Numerical Analysis of Silicon Carbide Schottky Diodes and Power MOSFETs

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Abstract

A silicon carbide (SiC) device simulator has been developed to exactly evaluate the electrical characteristics of SiC power devices. Avalanche breakdown voltages were predicted based on the ionization integral method for high resistivity n type diodes (< 1.0 e16 cm^{-3} donor concentration). The calculated value for 2.0 e15 cm^{-3} was 40 % lower than that of a previous prediction. It was predicted that 4500 V platinum-SiC diodes have a forward voltage drop of 3.3 V for 100 A/cm^2 and that 4500 V MOSFETs have a specific on-resistance of 0.023 Ω-cm^2. The breakdown voltages of Schottky diodes with low barrier height metals such as titanium is determined by large leakage currents and not by avalanche breakdown.

1. Introduction

Recently, silicon carbide (SiC) has been paid attention as a new material for high performance power devices [1]. It is expected that SiC Schottky rectifiers will have a low on-state voltage drop and a faster switching speed and SiC MOSFETs have 2 orders of magnitude lower specific on-resistance than Si counterparts, since SiC has many excellent properties such as a high breakdown electric field, high thermal conductivity, and high saturation electron drift velocity. However, these devices with breakdown voltages exceeding 1000 V have not yet been realized because of the difficulty of crystal growth and immature device technology [2]. This paper describes the development of a SiC device simulator and its employment to exactly evaluate SiC power devices.

2. Simulation Models

A SiC device simulator has been developed by modifying a silicon based simulator, TONADDE II C [3]. The main parts of the change include the bandgap energy (2.86 eV for 6H-SiC), impact ionization rate, and electron mobility.

The exact impact ionization rates for holes and electrons are required to predict SiC device breakdown voltages. The authors assumed an appropriate function for the electric field and checked its validity by comparing the results with published experimental results, since sufficient experimental data for the SiC ionization rate are not provided. For simplicity, the same function for the electric field dependence of the electron and hole ionization rates was assumed. This assumption is justified by the fact [4] that sufficiently exact breakdown voltage prediction can be obtained even for silicon devices by using the same appropriately determined ionization rate for electrons and holes. For example, Eq.(1) can be used for the breakdown voltage prediction of silicon devices instead of using real ones,

$$\alpha = C \times E^{n}. \qquad (1)$$

Fig. 1 shows the ionization rate versus reciprocal electric field for Si (α_n = 7.03 e5 x exp[-1.23 e6 / E], α_p = 1.58 e5 x exp[-2.04 e6 / E]) and SiC (C = 2.0 e-41 and 2.0 e-40, n=7). Fig. 2 shows the calculated avalanche breakdown voltage from the ionization integral and the corresponding critical electric field as a function of the donor concentration together with the experimentally obtained critical electric field [5,6]. Both optimistic (solid line: C = 2.0 e-41) and pessimistic (dotted line: C = 2.0 e-40) predictions for the SiC ionization rate were introduced, since the experimentally obtained critical electric field values scattered in a wide range. It can be seen that the optimistic prediction gives about two times larger breakdown voltages than the pessimistic one. In both cases, lower breakdown voltages were obtained for high resistivity n type diodes, as compared with a previous work [1]. The reason is that it has been assumed that the critical electric field decreases as the carrier concentration decreases, whereas [1] assumed a constant value (3.0 e6 V/cm).

The optimistic values (C = 2.0 e-41) will be used for the ionization coefficient in the following calculations.

The empirical relationship in [7] and [8] were used for the dependency of electron mobility (μ) on the doping concentration (n) and temperature (T) as follows,

$$\frac{1}{\mu}=Em\times\left[1+\left(\frac{E^2}{Ec^2}\right)^{\beta}\right]^{\frac{1}{2\beta}}+\frac{Ex\times\left[1+\left(\frac{E^2}{64Ec^2}\right)^{\beta}\right]^{-\frac{1}{2\beta}}}{\left(\frac{n}{1.0\times10^{17}}\right)^{-0.34}+0.0695},\quad(2)$$

where Ex, Em, Ec, and β are defined by the following equations,

$$\begin{cases}Ex=5.26\times10^{-3}\times T^{-0.2}\\ Ec=5.05\times T^{1.55}\\ Em=Ec/(2.86\times10^{9}\times T^{-0.87})\\ \beta=2.57\times10^{-2}\times T^{0.66}.\end{cases}\quad(3)$$

Fig. 3 shows the electron drift velocity and mobility for Si and 6H-SiC as functions of the electric field.

3. Calculated Results

3.1 Schottky diodes

3.1.1 Current-Voltage Characteristics
-- Schottky Barrier Height Lowering Effects

It is important to include the Schottky barrier height lowering effects due to the image potential. It was assumed that the barrier height change is given by [9],

$$\Delta\phi=\sqrt{qE/4\pi\epsilon}.\qquad(4)$$

Fig. 4 compares the calculated current voltage curves with (solid curve) and without (dotted curve) the barrier height lowering effects. The difference between these currents was obtained even for low bias and increased with reverse bias. It is obvious that these effects must be included for precise reverse breakdown voltage prediction.

Figs. 5 (a) and (b) show the calculated reverse current-voltage characteristics of Schottky diodes on a 16 micron thick 1.0 e-4 Ω-cm^2 (4.0 e16 cm^{-3} donor concentration) epitaxial layer. The assumed barrier heights (Φ_b) were 0.83 eV for a titanium-SiC contact and 1.10 eV for a platinum-SiC contact.

The leakage current for a diode with a barrier height of 0.83 eV was 4 orders of magnitude larger than that for 1.10 eV because the leakage current of a Schottky diode is proportional to $\exp[-q\Phi_b/kT]$. For titanium Schottky diodes, the leakage current for 300 K was larger than 1 mA/cm^2 at 200 V reverse bias. For such diodes, the breakdown voltage may be limited by the leakage current value. The details will be discussed later.

Fig. 6 shows the forward current-voltage characteristics for the platinum Schottky diode (Φ_b = 1.10 eV). The resistance of the substrate was assumed to be 3.0 e-3 Ω-cm^2. The forward current increased with temperature for the voltage range below the barrier height. However, for a higher voltage range above the barrier height, the current decreased as the temperature increased because of the dependency of mobility on temperature. The calculated forward voltage drops at 100 A/cm^2 ranged from 0.9 V to 1.1 V depending on the temperature.

3.1.2 Breakdown Voltages of Schottky Barrier Diodes

As mentioned in the previous section, the reverse current increased with the reverse bias as well as temperature. The lines in Fig. 5 indicate the constant power loss curves of 1 mW/cm^2 and 1 W/cm^2 defined by the product of the reverse current and reverse voltage. For example, the leakage current of the titanium diode at 350 V was 3.0 e-3 A/cm^2 and the power loss was over 1.0 W/cm^2. So we can regard that titanium diode breakdown will be determined by a large leakage current and not by avalanche breakdown. On the other hand, the power loss for platinum diodes (1.1 eV) was less than 1 mW/cm^2 for the avalanche breakdown voltage. Consequently, it has been predicted that breakdown voltages are determined by the avalanche phenomenon for platinum diodes.

3.1.3 Forward Voltage Drops for 4500 V SiC Schottky Diodes

Table 1 shows the calculated breakdown voltages (Vb) and forward voltage drops at 100 A/cm^2 current density (Vf) for Schottky diodes on four different donor concentration epi-layers. The values in parentheses mean that the device is not practical because of a large leakage current.

In Fig. 7, the forward voltage drops of SiC and Si Schottky diodes are plotted as a function of breakdown voltage. It is seen that a 4500 volt platinum Schottky diode is predicted to have a 3.3 V forward voltage drop from Fig. 7.

3.2 Transient Analysis

Fig. 8 shows the simulated system for the transient analysis of SiC Schottky diodes. The applied bias voltages were linearly changed from +5 V with a 100 A/cm^2 current density to -10 V in a time of t_s for the calculations of reverse recovery. The simulated device structure was the same as that in static calculations. The results of the reverse recovery waveforms of the Schottky diode are shown in Figs. 9 (a) and (b) with source voltage reversing time t_s as a parameter. Since Schottky barrier diodes are a majority carrier device, stored carriers are negligibly small. For a slow switching time such as 1 μs, the reverse current is very small (only 1% of the initial forward current). For a fast switching case, a reverse current flows, creating a depletion layer and a reverse recovery time is less than 10 ns.

3.3 Two-dimensional Device Structures

The TONADDE program can also be adapted to two-dimensional cases. Fig. 10 shows the calculated potential distribution for a Schottky barrier diode with 4.0 e16 cm^{-3} donor concentration which has a finite planar electrode at breakdown voltage. Since the electric field at the edge of the electrode was about five times larger than that at the center, the breakdown voltage was only 70 V and much lower than the one-dimensional result.

3.4 Forward Voltage Drops for 4500 V SiC MOSFETs

In the case of power MOSFETs, if the channel resistance is neglected, we only need to take the resistance in the drift region into account. So the current density of the MOSFETs is obtained by the following equation,

$$J = q \mu n \times \frac{V}{W} . \qquad (5)$$

The dotted-dash line in Fig. 7 indicates Vb and Vf for SiC MOSFETs. We can predict from this relation that a theoretical limit of 4500 V SiC MOSFET specific on-resistance is 0.023 Ω-cm^2, which is about four times larger than that previously predicted [1].

4. Summary

A SiC device simulator has been developed and employed to exactly evaluate SiC power devices. Lower breakdown voltages were obtained for high n type resistivity diodes (< 1.0 e16 cm^{-3} donor concentration), as compared with a previous prediction. It was predicted that 4500 V Schottky diodes have forward voltage drops of 3.3 V for 100 A/cm^2. 4500 V MOSFETs with a 2.5 e15 cm^{-3} donor concentration had a specific on-resistance of 0.023 Ω-cm^2, which was about four times larger than that previously predicted. Breakdown voltages for Schottky diodes with lower barrier height metals such as titanium are considered to be determined by a large leakage current and not by an avalanche phenomenon.

The reverse recovery time of a Schottky diode can be less than 10 ns even for fast switching case.

Acknowledgement

The authors wish to thank Mr.F.Umibe for reviewing the original manuscript and suggesting revisions in its English.

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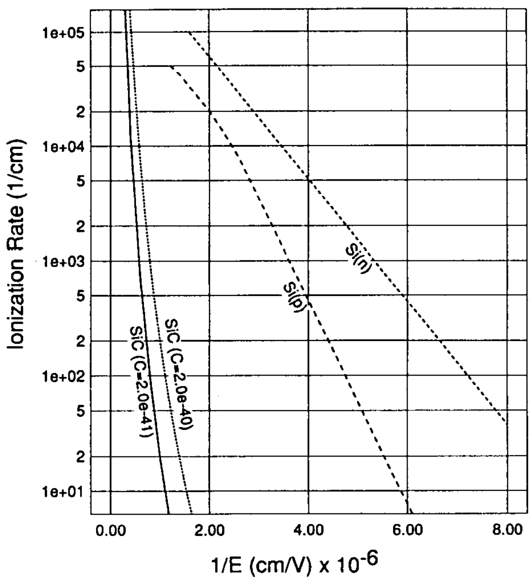

Fig. 1. Ionization rates versus reciprocal electric field for Si and SiC.

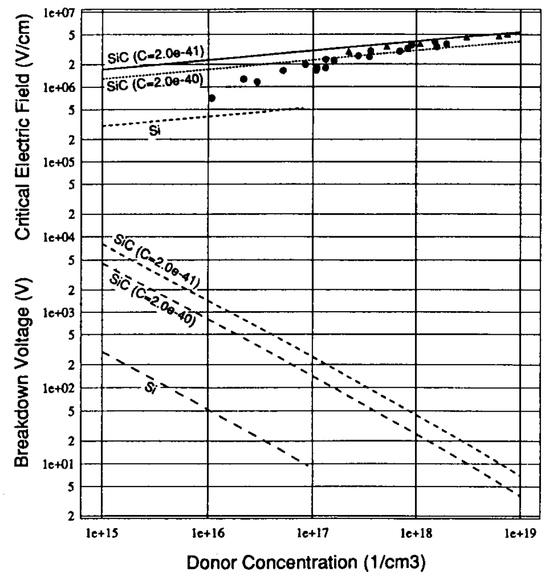

Fig. 2. Breakdown voltage and corresponding critical electric field as a function of donor concentration.

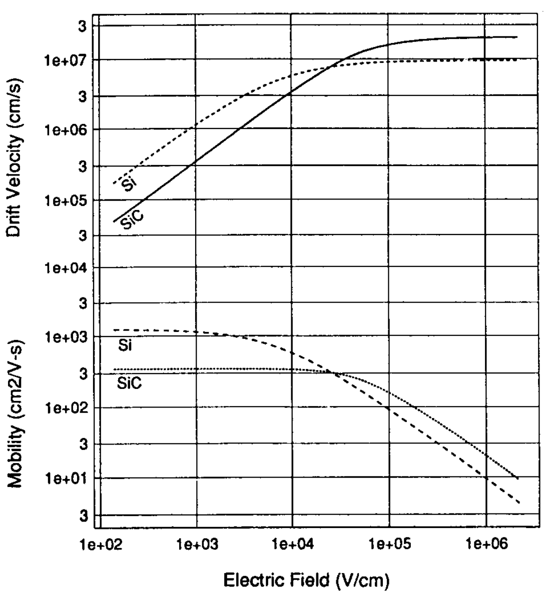

Fig. 3. Electron velocity and mobility for Si and SiC as a function of electric field.

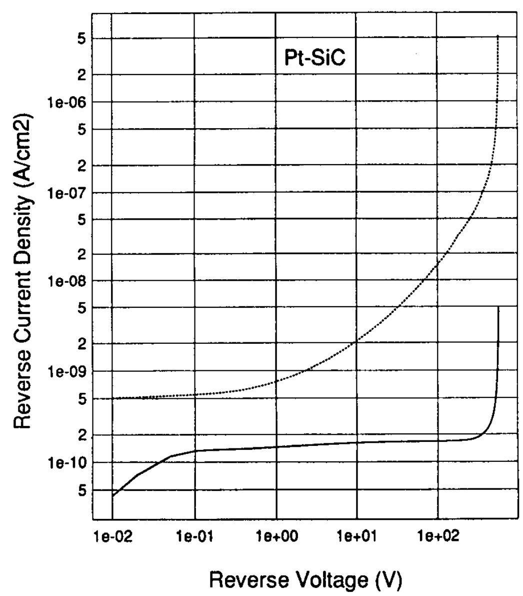

Fig. 4. Calculated reverse current-voltage curves with and without barrier height lowering effect.

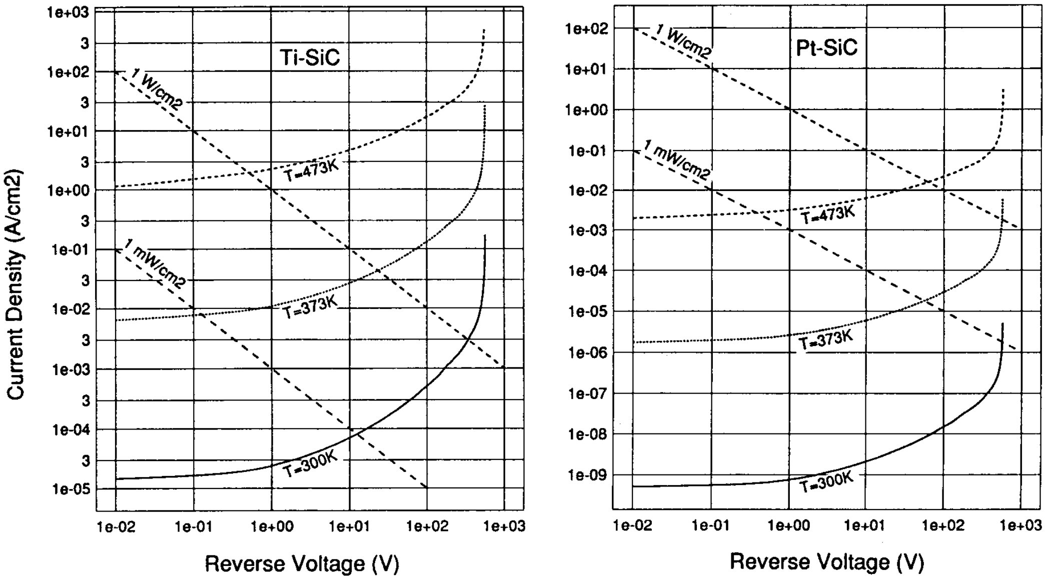

Fig. 5. Calculated reverse current-voltage characteristics for (a) Ti-SiC and (b) Pt-SiC Schottky diodes with 4.0 e16 cm^{-3} epitaxial layer for three temperatures.

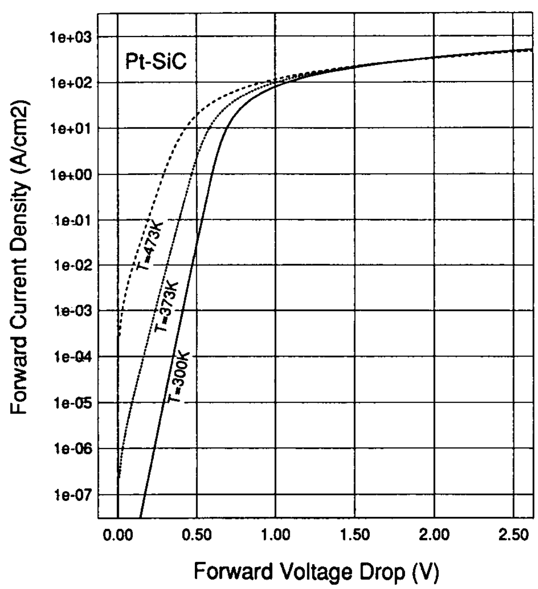

Fig. 6. Calculated forward current-voltage characteristics for Pt-SiC diode with 4.0 e16 cm^{-3} for three temperatures.

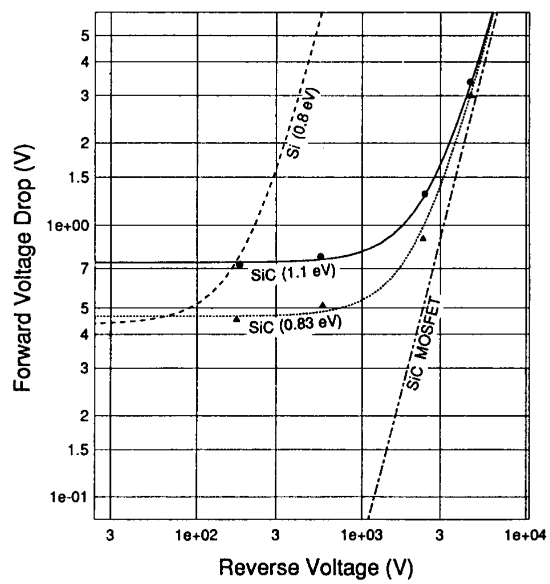

Fig. 7. Forward voltage drop for 100 A/cm^2 current density as a function of breakdown voltage with barrier height as a parameter.

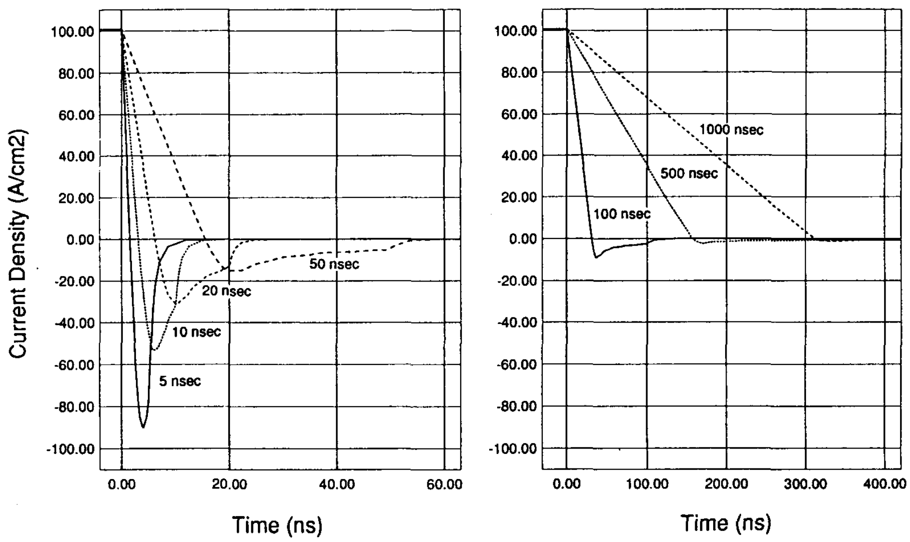

Fig. 9. Calculated reverse recovery transient of Schottky diode for various t_S values of (a) 5, 10, 20, 50ns and (b) 50, 500, 1000 ns. (for the definition of t_S, see Fig. 8)

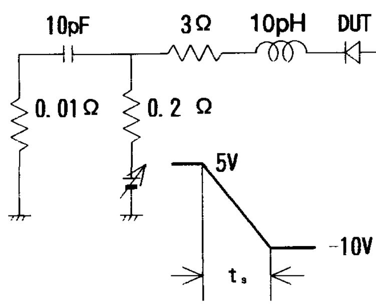

Fig. 8. Simulated system for transient analysis of SiC Schottky diodes.

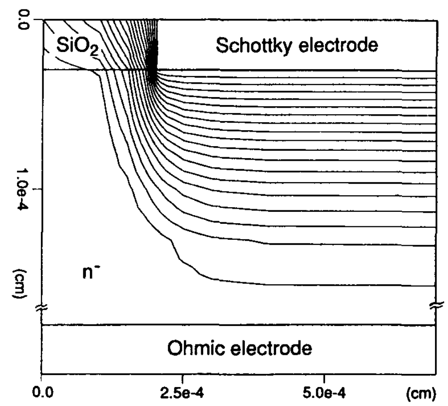

Fig. 10. Calculated potential distribution for plana Schottky electrode.

Table 1 Simulated results of Vb and Vf for four carrier concentrations.

Donor concentration (cm^{-3})	Vb (V)	Depletion width (μm)	Vf (Φ=1.1eV) (V)	Vf (Φ=0.83eV) (V)
2.0 e17	172	1	0.72	(0.45)
4.0 e16	570	4	0.78	(0.51)
6.0 e15	2400	22	1.28	(0.91)
2.5 e15	4600	47	3.35	(3.02)