charge, N_A is the doping density, V_{FB} is the flat band voltage and Ψ_B is the potential difference between the Fermi level and the intrinsic Fermi level.

For a given constant I_D and V_{DS} across the SiC MOSFETs, Eq. (1) can be rearranged into an equation for V_{GS} as follows:

$$V_{GS} = \left[\frac{2I_D}{\mu_n(T)C_{OX}}\frac{L}{W} + V_{TH}(T)\right]^{1/2} \quad (4)$$

The right side of Eq. (4) includes the temperature dependence parameters, and V_{GS} can be used as a temperature parameter to measure the junction temperature of the SiC MOSFETs.

A 600 V/10 A SiC MOSFET manufactured by "ROHM" was used as a DUT. The SiC MOSFET was assembled on a ceramic package (manufactured by "Kyocera") that had a copper bonded Al_2O_3 substrate using 88Au/12Ge solder for high temperature operation. The electrical connection in the package was completed with an Al wire (diameter of 300um). The package was filled with a high temperature resin manufactured by "ADEKA". The packaged SiC MOSFET is shown in Fig. 1.

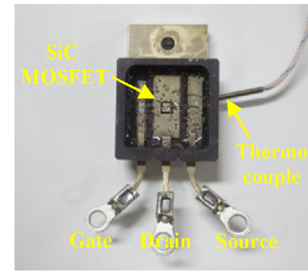
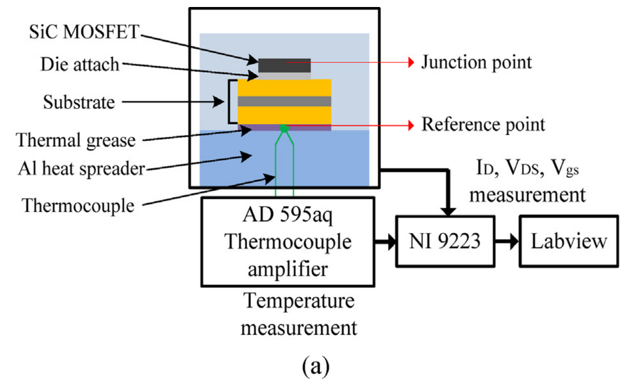


Fig. 1. Overview of the packaged SiC MOSFET with the thermocouple for reference temperature measurement.

A test circuit was developed to measure the transient thermal resistance of the SiC MOSFET in heating condition. The schematic diagram of the circuit is shown in Fig. 2. A SW1 is closed, and the current is injected into the SiC MOSFET. The injected current is sensed by R_s, and this signal is amplified by an inverting amplifier. The amplified signal is input into a feedback loop with a PI controller. The feedback control loop adjusts V_{GS} to match the sensing voltage V_{sense} with reference voltage (V_{Iref}). As the feedback control drives voltage drop of R_s to be kept constant, the constant I_D flows into the SiC MOSFET. Consequently, V_{DS} of the SiC MOSFET keeps the constant value, and the dissipated power in the SiC MOSFET calculated by $P = I_D \times V_{DS}$ is regulated as the constant value. In the test circuit operation, the variation of the voltage drop of SW1 (SPW20N60S manufactured by Infineon) due to self-heating was limited by the cooling system.

The DUT was fixed on an air cooled aluminium heat sink. A thermocouple was attached on the bottom copper layer of the



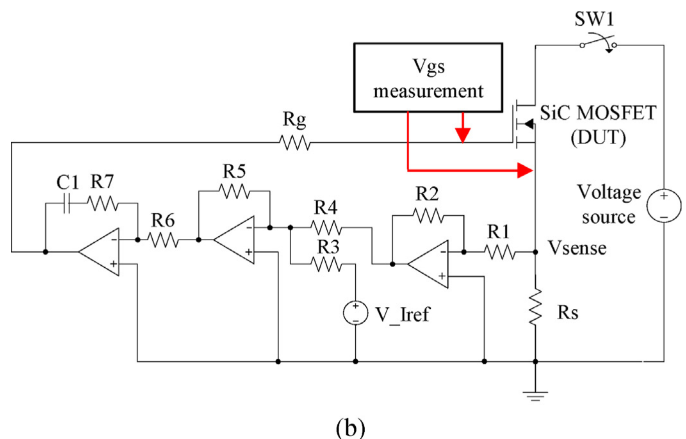


Fig. 2. Experimental setup. (a) schematic view of the experimental measurement system (b) the test circuit to measure the transient thermal resistance of the packaged SiC MOSFET.

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