Investigation of SiC p-i-n Diode Reverse-Recovery Effect for Compact Modeling

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INTRODUCTION

Recently, many reports about power devices using the wide bandgap material silicon carbide (SiC) have been published, because SiC has many advantages in comparison to silicon (Si) as e.g. a 10 times higher critical electric field [1]. Among SiC-based power devices, the p-i-n diode is intensively developed as a key device for ultrahigh-voltage applications over 5 kV. In this work, we investigate the reverse-recovery effect [2] of SiC p-i-n diodes. Main focus is given on the specific features of the SiC material, such as the extremely low intrinsic carrier density (n_i) in comparison to Si, and the resulting effects on compact model construction for circuit simulation.

INVESTIGATION WITH 2D-DEVICE SIMULATION

The reverse recovery currents of Si and SiC p-i-n diodes with the same structure (see Fig. 1) are compared by 2D-device simulation under identical initial forward current condition in Fig. 2. Figure 3 shows the carrier distributions at the 4 time points indicated in Fig. 2. Even if the on-current is kept the same (100 A), differences are observed in three aspects, namely, carrier density at the $\mathrm{p}^+/\mathrm{n}^-$ junction (n_j), carrier-distribution gradient ($\mathrm{d}n_\mathrm{j}/\mathrm{d}x$), and depletion width ($W_\mathrm{d}$). Since the lifetime is fixed to 1 μs for both diodes, it is concluded that n_j and $\mathrm{d}n_\mathrm{j}/\mathrm{d}x$ differences mainly result from mobility (μ) changes due to the different diffusion length. Regarding W_d, the different electric permittivity (ε) is considered as the reason. By setting μ and ε to the same values in the simulation experiments all above differences are eliminated, as verified in Fig. 4. In consequence, this agreement implies that the reverse recovery effect can be modelled based on the same fundamental physics, even at 10^{19} times lower n_i in SiC when compared to Si.

VERIFICATION WITH HiSIM-DIODE MODEL

HiSIM-Diode has been developed to model the reverse-recovery effect based on the dynamic carrier distribution using the non-quasi-static modelling method for carrier recombination [3, 4]. Here we verify that this modelling approach is also valid for SiC by considering its different material parameters from Si. As shown in Fig. 5, the 2D-device simulation results of Figs. 2 and 3 for the SiC diode are indeed reproduced by the compact model. In addition, the reproduction of measured data for a SiC p-i-n diode is verified in Fig. 6.

CONCLUSION

It is confirmed with 2D-device simulation that the reverse recovery effect in the SiC diode can be modelled based on the fundamental physics with the same concepts as applied for Si. Reproduction of measured reverse recovery data for a SiC p-i-n diode by HiSIM-Diode, which can properly handle the material parameters of SiC, makes this evident.

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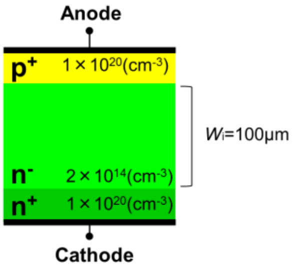

Fig. 1. Investigated p-i-n diode structure: In this work, the n$^-$ drift layer thickness and its impurity concentration are set to 100 μm and 2x10^{14} cm^{-3}, respectively.

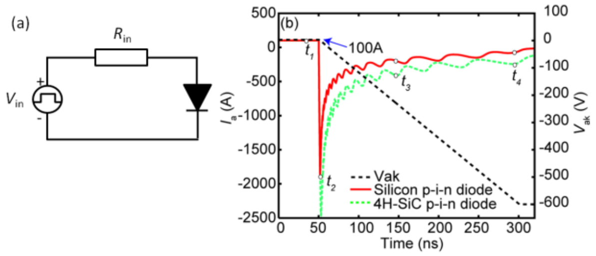

Fig. 2. (a) Test circuit. (b) Reverse recovery currents of Si and 4H-SiC diodes calculated by a 2D-device simulator, where the initial forward current is set to 100 A.

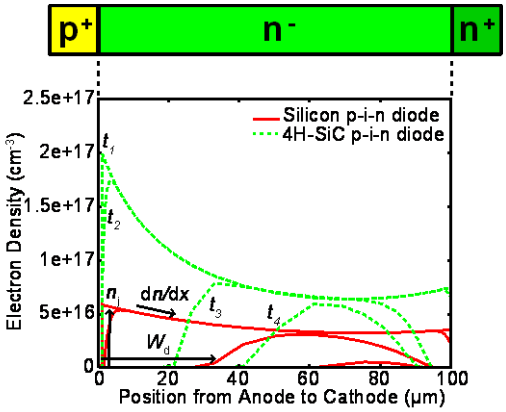

Fig. 3. Dynamic carrier distribution in the n$^-$ drift region calculated by a 2D-device simulator (Solid lines: Si diode, Dotted lines: 4H-SiC diode).

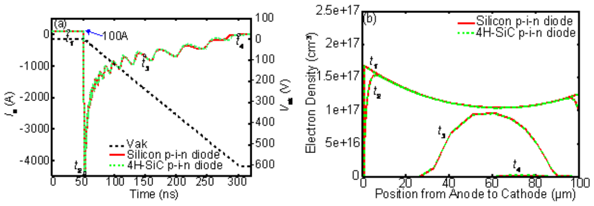

Fig. 4. (a) Reverse recovery currents and (b) the dynamic carrier distributions, with the same mobility and permittivity for both Si and 4H-SiC diodes.

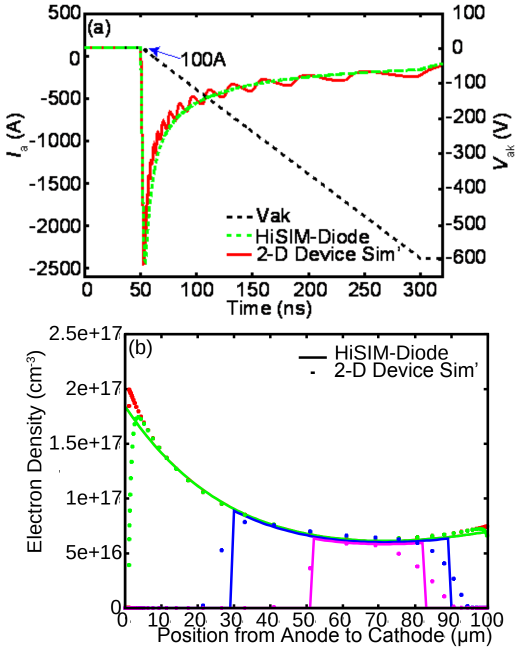

Fig. 5. Comparison of the 2D-device simulation results (shown in Figs. 2 and 3) and the HiSIM-Diode results. (a) Reverse recovery currents and (b) the dynamic carrier distributions of the 4H-SiC diode. The oscillation in the reverse recovery current with 2D-device simulation is also seen in the Si diode case of Fig. 2. (The reason for its occurrence is not yet confirmed.)

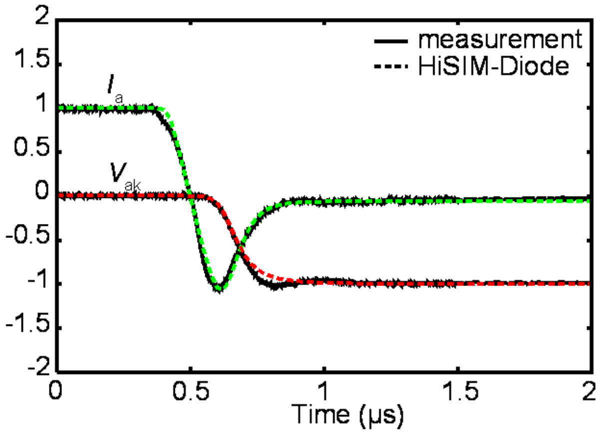

Fig. 6. Comparison of measured data and the HiSIM-Diode results for a 4H-SiC diode with a typical inductive-load test circuit at a voltage and current rating of 2000 V and 100 A/cm^2, respectively, where a Si IGBT is used as a switch. The reverse recovery currents and the voltage over the diode are shown on the vertical axis normalized by the rated current or voltage.