An experimental study on estimating dynamic junction temperature of SiC MOSFET

Shuhei Fukunaga and Tsuyoshi Funaki
Osaka University, Division of Electrical, Electronic and Information Engineering, Graduate School of Engineering, Suita, Osaka 565–0781, Japan

a) fukunaga@ps.eei.eng.osaka-u.ac.jp

Abstract: Thermal characterization and modeling of power module is inevitable to take full advantages of power semiconductor device. Dynamic thermal modeling of power module, which is related to packaging structure and material property, is attracted attention for power electronics system design. The transient thermal resistance measurement standard, called static test method (JESD51-14 [1]), utilizes temperature dependency in $I-V$ characteristics of power semiconductor device to estimate junction temperature. The dynamic gate threshold voltage shift of SiC MOSFET violates junction temperature estimation. This paper proposes accurate transient junction temperature estimation procedure for SiC MOSFET with advancing the static test method, and validates the temperature estimation with temperature sense diode embedded in SiC MOSFET. The proposed procedure enables to get accurate time response of $T_J$ for SiC MOSFET, which enables dynamic thermal modeling of power module with SiC MOSFET.

Keywords: SiC MOSFET, gate threshold voltage instability, junction temperature estimation, static test method, temperature sense diode

Classification: Power devices and circuits

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1 Introduction

Fast switching capability of SiC unipolar power device reduces switching losses and allows high switching frequency operation, which enables to miniaturize power conversion system [2, 3]. Miniaturization of power conversion system increases heat dissipation per unit area/volume, and makes thermal management difficult.

Thermal design of power module aims at spreading and dissipating heat generated in power semiconductor device. Heat spreading mainly depends on the structure and material property of power module constitution. The conventional static thermal resistance model evaluates the temperature difference between junction to case of power module in steady-state operation. But precise dynamic thermal model, which can estimate temperature of each component of power module, is necessary for assessing transient operation of power conversion system. Dynamic thermal model is also useful for the reliability evaluation of power conversion system to estimate the temperature of each component. Reference [4] used dynamic thermal model to estimate junction temperature \((T_J)\) in operating Si MOSFET. Reference [5] identified transient thermal model by using Fourier series expansion. Frequency-domain modeling is also conducted for several thermal circuit models in [6]. Static test method [1] is the standard method for identifying dynamic thermal circuit model of power module from time response of \(T_J\). This method estimates \(T_J\) by temperature dependency in \(I - V\) characteristics of power semiconductor device.

SiC MOSFET has difficulty of gate threshold voltage shift for gate voltage application, due to the carrier traps in the level of gate oxide or interface [7]. The gate threshold voltage shift varies the temperature dependent electrical characteristics of MOSFET. The static gate threshold voltage shift has been improved, but dynamic gate threshold voltage shift, such like negative bias temperature instability (NBTI) problem [8], remains the great concern. The shifted gate threshold voltage causes the error in estimating time response of \(T_J\) for SiC MOSFET with its temperature dependency in \(I - V\) characteristics [9]. This error makes it difficult to identify transient thermal model of power module with SiC MOSFET. This paper proposes accurate \(T_J\) estimation procedure with temperature dependency in \(I - V\)
characteristics of body diode for SiC MOSFET, which advances the conventional static test method. The estimated time response of $T_J$ is validated with temperature sense diode embedded in SiC MOSFET.

2 Dynamic thermal characterization setup of MOSFET

The standardized static test method measures $T_J$ in cooling operation from thermal equilibrium condition of self heating. Thermal sensitive electrical parameter of MOSFET is used for in-situ measurement of $T_J$. The two parameters are available for $T_J$ estimation of MOSFET. One is gate threshold voltage. The other is knee voltage of parasitic body diode. This paper evaluates the influence of dynamic gate threshold voltage shift of SiC MOSFET on transient $T_J$ estimation for following 4 mode characterization setup. Mode 1, 2 and 3 are subject to the conventional static test method. Mode 4 is the proposed method in expanding Mode 2.

Mode 1: MOS-diode mode: Fig. 1a).

Shunt gate and drain terminal ($V_{gs} = V_{ds}$).

Mode 2: Body-diode mode (GS-short): Fig. 1b).

Shunt gate and source terminal ($V_{gs} = 0$).

Mode 3: Body-diode mode (GD-short): Fig. 1c).

Shunt gate and drain terminal ($V_{gs} = V_{ds}$).

Mode 4: Body-diode mode (with negative bias $V_{gs}$ application): Fig. 1d).

A constant negative bias voltage is applied across gate and source terminal ($V_{gs}$) by external voltage supply.

The both large current for self heating and small current for measurement flows in the direction of allows in the Fig. 1. Mode 1 estimates $T_J$ from the measured gate threshold voltage with flowing small forward current. Mode 2, 3 and 4 estimates $T_J$ from the measured knee voltage of body diode with flowing small reverse current through body diode. The measurement current is set small enough to neglect self heating effect.

3 Experimental setup based on static test method

Fig. 2 illustrates the overview of studied SiC MOSFET module. Temperature sense diode (TSD) is embedded in the top of SiC MOSFET to estimate device temperature. G, D and S denote gate, drain and source terminal of SiC MOSFET, respectively. A and C denote anode and cathode terminal of TSD, respectively. This SiC MOSFET die is attached on Si$_3$N$_4$ ceramic substrate with 80 µm solder as shown in Fig. 2b).

$I_d - V_{ds}$ characteristics of body diode at room temperature is shown in Fig. 3. $I_d - V_{ds}$ characteristics does not change when gate bias voltage $V_{gs}$ is lower than $-12.5$ V, because current path through body diode is fixed for large negative gate bias voltage. $-18$ V bias voltage is applied in Mode 4 by battery as isolated voltage supply.

The voltage across drain and source terminal of MOSFET for each measurement mode and TSD for fixed small current (5 mA) to the temperature are shown in Fig. 4. They are approximated with linear function of temperature, and their slopes are referred as K factor [10] listed in Fig. 4.
4 Evaluation of estimated junction temperature

Fig. 5 shows $V_{gs}$ and $V_{gd}$ time response in switching transient from heating to cooling for each measurement mode. The estimated time response of $T_J$ for each measurement mode in cooling operation of SiC MOSFET after 300 s heating is shown as semi-log plot in Fig. 6. Time response of voltage for small constant current is measured as $T_J$ with T3Ster (MentorGraphics). The estimated temperature with MOSFET and TSD are given as solid and dashed line, respectively. Measurement current is 5 mA, and heating power $P_{in}$ is shown in Fig. 6.

Fig. 6a) shows the estimated time response of $T_J$ for MOSFET in Mode 1, which does not correspond with that for TSD in the entire measurement period. Moreover, initial rise of estimated $T_J$ in cooling operation is observed. This temperature response is inconsistent with physical phenomenon, and can be
attributed to the influence of dynamic gate threshold voltage shift in SiC MOSFET by large $V_{gs}$ change for switching large heating drain current to small measurement current as shown in Fig. 5a) [7]. The temperature difference converges in a several days. Mode 1 does not give accurate time response estimation of $T_J$ for SiC MOSFET.

Fig. 6b) and Fig. 6c) show the estimated time response of $T_J$ in Mode 2 and 3. These modes also show initial rise of estimated $T_J$. The gate bias voltage from heating to cooling operation as shown in Fig. 5b) and c), and this induces dynamic gate threshold voltage shift. The estimated $T_J$ does not coincide with $T_J$ for TSD in the measurement time scale. In Mode 2 and 3, the negative gate bias voltage applied by voltage drop with heating and measurement drain current is insufficient to fix $I - V$ characteristics of body diode in Fig. 3.

Fig. 6d) shows the estimated time response of $T_J$ in Mode 4. The influence of dynamic gate threshold voltage shift is not observed for the monotonic temperature fall. Fig. 5d) shows $V_{gs}$ and $V_{gd}$ response in switching transient. The influence of gate threshold voltage shift does not occur. Because $V_{gs}$ and $V_{gd}$ kept lower than $-12.5$ V in the entire time scale, where $I - V$ characteristics of body diode is fixed.
The estimated time response of $T_J$ for MOSFET is almost consistent with the estimated time response of $T_J$ for TSD. TSD temperature does not completely correspond with $T_J$ of SiC MOSFET during fast transient for several msec. TSD embedded in MOSFET is not located in the same position of PN junction of body diode in MOSFET. TSD temperature is consistent with $T_J$ of MOSFET in thermal equilibrium condition for start and end of cooling operation and expected to be close to the “true” $T_J$ of MOSFET during transient condition. The gate bias voltage in Mode 4 is large enough to fix $I - V$ characteristics of body diode in Fig. 3, and the proposed method is useful in estimating $T_J$ for SiC MOSFET.

5 Conclusion

This paper proposed $T_J$ estimation method for SiC MOSFET in transient thermal characterization with expanding the static test method. The error of estimated temperature with gate threshold voltage and knee voltage of body diode in SiC MOSFET for the conventional method is evaluated with the temperature from embedded TSD. The dynamic gate threshold voltage shift of SiC MOSFET violates $T_J$ estimation. The proposed negative gate bias voltage application estimates accurate time response of $T_J$ for SiC MOSFET. This enables to extract transient thermal resistance of power module with SiC MOSFET.

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