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Letter

Electric-field dependence of electron drift velocity in 4H–SiC

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Room temperature isothermal forward current–voltage characteristics of mesa-epitaxial 4H–SiC Schottky diodes were measured at high electric fields (beyond 10^5 V/cm) in the 34-μm thick *n*-base doped at 1×10^{15} cm^{-3}. The effect of diode self-heating on current was minimized when using single 4-ns pulses. The analytical formula was derived for the dependence of electron drift velocity on electric field along *c*-axis.

1. Introduction

It is well known that drift velocity of carriers in semiconductors cannot be indefinitely increased with applied electric field. Carriers speed up in response to a stronger field until velocity saturation occurs, where higher fields do not result in any increase beyond the saturation drift velocity. The saturation velocity is one of the key material properties that determine device performance such as transistor's ultimate limit of speed of response and frequency.

Silicon carbide 4H polytype (4H–SiC) is widely considered as a promising wide bandgap semiconductor material for high-power and high-frequency applications [1]. The high-field transport properties of different SiC polytypes have been theoretically studied by Monte Carlo (MC) simulations (see, e.g., [2–4]). In [3], a full-band-ensemble MC simulation was used to study the high-field carrier transport properties of 4H–SiC. The peak velocities for electrons were 2.12×10^7 cm/s and 1.58×10^7 cm/s for electric fields in the directions perpendicular to, and along *c*-axis, respectively.

Experimental studies of high-field electron drift velocity in 4H–SiC were reported in a few papers [5–8]. The common approach used is that the dependence of current density (j) on electric field (E) is measured to derive the electric-field dependence of the carrier drift velocity $v(E)$: $v(E) = j(E)/qn$, where q is the elementary charge, n is the density of free electrons. When measuring current–voltage (I–V) characteristics of planar resistive elements, the maximum electron drift velocity in the direction perpendicular to *c*-axis was found to be 2.2×10^7 cm/s [5]. The estimate of the saturated electron velocity along *c*-axis (3.3×10^6 cm/s) was made when measuring I–V characteristics of 4H–SiC n^+–p–n^+-structures in the regime of unipolar injection of electrons into the *p*-base [7]. This value is much lower as compared to that obtained by MC simulations. In [8], reverse I–V characteristics of 4H–SiC p^+–n–n^+-diodes were measured in the avalanche breakdown regime. At very high average electric fields (above 1 MV/cm), the saturation velocity was found to be 8×10^6 cm/s. Thus, the experimental data vary between different reports. Moreover, they also differ from theoretical results. Therefore, additional experimental studies are necessary for more precisely determining the electron drift parameters.

In this study, isothermal forward I–V characteristics of mesa-epitaxial 4H–SiC small Schottky diodes with a low-doped (10^{15} cm^{-3}), 34-μm thick *n*-base were measured and analyzed in order to determine the electric-field dependence of the electron drift velocity along *c*-axis. High-field electron transport experiments were performed under conditions of well-controlled diode temperature: the effect of diode self-heating on current can be minimized when nanosecond-pulsed technique is used [6,9].

2. Schottky diode fabrication

The Schottky diodes were fabricated from commercial 4H–SiC epi-wafer purchased from Cree, Inc. The schematic cross-section of the diode is shown in the inset of Fig. 1. The supplier's

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specification for the epi-wafer is as follows: the resistivity of 360-μm n^+-substrate is 0.02 Ω cm; the nitrogen (donor) concentration of 34-μm thick blocking *n*-epilayer is 10^{15} cm^{-3}. Schottky contacts were formed by electron beam evaporation of 100-nm thick Ti film followed by the thermal annealing at 500 °C for 5 min. Magnetron sputtered, 500-nm thick, Ni film was deposited onto the Ti layer. The diameter of the Schottky contacts was 290 μm. To form ohmic contact on the back side of the wafer, 100-nm Ni film was deposited by magnetron sputtering followed by the thermal annealing at 950 °C for 15 min. Then the sintered Ni contact was covered by Ag layer. To prevent the lateral current spreading from the anode contact into the epilayer, the diodes were fabricated as mesa-structures by reactive ion etching in SF_6 plasma. The mesa's height is equal to the epilayer thickness. Thus the diode base was formed as a vertical, cylindrical shaped small resistor. After diode structures fabrication, the wafer was cut into separate 1 × 1 mm chips. To perform high voltage measurements the chips were mounted on a strip line (the Schottky contact and back metallizations were covered by soldering alloy for die-attach and wire bonding) and covered with silicone gel.

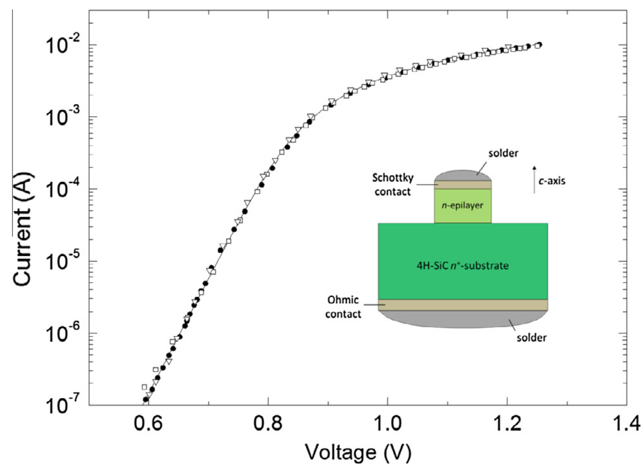

Fig. 1. DC forward *I–V* characteristics of three 4H–SiC Schottky diodes measured at low currents (symbols). Solid line is a fitting curve obtained with the use of Eq. (1). The inset shows schematic cross-section of the Schottky diode chip.

3. Experimental results and discussion

3.1. Low currents and voltages

Fig. 1 shows DC forward *I–V* characteristics of three 4H–SiC Schottky diodes measured at low currents ranging from 100 nA to 10 mA. As can be seen, there are no essential distinctions between these *I–V* characteristics. At currents ranging from 0.1 to 200 μA, the *I–V* characteristic has the form of a purely expotnential dependence of current *I* on voltage *V*. As the current increases further, differential resistance of the Schottky barrier becomes comparable with its series resistance (R_s) and the *I–V* characteristic departs from exponential behavior.

Solid line in Fig. 2 represents the *I–V* characteristic obtained by computer approximation of the experimental data in terms of thermionic emission model, with the effect of series resistance R_s taken into account:

$$I = I_o \exp\left(\frac{qV_b}{mkT}\right); \quad V = V_b + IR_s \tag{1}$$

where V_b is the voltage drop across the depleted layer of the Schottky contact, *k* is the Boltzmann constant, *T* is the temperature, and *m* is the ideality factor. The approximation yielded the following values of the fitting parameters: $I_o = 4 \times 10^{-17}$ A, *m* = 1.09, and R_s = 34 Ω.

The series resistance R_s constitutes the resistance of the *n*-base epilayer, substrate resistance, and resistance of the backside ohmic contact. The substrate spreading resistance was calculated to be about 0.3 Ω by using analytical formula given in [10]. The measured resistance of the backside ohmic contact is smaller than 0.1 Ω. It can be concluded that the measured series resistance is due to the epilayer resistance: $R_{epi} \approx R_s$ = 34 Ω. The resistance of the *n*-base epilayer is given by

$$R_{epi} = \frac{1}{qn\mu} \cdot \frac{d}{S} \tag{2}$$

where $n = N = 1 \times 10^{15}$ cm^{-3} is the electron concentration (the degree of ionization of nitrogen donors in low doped 4H–SiC ($\sim 10^{15}$ cm^{-3}) is close to 100% at room temperature [1]), $S = 6.6 \times 10^{-4}$ cm^2 is the diode area, *d* = 34 μm is the epilayer thickness, and μ is the low-field electron mobility. The extracted low-field electron mobility μ = 950 cm^2/(V s).

3.2. High currents and voltages

The *I–V* characteristics at higher voltages and currents were measured in very short single-pulse mode to prevent diode self-heating. A high-voltage pulse generator was used as the source of short pulses. The amplitude and duration of voltage pulses are 5 kV (with a 50-Ω load) and 4 ns, respectively. The electrical circuit for measuring the pulse *I–V* characteristics is shown in Fig. 2a.

The amplitude of input voltage pulses can be adjusted by an attenuator with variable attenuation coefficient. The time dependences of diode current and voltage were recorded with a 0–1 GHz bandwidth Tektronix DPO 4104 multichannel digital oscilloscope. The following equations were used to calculate the diode voltage and current:

$$U[V] = \{(100 \times U_A[V])/50\} \times 550 - 100 \times U_B[V]; \quad I[A] = (100 \times U_B[V])/50 \tag{3}$$

where U_A and U_B are the signals measured at 50-Ω oscilloscope channels A and B, respectively. The diode current and voltage oscillograms obtained in the single-pulse mode at the maximum amplitude of the input voltage pulse are shown in Fig. 2b. The *I–V* characteristic was plotted on the basis of measured amplitudes of current and voltage pulses (Fig. 3a). To control the accuracy of the pulse measurements, *I–V* characteristic of a resistor with a priori known resistance (406 Ω) was measured (Fig. 3b). The measured resistance is 399 Ω. So, the precision of pulse measurements is about 1.5%.

It is important to ascertain that the measured *I–V* characteristic is isothermal one. At 1300-V voltage and 3.6-A current (Fig. 2b), the peak power is *P* = 4.7 kW. The maximum *n*-base overheating can be estimated if we assume that the full electrical power is transformed into Joule heat in the *n*-base without heat exchange:

$$\Delta T < \frac{P\Delta t}{CdS\rho} \tag{4}$$

where Δt is the pulse duration, and *C* = 0.69 J/g K and ρ = 3.21 g/cm^3 are, respectively, the heat capacity and density of 4H–SiC [11]. At Δt = 4 ns and *P* = 4.7 kW, the overheating is ΔT < 3.8 K. Thus, even at the maximum voltage and current amplitudes, the self-heating is negligible and the measured pulse *I–V* characteristic (Fig. 3a) is isothermal.

The characteristic is nonlinear, but the current is not completely saturated. The absence of current saturation is explained by that