Compact Modeling of the Punch-Through Effect in SiC-IGBT for 6.6kV Switching Operation with Improved Performance

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Abstract. We developed a compact model of SiC-IGBT for circuit simulation of power conversion systems under 6.6kV / 100A/cm\textsuperscript{2} bias operation at a few hundred Hz switching frequency. The model includes punch-through effects occurring at the base/buffer surface of the base region. The model allows accurate prediction of switching waveforms and energy loss improvement caused by the punch-through effect (PT-effect).

Introduction

Wide-bandgap SiC-IGBTs have a lower on-state voltage than conventional silicon thyristors in the voltage range over 5kV [1, 2, 3]. At such high-voltage operations of SiC-IGBTs, the punch-through effect [4] is often observed [5], which is characterized by a base region that is void of carriers and highly resistive. These differences from silicon IGBTs originate from material parameters shown in Table 1 [6].

Investigation with Mixed-Mode 2D-Device Simulation

Figure 1 shows the simulation setup of the switching test circuit and its typical operation example depicting the turn-off operation by the dashed rectangle. The collector-emitter voltage rapidly turns on immediately after the PT occurs as shown in Figs. 2 and 3, causing a large voltage overshoot that can trigger a ringing phenomenon. This is more prominent if the parasitic stray inductance is relatively large (> 1\muH) as shown in Fig. 4. However, the turn-off energy loss is suppressed by the PT-effect as shown in Fig. 5 because a reduced tail current flow as shown in Fig. 2b. To exploit the advantage while at the same time avoid the ringing, the PT-effect must be modeled accurately.

Modeling and Results

In this work, we developed a physics-based compact model for SiC IGBTs [7] including the PT-effect explicitly by extending the HiSIM-IGBT model [8] as depicted in Fig. 6. HiSIM-IGBT consists of the surface-potential-based bulk-MOSFET model HiSIM, a bipolar junction transistor model considering the Kirk effect, a carrier-distribution-based base/JFET resistance model ($R_{\text{base}}$), and a carrier-distribution-based excess base charge model ($Q_{\text{base}}$) considering the non-quasi-static effect. In this model, the carrier distribution is determined by the depletion width with the inclusion of the PT-effect. The model is implemented in a circuit simulator [9] and is verified to correctly predict 2D device simulator [10] results of the device turn-off switching characteristics for different supply voltages as shown in Fig. 7.
Table 1: Material parameters: energy bandgap $E_g$, intrinsic carrier density $n_i$, critical field $E_c$, dielectric constant $\epsilon_r$.

<table>
<thead>
<tr>
<th></th>
<th>Silicon</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>1.1</td>
<td>3.26</td>
</tr>
<tr>
<td>$n_i$ (cm$^{-3}$)</td>
<td>$1.45 \times 10^{10}$</td>
<td>$9.7 \times 10^{-9}$</td>
</tr>
<tr>
<td>$E_c$ (V/cm)</td>
<td>$0.3 \times 10^6$</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>$\epsilon_r$ (-)</td>
<td>11.8</td>
<td>10</td>
</tr>
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</table>

Fig. 1: (a) Half cell structure of the planar-gate p-channel 4H-SiC IGBT investigated with a 2D-device simulator. Line A is referred to in Fig. 3. (b) Switching test circuit with an inductive load. The 4H-SiC p-IGBT shown in (a) is tested. $V_{cc}$ is the power supply voltage. In this work, $R_g$ is very small, which results in $V_{in} \approx V_{ge}$. (c) Schematic of typical waveforms during operation of the circuit (b). The dashed rectangle indicates the turn-off operation studied in detail.

Fig. 2: Comparison of the 8$\mu$s turn-off behaviors calculated by the mixed-mode 2D-device simulator for (a) 650V and (b) 6.6kV operation of the circuit shown in Fig. 1(b). Reduction of the tail current lowers the turn-off energy loss, while the rapid increase of $V_{ce}$ may induce a voltage overshoot and ringing phenomena. Time points (1), (2), (3), (4), (5) and (6) are referred to in Fig. 3.

Fig. 3: Dynamic electron distribution within the base region along the Line A of Fig. 1(a) during the turn-off operation at time points (1), (2), (3), (4), (5) and (6) corresponding to Fig. 2. (a) Depletion region does not reach the buffer layer (650V operation). (b) Depletion reaches the buffer (6.6kV operation). Regions highlighted by lines are the important device characteristics that are included in the modeling.
Fig. 4: Ringing phenomena due to the rapid $V_{ce}$ increase. The mixed-mode 2D-device simulation is performed for different stray inductance values $L_s$ in Fig. 1(b), where $\frac{V_{ce}}{dt}$ is higher than 50kV/µs. Ringing phenomena are observed with increased stray inductance $L_s$ of 1µH and 10µH, whereas no such phenomenon is observed with smaller $L_s$ of 1nH and 100nH.

Fig. 5: Positive effect brought by the punch-through effect seen in the relation between the turn-off energy loss $E_{off}$ and the supply voltage $V_{cc}$. The mixed-mode 2D-device simulation is performed for different power supply voltages $V_{cc}$ in Fig. 1(b), where $R_g$ and $L_g$ are fixed to 10Ω and 1nH, respectively, and $L_c$ is adjusted to fix $\frac{dI_c}{dt} (\approx \frac{V_{ce}}{L_c})$.

Fig. 6: (a) Half cell structure of the planar-gate p-IGBT. (b) Conceptual model framework corresponding to the structure in plot (a). $R_{base}$ and $Q_{base}$ are written as functions of the carrier distribution within the base region.

Fig. 7: Overlay of the SiC-IGBT turn-off waveforms with the extended HiSIM-IGBT model and the mixed-mode numerical device simulator for different $V_{cc}$ conditions of the circuit shown in Fig. 1(b). Note that the punch-through voltage $V_{pt}$ of the device shown in Fig. 1(a) is around 2kV.
Summary

In this work, the HiSIM-IGBT model is extended to model the SiC IGBT device. The material parameters of SiC are included through the Poisson equation of the MOSFET part and through the excess carrier density in the base region. The punch-through effect is also considered in the modeling of the depletion width. Correct turn-off characteristics of the 4H-SiC IGBT for different supply voltages are verified, which is important for accurate calculation of energy loss.

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References


