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Current-voltage characteristics of Cr/SiC(4H) Schottky diodes

A.M. Strel'chuk ✉, E.V. Kalinina
Ioffe Institute, St. Petersburg, Russia
✉ anatoly.strelchuk@mail.ioffe.ru

Abstract. Forward and reverse current-voltage characteristics (*I–V*) of Cr/SiC(4H) Schottky diodes (SDs) manufactured using the same technology based on a single weakly-doped (~ $4\cdot10^{14}$ cm^{-3}) epilayer are investigated. SDs are close to ideal, but a significant spread of *I–V* and excess current which sometimes unstable were found, unrelated to the difference in the area of the SDs. Investigation in the temperature range 20–210 °C revealed the annealing effect and allowed to estimate the potential barrier height of different diodes before and after annealing. It is suggested that the main diode is shunted by a parasitic diode, which determines forward *I–V* in the region of *I–V* exponential dependence.

Keywords: SiC, Schottky diodes, current-voltage characteristics, spread, defects

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Вольт-амперные характеристики Cr/SiC(4H) диодов Шоттки

А.М. Стрельчук ✉, Е.В. Калинина
Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия
✉ anatoly.strelchuk@mail.ioffe.ru

Аннотация. Исследованы прямые и обратные вольт-амперные характеристики (*I–V*) Cr-SiC(4H) диодов Шоттки (SDs), изготовленных по одной и той же технологии на основе одного слаболегированного (~ $4\cdot10^{14}$ см$^{-3}$) эпислоя. SDs близки идеальным, но был обнаружен значительный разброс *I–V* и избыточный ток, который иногда нестабилен, не связанный с разницей в площади SDs. Исследование в диапазоне температур 20–210 °C выявило эффект отжига и позволило оценить высоту потенциального барьера различных диодов до и после отжига. Предполагается, что основной диод во всех случаях шунтируется паразитным диодом, который определяет прямые *I–V* в области экспоненциальной зависимости тока от напряжения.

Ключевые слова: SiC, диоды Шоттки, вольт-амперные характеристики, разброс, дефекты

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Introduction

The study of semiconductor SiC began, apparently, just with the description of the properties of Schottky diodes (SDs) (letter to the editors in 1907 [1] and a series of studies starting in 1923 [2]). Studies of metal-semiconductor contact are summarized, for example, in [3]. The most widely used method for determining Schottky barrier height φ_b has long been the study of capacitance-voltage characteristics (CVs; for SiC SDs see, for example, the review in [4]) and some regularities of the change in φ_b were established when the metal in contact with SiC varied [4]. An attempt to conduct a similar experiment using current-voltage characteristics (*I*–*V*) to determine φ_b showed that in many cases the current *I* in a significant range of small currents depends on the voltage *U* exponentially $I = I_0\exp(qU/(nkT))$ (n is the ideality coefficient), at high currents the dependence becomes linear, but, at the same time along with other effects, there is a significant spread of *I*–*V* of completely identical SDs (manufactured under absolutely identical conditions on the same SiC monocrystal) (E-MRS 1996, [5]). For diodes characterized by approximately the same value of n, the effect is expressed in a parallel shift of the *I*–*V* in the region of exponential *I*–*V* dependence. With the n close to 1, the shift of the *I*–*V* of different SDs is probably caused by a different value of φ_b (assuming the same area). In [5], strongly doped 6H-SiC Lely monocrystals and epilayers were studied (uncompensated donors concentration (doping level) was N_d-N_a ~ (0.6–3)·10^{18} cm^{-3}). The improvement of the technology allowed to reduce the doping level of SiC. A study of the *I*–*V* of SDs based on 4H-SiC epilayers with N_d-N_a ~ 3·10^{15} cm^{-3} revealed similar effects [6, 7]. This work continues the research [6, 7] with the use of an even weaker doped 4H-SiC; in addition, compared with [7], the number of small-area SDs studied has been increased.

Materials and Methods

All SDs are made on the basis of one commercial 4H-SiC epitaxial layer N339 with N_d-$N_a \approx 4\cdot10^{14}$ cm^{-3} and with a thickness of 5 μm, grown on a substrate with N_d-$N_a \gg 10^{18}$ cm^{-3}. The Cr films for Schottky contact (with Cr thickness of 0.1 μm) and Cr/Al films for ohmic contact to substrate were deposited by thermal evaporation in a vacuum at a substrate temperature close to room temperature (RT) (before metal deposition, the same standard chemical treatment in acetone, toluene and hydrofluoric acid was carried out). The diameter of the SDs was in range 0.2–8 mm. Annealing of diodes was performed in air for 1–3 hours in increments from 20° to 40°, starting from a temperature of 60 °C to 210 °C. After each annealing, the diodes were cooled to RT. *I*–*V* were measured in DC mode at RT before annealing, at all annealing temperatures (first heating), at RT after each annealing (annealed diodes) as well as (after annealing at highest temperature 210 °C) the characterization of the SDs was carried out again with monotonous reheating in the same temperature range (second heating). The *I*–*V* were measured with a KEITHLEY 6485 picoammeter using a clamped contact and a tungsten probe.

Results and Discussion

Figure 1, *a* shows at RT the forward *I*–*V* of SDs of different areas on one epilayer. In the region of exponential I(V) dependence almost all *I*–*V* are characterized by *n* close to 1 (mostly $n \approx 1.1$ with the exception of curve 1, for which $n \approx 1.25$). However, the spread of *I*–*V* is very large, even for diodes of the same area (see curves 5–7). Reducing the *I*–*V* to the unit of area (of the Cr-SiC contact area) does not solve the problem: the spread of *J*–*V* at the same current density *J* reaches 0.6 V (Fig. 1, *b*). The number of the investigated SDs of different diameters, shown in Figure 1, *a*, *b*, is relatively small. In order to increase the reliability of the conclusions, SDs were manufactured in an amount of more than 70 pieces with a SD diameter *D* of 0.3 mm. Almost all forward *I*–*V* of these diodes in the low-current region are exponential and are characterized by *n* = 1.05–1.1, but the spread of *I*–*V* at the same current reaches 0.3 V (Fig. 1, *c*). For comparability of these results with the results presented in [5], we present a histogram of the SDs voltage drop distribution at a forward current of 1 μA, however, for some SDs at a current of 1 μA, a deviation from the exponential *I*–*V* dependence is already noticeable (Fig. 1, *c*). Therefore, we also present a histogram at a forward current of 1 nA (Fig. 1, *d*). An estimate of *n* of an artificial *I*–*V* constructed from the coordinates of the maxima of the distribution gives a value of $n \approx 1.25$, which reflects the mentioned deviation at a 'large' current (1 μA), which also manifests itself in a certain broadening of the distribution. Since n is close to 1, the spread of the $I-V$ apparently reflects mainly the spread of the φ_b, however, the temperature dependence of the forward and reverse currents gives more definite information about the φ_b ([3]).

For temperature measurements, 6 SDs were selected, characterizing both the edges and the center of the distributions (Fig. 1, *d*). Figures 2, *a*, *b*, *c* show the temperature dependences of the forward and reverse $I-V$, as well as the effect of annealing on the forward $I-V$ for SD N5 on the right edge of the distribution (Fig. 1, *c*, *d*) and also shows (Fig. 2, *d*) the temperature dependences of the parameters I_0, n, I_{rev}(10 V) at U_{rev} = 10 V for SD N5, as well as for SD N1 on the left edge of the distribution (Fig. 1, *c*, *d*). The situation is complicated by the fact that in some cases, with an increase in the number of measurements of the $I-V$ of one diode, a kind of 'bistability' of the $I-V$ position is observed. An example is shown in Figure 2, a for SD N5, for which out of 10 measurements, in 8 cases, the $I-V$ represented by curve 0a was observed, and in 2 cases – by curve 0b. In both cases, there are significant areas of exponential $I(V)$ dependence and n close to unity (n = 1.05–1.1). The reverse current start to be registered at elevated temperatures, it is characterized by power-law dependences on the voltage $I \sim U^m$ with an exponent m close to 0.25 (Fig. 2, *c*), characteristic of high-quality diodes [3]; the value of reverse current and it activation energy at high temperatures correlates with the corresponding characteristics of the parameter I_0 of the forward current. The current represented by the curve 0b (Fig. 2, *a*) can be considered as excess in relation to the current represented by the curve 0a ('main' diode), and caused by a barrier-type shunt. Thus, there is no complete certainty whether the $I-V$ at elevated temperatures and after annealing characterize the 'main' diode, shunt, or both diodes together. Nevertheless, the general trend for all 6 SDs investigated at RT–210 °C temperatures range is that annealing leads to a decrease in the 'initial' activation energy (which reaches ~ 1.7 eV before annealing, and stabilizes at ~ 1 eV after annealing (for example, $E_a \approx 1.7$ eV for SD N5 and ≈ 1.1 eV for SD N1

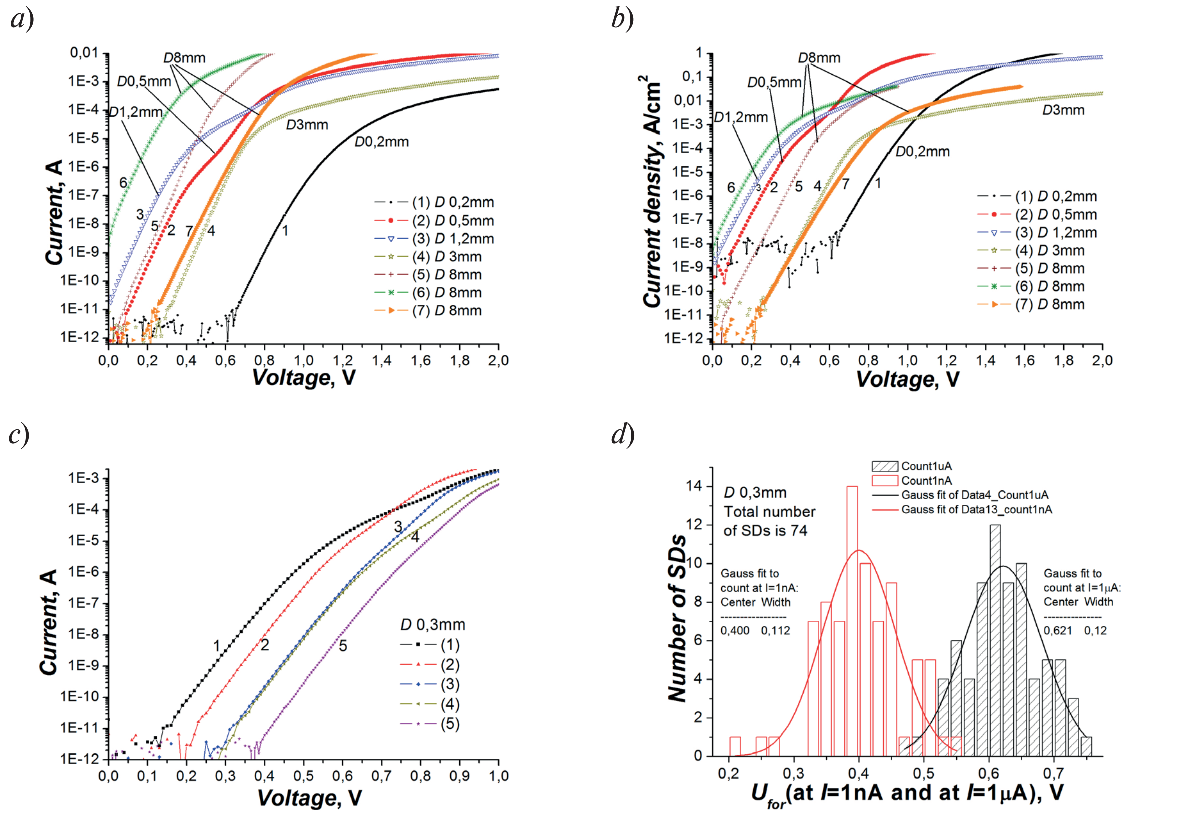

Fig. 1. Forward current-voltage (*a*, *c*) and current density-voltage (*b*) characteristics at RT of 7 SDs (curves 1–7) of different diameters D in the range 0,2–8 mm (*a*, *b*) and of 5 different SDs (curves 1–5) of D = 0,3 mm (*c*) and also the forward voltage drop (at 1 nA and 1 μA forward currents) histograms for SDs of D = 0.3 mm (*d*). The results of the first measurement of the $I-V$ are presented

before annealing, and $E_a \approx 1.04$ eV for SD N5 and ≈ 0.88 eV for SD N1 after annealing (Fig. 2, *d*)). The activation energy of forward and reverse currents of ideal SDs roughly corresponds to the metal- semiconductor contact barrier height φ_b [3]. Thus, the φ_b of different Cr-SiC (4H) SDs manufactured under the same conditions on the same epitaxial layer can vary greatly and decrease in some cases even with low-temperature annealing (see also [6, 7]).

Thus, when studying the *I*—*V* characteristics of SDs manufactured by the same method based on a single 4H-SiC epitaxial layer with an doping level of N_d-$N_a \approx 4 \cdot 10^{14}$ cm^{-3}, it was found that:

A) For some diodes, the *I*—*V* curve is exponential at low currents and turning into a power-law (approaching linear) at high currents, while there is a significant spread of *I*—*V* of identical SDs regardless of the metal-semiconductor contact area (Fig. 1, *a*, *b*, curves 1, 4—7). This is an effect similar to that previously observed in diodes based on more strongly doped SiC ($3 \cdot 10^{15}$ cm^{-3}— $3 \cdot 10^{18}$ cm^{-3}) [5—7] (see Introduction). This effect of the spread of *I*—*V* will be called the N1 effect ('spread' or 'shift').

B) For the other part of the SDs (Fig. 1, *a*, *b*, curves 2, 3 and Fig. 1, *c*, curves 1, 3, 4), the dependence of current on voltage, in contrast to the one described above, in addition to the exponential section, is characterized by the presence of a more or less pronounced additional power section and an inflection point, which is a characteristic sign of excess current and the presence of barrier-type shunts. In this case, when the current increases, before the inflection point, the current is mostly excess (through the shunt), and after the inflection point it is mostly the current of the main diode.

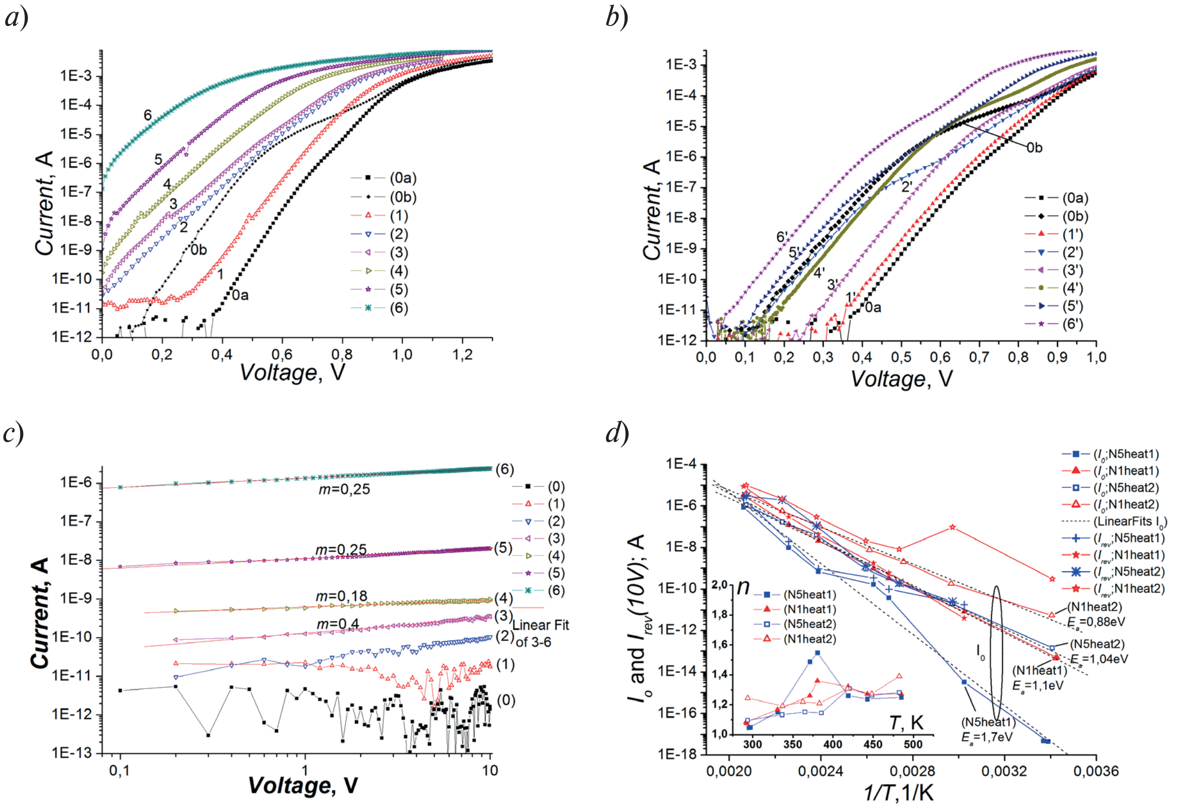

Fig. 2. Forward (*a*) and reverse (*c*) *I*—*V* of the SD N5 at temperatures: RT = 289—295 K (curves 0), 331 K (curves 1), 371 K (curves 2), 380 K (curves 3), 419 K (curves 4), 443 K (curves 5), 485 K (curves 6); *m* is an exponent of power-law dependence of reverse current versus voltage. Forward *I*—*V* (*b*) at RT = 289—296 K (curves 1'—6') of the annealed SD N5 after cooling from the corresponding elevated temperatures (1—6). Curves 0a and 0b in Fig. 2, *a*, *b*, show results of two measurements of the *I*—*V* of the SD N5 at RT before heating. Temperature dependencies (*d*) of the parameters I_0 and *n* (inset) of the forward *I*—*V* and reverse current I_{rev}(10 V) of the SDs N5 and N1 during first heating (heat1) and second heating (heat2). SDs diameter is 0.3 mm

The position of the inflection point along the axis of currents characterizes the shunt resistance; it different for different diodes and can be quite high. Apparently for the first time in SiC-based diodes, barrier-type shunts identified by forward *I–V* are described in 6H-SiC p-n structures (E-MRS 1996, [8]). The characteristic size of the shunt (~ 1μm) was estimated by the magnitude of the shunt series resistance, taking into account the spreading effect in the substrate [9], and the potential barrier height of the barrier-type shunt (~ (1–1.3) eV) was estimated by the temperature dependence of the current exponentially dependent on voltage. The presence of such excess forward current will be called the N2 effect (‘shunt’). Later, similar effect was observed in 3C-SiC [10] and 4H-SiC [11–15] pn structures, as well as in SDs based on 4H-SiC [16–22] and 6H-SiC [23, 24].

C) For some SDs (Fig. 2, *a*, curves 0a, 0b), a ‘bistable’ state of the forward *I–V* is observed in the region of exponential *I*(*V*) dependence, when the current in the second stable state (curve 0b in Fig. 2, *a*) is excess at relatively small currents (up to the inflection point), and at high current it is equal to the current through the same diode in the first stable state (curve 0a in Fig. 2, *a*). Such an excess current is a characteristic feature of a barrier-type shunt, i.e. a parasitic diode connected in parallel to the main diode (with *n* close to 1 in both cases). Previously, similar effects of instability were observed in 4H-SiC pn structures [13, 14], as well as in SDs based on 4H-SiC [25, 22]. The presence of unstable excess forward current will be called the N3 effect (‘instability').

In addition, previously, the effects of:

D) the appearance of excess current and a barrier-type shunt in 6H-SiC [8] and 4H-SiC [11, 12] p-n structures as a result of partial degradation of the diode when operating under extreme conditions (when applying a relatively large reverse voltage and/or when operating at elevated temperatures), the N4 effect (‘diode degradation');

E) a variation in the series resistance of the SDs, reaching 12 orders of magnitude, as a result of He^{+}-irradiation and fully compensation of epilayer in 4H-SiC SDs with shunts [22], the N5 effect (‘resistance spread’); and

F) a suppression (and then recovery after annealing) of the forward and reverse excess currents after electron and proton irradiation for 6H-SiC pn structures with shunts [26], the N6(7) effect (‘shunt degradation’ (‘shunt restoration’)) were found.

Interpretation of the effect N1 (‘spread’) is generally difficult due to the likely manifestation of several effects at once, however, in the particular case of SDs close to ideal (*n* is close to 1), the most likely explanation of the effect N1 is the spread of the φ_b (assuming the same area). When explaining the effect of N2 (‘shunt’) in p-n structures, we consistently moved from the hypothesis of the inclusion of the second phase (3C-SiC, Si) to the hypothesis of a shunt in the form of a parasitic Schottky diode formed due to ‘hole’-type structural defects [8, 10–14] (pits, open core dislocations, see also [16–18]) with the possible participation of carbon as a metal substitute in the formation of the Schottky barrier (it is well-known that the nonstoichiometric sublimation of SiC leads to graphitization of the SiC surface, is currently used to form graphene on the SiC surface and can form a Schottky barrier [27]; by the way the shunting of the SiC pn junction with a carbon particle was proposed already in [28]). The estimate of the barrier height of a parasitic diode in 6H- and 4H-SiC pn structures (1.3–1.4 eV [8, 11]) is close to the typical barrier height of Schottky diodes based on SiC (1–1.5 eV). The effects of N3 (‘instability’), N4 (‘diode degradation’) and N6 (‘shunt degradation’) in pn structures, as well as the effects of N2 (‘shunt’), N3 (‘instability’) and N5 (‘resistance spread’) in SDs, it seems to us, closely tied and also can be explained by the hypothesis of a parasitic Schottky diode, considering the conductivity as percolation through carbon-coated surfaces of penetrating structural defects in the form of ‘holes’ of small cross-section and/or complex shape. Moreover, the results of present study, as well as [5, 12, 13], allow to assume that the effect of N1 (‘spread’) differs from the effect of N2 (‘shunt’) only by the ‘power’ of the shunt (first of all, by the defect area, as well as by the value of φ_b). Thus, in our opinion, all 6 effects in SiC-based diodes (both in SDs and p-n structures) are related and can be explained from a single position. This is difficult to do with the help of the models [29–31], which are usually used to explain the appearance of excess currents in Schottky diodes (in these models a potential relief on the surface of the semiconductor is considered, which leads to a spread in the Schottky barrier height). In addition, according to [29–31], the φ_b spread decreases when using a weaker doped semiconductor, which is not confirmed by our observations in case of SiC-based SDs. In *CV* measurements, in the presence of a barrier-type shunt, the main diode of a large area will most likely dominate and also, considering the spread of the φ_b determined by *CV* [4], it is necessary to take into account the methodological complexity of the exact determination of φ_b associated with the need to use a highly-uniform doped semiconductor.

Conclusion

The study of forward and reverse *I—V* of Cr-SiC SDs based on weakly doped (~$4\cdot10^{14}$ cm^{-3}) 4H-SiC showed that SDs are close to ideal, however, there is a spread of *I—V*, not related to the difference in the area of the diodes (of the Cr-SiC contact area). There are also specific excess currents, sometimes unstable. Even a slight heating leads to an irreversible change in the properties of the SDs. It is suggested that the main Schottky diode is shunted in all cases by a parasitic diode, which manifests itself in forward *I—V* in the region of exponential current on voltage dependence.

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THE AUTHORS

STREL'CHUK Anatoly M.
anatoly.strelchuk@mail.ioffe.ru
ORCID: 0000-0001-5321-0237

KALININA Evgenia V.
evk@mail.ioffe.ru

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