An Experimental Study on Dynamic Junction Temperature Estimation of SiC MOSFET with Built-In SBD

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Abstract Thermal characterization with static test method [1], which utilizes \( I - V \) characteristics of power semiconductor devices to estimate junction temperature \( (T_J) \), has attracted attention for high density power conversion system design. However, the dynamic gate threshold voltage shift distorts \( T_J \) estimation for SiC MOSFET. This paper evaluates time response of \( T_J \) with junction voltage \( (V_J) \) for the developed SiC MOSFET, which embeds Schottky barrier diode (SBD) in this structure. This sophisticated structure enables to get accurate time response of \( T_J \) for SiC MOSFET, and hence to design dynamic thermal characteristics of power modules with SiC MOSFET.

**key words:** SiC MOSFET, SWITCH-MOS, junction temperature estimation, static test method, built-in SBD

**Classification:** Power devices and circuits

1. Introduction

Fast switching capability of SiC unipolar power devices gives low switching loss and allows high frequency switching operation, which enables to miniaturize power conversion systems [2]-[6]. However, miniaturizing power conversion systems increases heat dissipation per unit area/volume, and makes thermal management difficult.

Thermal design of power modules aims at spreading and dissipating heat generated in power semiconductor devices. The precise thermal model, whose characteristics depends on the structure and material property of power module constitutions, is necessary for estimating junction temperature \( (T_J) \) of power semiconductor devices. Dynamic thermal network model represented by thermal resistance and thermal capacitance is often used for \( T_J \) estimation in over or fault current [7]-[16]. References [9, 10] consider thermal coupling effect for multi-chip power module package. References [12]-[15] identify transient thermal model using Fourier series expansion. Frequency-domain modeling is also conducted for several thermal circuit models in reference [16]. Static test method [1] is the standardized method for identifying thermal network model of power module package from time response of \( T_J \).

SiC MOSFET has difficulty of the gate threshold voltage shift due to the carrier traps in the level of gate oxide or interface [17]. The static gate threshold voltage shift has been improved, but the dynamic gate threshold voltage shift, for example negative bias temperature instability (NBTI) problem [18, 19], still remains great concern. The latter causes an error in \( T_J \) estimation of SiC MOSFET using its temperature dependency of \( I - V \) characteristics [20]. This error makes it difficult to identify transient thermal model of power module package with SiC MOSFET. The authors proposed the modified static test method to avoid difficulty in SiC MOSFET by clamping negative gate bias voltage \( (V_{gs}) \) in previous research, and realized accurate \( T_J \) estimation for SiC MOSFET [21]. However, this method applies a larger than rated negative \( V_{gs} \), which damages the reliability of gate oxide.

SiC MOSFET with built-in Schottky barrier diode (SBD) has been reported by some researchers [22]-[27]. This structure enables reverse current to flow through built-in SBD regardless of body diode, whose \( I_d-V_{sd} \) characteristic does not depend on \( V_{gs} \). The estimated \( T_J \) from knee voltage of SBD in SiC MOSFET is independent of the dynamic gate threshold voltage shift. This paper evaluates time response of \( V_J \) for the developed trench gate SiC MOSFET with built-in SBD, which does not require to apply negative \( V_{gs} \) to estimate \( T_J \).

2. Studied SiC MOSFET with built-in SBD

2.1 Device structure

Trench gate SiC MOSFET is attractive for the reduction of specific on-resistance characterized by a small cell pitch and high channel mobility on the trench sidewall [26, 29]. Knee voltage of body diode in SiC MOSFET is relatively large due to its wide bandgap, which results in large conduction losses in the free wheeling operation. In addition, current conduction induces the bipolar degradation of body diode due to the recombination of injected minority carriers [28].

Fig. 1 shows the device structure of trench gate SiC MOSFET. Fig. 1a) is the conventional double-trench gate SiC MOSFET [29], and Fig. 1b) is the developed trench
gate SiC MOSFET with built-in SBD [24, 26]. The latter is also named as Sbd-Wall-Integrated Trench MOSFET (SWITCH-MOS). SWITCH-MOS is designed to have the reverse current flow through built-in SBD, rather than through pn body diode. This results in suppressing conduction losses and bipolar degradation, and reducing the chip area for the external free wheeling diode. Because reverse conducting characteristic through SBD is not affected by the dynamic gate threshold voltage shift, this structure enables to estimate accurate time response of $T_J$ from $V_J$ without clamping negative $V_{gs}$ such as reference [21].

2.2 Static characteristics of MOSFET

Fig. 2 shows $I_d - V_{sd}$ characteristic of each studied SiC MOSFETs at reverse conduction at room temperature. Knee voltage of body diode in the conventional SiC MOSFET changes with $V_{gs}$. Knee voltage of SWITCH-MOS $V_{ds} = 1.2V$ does not change for $V_{gs} < 4V$. Almost all reverse current in SWITCH-MOS flows through built-in SBD and is not affected by the applied $V_{gs}$ when channel is not formulated.

3. Dynamic thermal resistance measurement setup for MOSFET

The standardized static test method measures $V_J$ to estimate $T_J$ of MOSFET in cooling operation from thermal equilibrium condition of self heating. There are two $V_J$s for MOSFET characterization: gate threshold voltage and knee voltage of intrinsic body diode. Forward conducting characteristic does not change regardless of built-in SBD, and the dynamic gate threshold voltage shift occurs even for SWITCH-MOS in $T_J$ estimation with the gate threshold voltage. Therefore, this paper evaluates the influence of the dynamic gate threshold voltage shift of each SiC MOSFET on transient $V_J$ measurement for following two modes characterization setup with knee voltage of body diode/built-in SBD.

Mode 1: Body-diode mode (GS-short): Fig. 3a).
Shunt gate and source terminal ($V_{gs} = 0$).

Mode 2: Body-diode mode (GD-short): Fig. 3b).
Shunt gate and drain terminal ($V_{gs} = V_{ds}$).

Both large current for self heating and small current for measurement flow in the direction of arrows in Fig. 3. These modes measure $V_J$ as knee voltage of body diode/built-in SBD in SiC MOSFET for the small reverse current. The measurement current 5mA is small enough to neglect the self heating effect. The time response of $V_J$ for each measurement mode in cooling operation of SiC MOSFET after 100s self heating is measured using T3Ster (MentorGraphics).

The relationship of knee voltage of body diode/built-in SBD and temperature for 5mA is shown in Fig. 4. They are approximated with linear functions of temperature, and their slopes are referred to as K factor [30] in Fig. 4. K factor of Mode 1 for SWITCH-MOS coincides with Mode 2, and overlapped in the figure. This is because $I_d - V_{sd}$ characteristic does not depend on $V_{gs}$.

4. Measurement results

Figs. 5 and 6 show the time response of $V_J$ for the conventional SiC MOSFET and SWITCH-MOS, respectively in each measurement mode. The heating current shown in the legend is used as the parameter for thermal equilibrium temperature.

The initial drop of $V_J$ in Figs. 5a) and b) is observed for all heating current, which corresponds to the $T_J$ rise in cooling operation. This is inconsistent with the physical phenomenon, and can be attributed to the influence of the...
dynamic gate threshold voltage shift in SiC MOSFET illustrated in [19]. There is the voltage change between gate to drain (Mode1) and gate to source (Mode2) for switching from large heating current to small measurement current. The monotonic increase of $V_g$ is observed irrespective of heating current as shown in Figs. 6a) and b). This result shows that the gate threshold voltage shift does not influence on the time response of $T_d$ in SWITCH-MOS. Because the reverse current flows through built-in SBD, $I_d - V_{sd}$ characteristic does not change with $V_{gs} < 4V$. This result shows that the developed SWITCH-MOS, which embeds SBD on trench gate SiC MOSFET, can estimate the accurate time response of $T_d$ from $V_g$. This enables to evaluate transient thermal characteristics of power modules with SiC MOSFET.

5. Conclusion

This paper evaluates time response of $V_g$ for the developed trench gate SiC MOSFET with built-in SBD (SWITCH-MOS) to estimate $T_d$ dynamically. $I_d - V_{sd}$ characteristic of SWITCH-MOS at the reverse current does not depend on $V_{gs}$ because the reverse current flows through built-in SBD. As the result, an accurate time response of $T_d$ can be estimated for SWITCH-MOS without clamping negative $V_{gs}$. This enables to extract early transient thermal characteristics of power modules with SiC MOSFET.

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References

[1] JESD51-14: JEDEC (2010).
[2] J. L. Hudgins, et al.: IEEE Trans. Power Electron., 18 (2003) 907. (DOI:10.1109/TPEL.2003.810840)
[3] T. Funaki, et al.: IEICE Electron. Express, 7 (2010) 1008. (DOI:10.1587/exelect.7.1008)
[4] J. Millián, et al.: IEEE Trans. Power Electron., 29 (2014) 2155. (DOI:10.1109/TPEL.2013.2268900)
[5] H. A. Mantooth, et al.: IEEE JESTPE, 2 374. (2014) (DOI:10.1109/JESTPE.2014.2313511)
[6] T. Kimoto, et al.: “Fundamentals of silicon carbide technology: Growth, characterization, devices, and applications,” Wiley-IEEE Press (2014).
[7] M. Carmona, et al.: IEEE Trans. Components and Packaging Technology, 22 (1999) 238. (DOI:10.1109/6144.774738)
[8] S. Yin, et al.: IECEN (2013). (DOI:10.1109/IECON.2013.6699223)
[9] J. Li, et al.: IEEE Trans. Power Electron., 33 (2018) 2494. (DOI:10.1109/TPEL.2017.2697959)
[10] A. S. Bahman, et al.: IEEE Trans. Power Electron., 33 (2018) 2518. (DOI:10.1109/TPEL.2017.2694548)
[11] Y. Mukanoki, et al.: APEC (2018). (DOI:10.1109/APEC.2018.8341422)
[12] B. Du, et al.: IEEE Trans. Power Electron., 25 (2010) 237. (DOI:10.1109/TPEL.2009.2091005)
[13] A. Bryant, et al.: IEEE Trans. Power Electron., 27 (2012) 248. (DOI:10.1109/TPEL.2011.2148729)
[14] A. Bryant, et al.: IEEE Trans. Power Electron., 27 (2012) 258. (DOI:10.1109/TPEL.2011.2148730)
[15] J. Reichl, et al.: IEEE Trans. Power Electron., 30 (2015) 3300. (DOI:10.1109/TPEL.2014.2338278)
[16] K. Ma, et al.: IEEE Trans. Power Electron., 31 (2016) 7183. (DOI:10.1109/TPEL.2015.2509506)
[17] M. Gurfitkel, et al.: IEEE Trans. Electron Devices, 55 (2008) 2004. (DOI:10.1109/TED.2008.926662)
[18] S. Pae, et al.: IEEE Trans. Device and Materials Reliability, 8 (2008) 519. (DOI:10.1109/TDMR.2008.2002351)
[19] A. J. Lelis, et al.: IEEE Trans. Electron Devices, 62 (2015) 316. (DOI:10.1109/TED.2014.2356172)
[20] T. Funaki, et al.: THERMINIC (2016). (DOI:10.1109/THERMINIC.2016.7749042)
[21] S. Fukunaga, et al.: IEICE Electron. Express, 15 (2018) 1. (DOI:10.1587/exelect.15.20180251)
[22] Y. Kobayashi, et al.: IEDM (2011). (DOI:10.1109/IEDM.2011.6131619)
[23] C-T. Yen, et al.: ISPSD (2011). (DOI:10.1109/ISPSD.2015.7123440)
[24] Y. Kobayashi, et al.: Jpn. J. Appl. Phys., 56 (2017) (DOI:10.7567/JJAP.56.04CR08)
[25] K. Kawahara, et al.: ISPSD (2017). (DOI:10.23919/ISPSD.2017.7988888)
[26] Y. Kobayashi, et al.: IEDM (2017). (DOI:10.1109/IEDM.2017.8268356)
[27] Y. Yonezawa, et al.: IEDM (2018). (DOI:10.1109/IEDM.2018.8614600)
[28] J. Q. Liu, et al.: Appl. Phys. Lett., 433 (2002) 749. (DOI:10.1063/1.1466212)
[29] T. Nakamura, et al.: IEDM (2011). (DOI:10.1109/IEDM.2011.6131619)
[30] JESD51-1: JEDEC (1995).