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Effect Evaluation and Modeling of p-Type Contact and p-Well Sheet Resistance of SiC MOSFET with Respect to Switching Characteristics

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Abstract. SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) exhibit excellent high-speed switching characteristics. However, the sheet resistance of the p-body region and the contact resistance between the p-body region and source electrode significantly degrade the switching performance. In this study, to clarify the effect of resistance on switching speed, which has not been sufficiently explored before, we used the temperature dependence of sheet and contact resistance and conducted switching tests under different temperature conditions. Furthermore, we created a circuit model that considered body effects and compared the results of the models with the measurements. We were able to reproduce the same temperature and resistance dependences as those exhibited by the experimental results, thus confirming the effectiveness of the model.

Introduction

SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) exhibit excellent switching characteristics [1]. A significant advantage of SiC MOSFETs is their fast-switching capability. However, the sheet resistaance (Rsheet) in the p-body region and the p-type contact resistance (Rpk) between the p-body region and the source electrode are higher than those in Si power devices [2,3]. In addition, the evaluation of the effects of Rpk and Rsheet on switching characteristics is insufficient [4].

In our previous study, we experimentally and computationally evaluated the effects of Rpk on switching characteristics. Under high-speed switching conditions, the switching speed decreased owing to the effect of Rpk, and the switching loss increased. Similar results were obtained from previous calculations [5]. However, the device simulator used in the previous study had drawbacks in terms of calculation speed and application to the coupled analysis of complex circuits, such as converters. On the other hand, SPICE circuit model is often used for circuit analyses [6]. However, the effects of Rpk and Rsheet were not considered in ordinary models. Therefore, we decided to create a MOSFET SPICE model to analyze the effects of Rpk and Rsheet.

To validate the model, it was necessary to adjust the values of Rpk and Rsheet and compare the simulation and experimental results. In this study, we used the property that Rpk and Rsheet depend on the temperature of p-body [7]. We measured the temperature dependence of the MOSFET switching characteristics and compared the characteristics with those of the model.

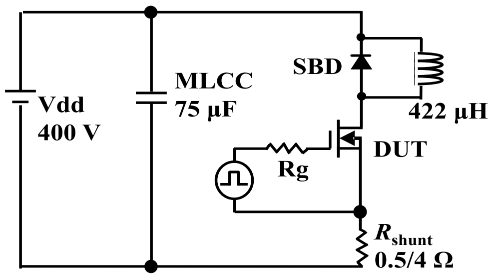

Fig. 1. Experimental circuit used in this study.

Experimental Setup and Results

Fig. 1 shows the experimental circuit for the half-bridge configuration used in this study. The effects of Rpk and Rsheet on the switching speed were measured by adjusting the gate resistance (Rg) and junction temperature. The output voltage of the gate drive circuit used in this experiment was -10/+17 V.

Fig. 2 shows the drain–voltage (Vds) waveform during the switching period when Rg = 2 Ω. Figs. 2(a) and (b) show the waveforms during the turn-on and turn-off periods, respectively, at various temperature. The figures indicate that the fall and rise times of the drain voltage increase as the temperature decreases.

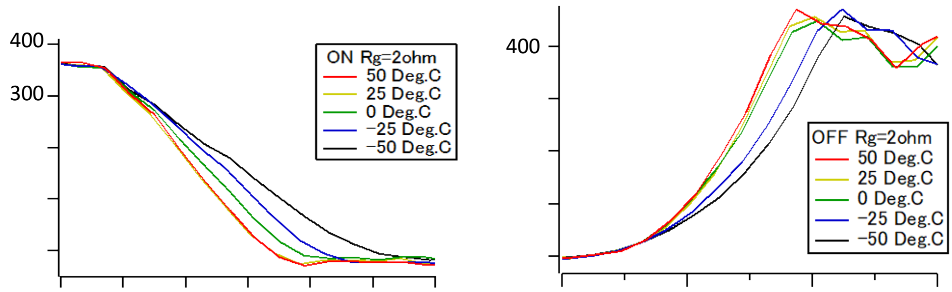

Fig. 2. Drain voltage waveform at Rg = 2 Ω: (a) during turn-on period and (b) during turn-off period.

Figs. 3 (a) and (b) show the switching loss dependence on temperature when Rg= 2 Ω and the drain current is 5 A. As shown in the figures, the switching loss is higher at lower temperatures. This was attributed to the decrease in time variation of Vds (dV/dt) at low temperatures.

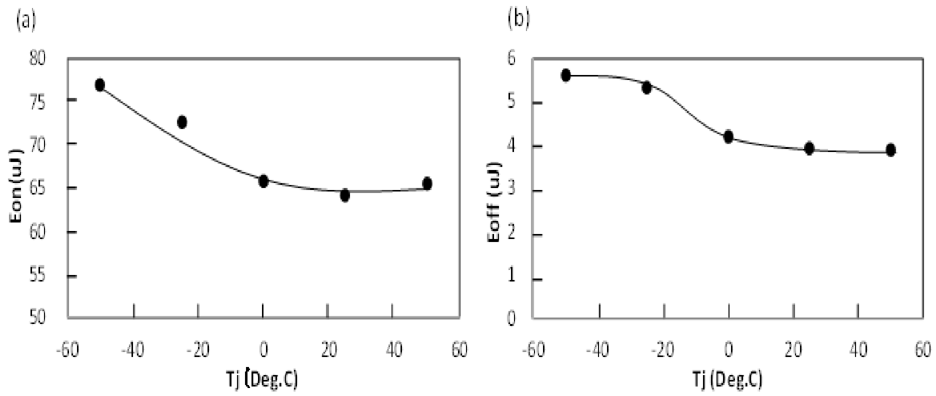

Fig. 3. Dependence of switching loss on temperature: (a) turn-on loss at 5 A and (b) turn-off loss at 5 A.

It has been reported that dV/dt during switching depends on the feedback capacitance. When we measured the temperature dependence of the feedback capacitance, we found that the lower the temperature, the smaller the feedback capacitance, which is inconsistent with the results shown in Fig. 2.

Figs. 4 (a) and (b) show the relationship between the temperature and time derivative of the drain–source voltage (dV/dt) during the turn-on period; Figs. 4 (c) and (d) show the relationship during the turn-off period. In addition, Figs. 4 (b) and (d) show the values obtained by normalizing dV/dt at each temperature with respect to 25 °C (hereafter referred to as normalized dV/dt).

Fig. 4(a) shows that, during the turn-on period, dV/dt decreases at lower temperatures especially when the gate resistance is small. In addition, Fig. 4(b) shows that the temperature dependence of dV/dt becomes weaker as the gate resistance increases from 100 Ω.

For the turn-off period, Fig. 4 (c) shows that the temperature dependence of dV/dt is very small when the gate resistance is as small as 2 Ω. However, as the gate resistance increases, dV/dt decreases at low temperatures. Moreover, Fig. 4 (d) shows that the temperature dependence of dV/dt weakens again when the resistance becomes 500 Ω or more.

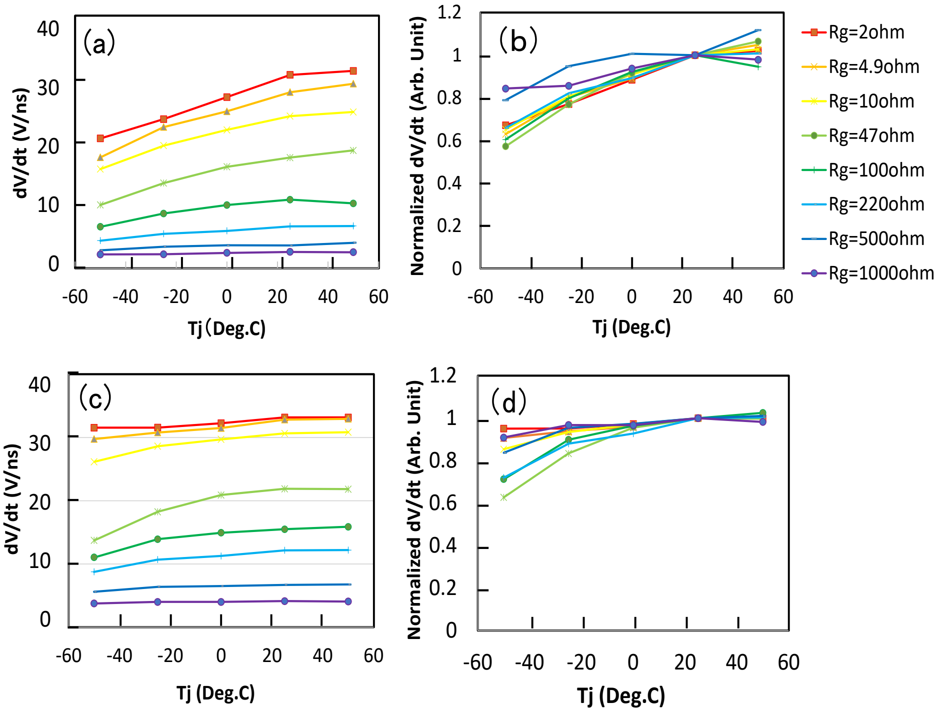

Fig. 4. Temperature dependence of dV/dt and normalized dV/dt during turn on (a and b) and turn off (c and d).

Discussions

Fig. 5 shows the SPICE model used to simulate the switching characteristics. As shown in the figure, the contact resistance between the node (P) and the source electrode is represented by Rpk and sheet resistance is represented by Rsheet comprises five resistances between nodes (P) and (Q). To incorporate the body effect, we assume that the threshold voltage varies in proportion to the potential at point Q, and the proportional coefficient is −1.0.

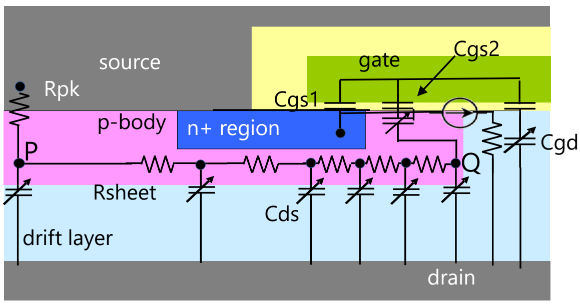

Fig. 5. Developed MOSFET SPICE model used for simulation.

Fig. 6 shows the Vds waveforms obtained by SPICE calculation when the gate resistances are 2, 47, and 500 Ω, including the body effect (solid line) and excluding the body effect (dotted line). As shown in Fig. 6, the body effect degrades the rise and fall times of the drain voltage during the turn-on and turn-off periods.

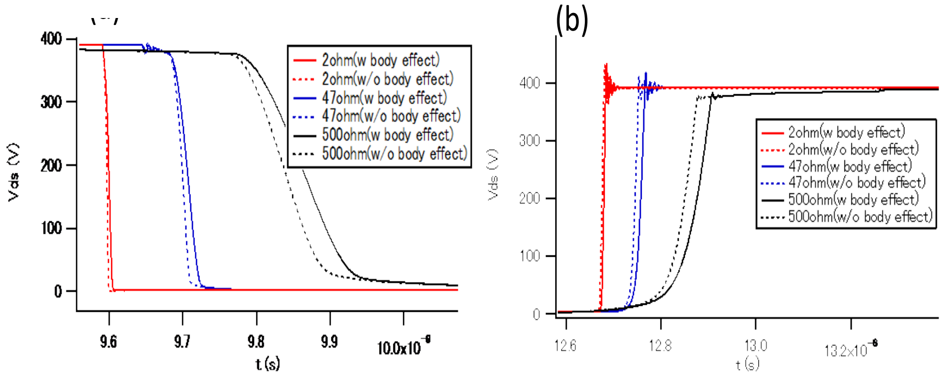

Fig. 6. Simulated Vds waveform during (a) turn-on and (b) turn-off periods at gate resistances of 2, 47, and 500 Ω. The solid and dotted lines indicate the results including and excluding the body effects, respectively.

Figs. 7 (a) and (b) compare the simulated and experimental results for a normalized dV/dt value for −50 °C depending on the gate resistance during the turn-on and turn-off periods. As shown in Fig. 7(a), the normalized dV/dt value decreases as the gate resistance decreases from 1000 Ω. However, the normalized dV/dt values remain nearly constant when the gate resistance is < 100 Ω. A similar trend is observed in the simulation, and the experimental results are well reproduced.

According to the simulation results, this phenomenon can be interpreted as follows. During the turn-on period, the displacement current flows through the channel, source electrode, Rpk, and p-body (Rsheet). Therefore, the p-body potential decreases because of the displacement current flowing through Rpk and Rsheet. Consequently, the threshold voltage increases owing to the body effect, and the discharge current of the feedback capacitor decreases, which reduces the switching speed. As the resistances Rpk and Rsheet have negative temperature coefficients, the p-body potential drops further, and the threshold voltage increases at low temperatures. This results in low switching speeds at low temperatures and normalized dV/dt values less than one. In addition, as the gate resistance decreases and the displacement current increases, the body effect becomes more pronounced, and the normalized dV/dt value decreases.

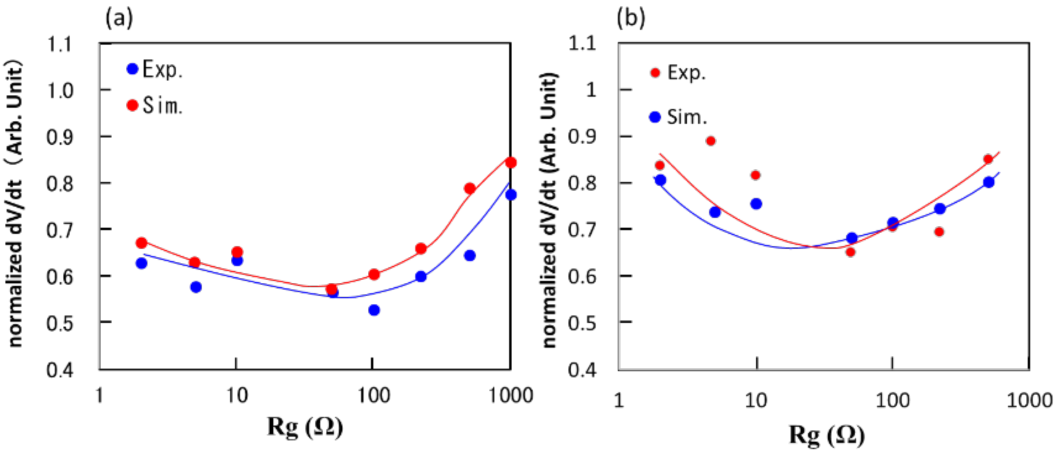

Fig. 7 Comparison of simulated and experimental results for normalized dV/dt values versus gate resistance during (a) turn-on and (b) turn-off periods.

If the gate resistance decreases further, the increase in the gate current slows owing to the parasitic inductance of the drive circuit. Consequently, more gate current flows during the Miller period. Even when the threshold voltage increases, the decrease in the discharge current of the feedback capacitor is mitigated, and the impact on dV/dt decreases. Consequently, the normalized dV/dt is less dependent on the gate resistance.

Next, the gate resistance dependency during the turn-off period is described. Fig. 7(b) shows that the experimentally obtained normalized dV/dt values decrease as the gate resistance decreases from 1000 Ω, reach a minimum value when the resistance falls below 100 Ω, and then gradually increase as the resistance decreases further. A similar trend is observed in the simulations.

When the gate resistance is high, the p-body potential increases because of the displacement current generated by the change in Vds flowing through the p-body to the source electrode. This increase in p-body potential causes a decrease in the threshold voltage. A decrease in the threshold voltage reduces the charge current of the feedback capacitor and lowers the switching speed. The negative temperature coefficient of the resistance causes the decrease of the threshold voltage at low temperature owing to the body effect. This results in low switching speeds at low temperatures, and the normalized dV/dt values are less than one. Similar to the trend observed during the turn-on period, decreasing the gate resistance decreases the normalized dV/dt value.

If the gate resistance is low, the load current will limit the dV/dt. Therefore, the dV/dt value tends to saturate as the resistance decreases. However, under low temperature conditions, Rpk and Rsheet increase and dV/dt becomes smaller than under room temperature conditions owing to the body effect. Therefore, as the resistance value decreases, dV/dt increases and the tendency of dV/dt to saturate disappears. As a result, it is considered that in the low resistance region, the normalized dV/dt value increases as the resistance decreases.

Summary

In this study, switching tests were conducted under different temperature conditions to clarify the effects of contact resistance and sheet resistance on the switching speed. In addition, we created a circuit model that considered the effect of the contact and sheet resistance and compared the results with the measured values. We could reproduce the same characteristics and dependences on temperature and gate resistance as those exhibited by the measured values, thus confirming the effectiveness of the model.

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