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Irradiation with argon ions of Schottky diodes based on $4H$-SiC

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The effect of irradiation with argon ions with an energy of 53 MeV in the dose range $(1-7)\cdot 10^{10}\,\mathrm{cm}^{-2}$ on the current-voltage characteristics of Cr/SiC($4H$) Schottky diodes with an epitaxial layer doping level of $\sim 10^{14}-3\cdot 10^{15}\,\mathrm{cm}^{-3}$ has been studied. In the characteristics of diodes both before and after irradiation, effects have been discovered and discussed that make it difficult to interpret the results, assess the radiation resistance of diodes and confirm the influence of epitaxial layer defects on the characteristics of diodes. An upper estimate of the threshold dose D_{th} ($\sim 6\cdot 10^{9}\,\mathrm{cm}^{-2}$) irradiation with Ar^{8+} ions with an energy of 53 MeV is given.

Keywords: SiC, Schottky diode, Ar^{8+} irradiation, IV characteristics, shunts, defects.

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1. Introduction

It is known that many types of semiconductor devices can be created based on SiC. In addition, semiconductor SiC was considered as a promising material for operation under irradiation conditions in early studies. Most efficient devices require moderately or slightly doped SiC ($(N_d-N_a)\sim 10^{14}-10^{16}\,\mathrm{cm}^{-3}$), which has been available since the second half of the 1990s. Then it was found that the forward IV characteristics of the diode is the most sensitive to radiation [1]. The series resistance (R_s) of the diode can be selected as a parameter reflecting radiation resistance. This resistance practically does not change up to a certain threshold radiation dose D_{th}, and when D_{th} is exceeded, it increases sharply by 10 or more orders of magnitude approximately in accordance with the power dependence $R_s\sim D^m$ with the exponent $m\sim(7-15)$ (see [2] and references in it). Threshold doses for certain types of radiation were determined. For example, in case of irradiation of SiC with a doping level of $\sim 5\cdot 10^{15}\,\mathrm{cm}^{-3}$ with electrons with an energy of 0.9 MeV $D_{\mathrm{th}}\sim 1.5\cdot 10^{16}\,\mathrm{cm}^{-2}$, and with protons with an energy of 15 MeV $D_{\mathrm{th}}\sim 5\cdot 10^{13}\,\mathrm{cm}^{-2}$. Irradiation with heavier ions is also of interest, in particular in paper [3] (see [3] and references in it), UV detectors based on SiC were studied when irradiated with argon ions. This paper presents a study of the IV characteristics (IVs) of Schottky diodes Cr/SiC($4H$) irradiated with argon ions.

2. Objects and methods of research

Schottky diodes were formed on the basis of two commercial epitaxial layers of $4H$-SiC: 1) N585, thickness 5 μm with a concentration of uncompensated donors $N_d-N_a=1\cdot 10^{14}\,\mathrm{cm}^{-3}$ — four diodes (#1, 12, 20, 33) and 2) #729-15, thickness of 9 μm with $N_d-N_a=3\cdot 10^{15}\,\mathrm{cm}^{-3}$ — one diode N26. The layers were grown by gas phase epitaxy on n^+-$4H$-SiC substrates with $N_d-N_a>10^{18}\,\mathrm{cm}^{-3}$. The ohmic Cr/Al contact to the substrate and the barrier Cr contact to the epitaxial layer (thickness Cr <0.1 mm) were created by thermal sputtering in vacuum (see [3] and references therein). The diameter of the Schottky diodes was 8 mm. The diodes were irradiated at a temperature of 25°C by Ar^{8+} ions with an energy of 53 MeV dose/fluence $(1-7)\cdot 10^{10}\,\mathrm{cm}^{-2}$ on a cyclotron of the Ioffe Institute of Physics and Technology. The terms dose and fluence are equally applicable in this paper, since the irradiation is carried out with a beam perpendicular to the target and with the specified energy. This article uses the term dose. The dose was determined by the total charge of the argon ion beam applied to the irradiated target; uniformity of the density of defects on the sample surface was ensured at least 7%. The first irradiation of 4 diodes on the N585 layer was carried out with 4 different doses: $D1=1\cdot 10^{10}\,\mathrm{cm}^{-2}$ (#20), $D2=2\cdot 10^{10}\,\mathrm{cm}^{-2}$ (#12), $D3=3\cdot 10^{10}\,\mathrm{cm}^{-2}$ (#1), $D5=5\cdot 10^{10}\,\mathrm{cm}^{-2}$ (#33); then all 4 diodes were additionally irradiated with a dose of $D1=1\cdot 10^{10}\,\mathrm{cm}^{-2}$. One diode #26 on the layer #729-15 was successively irradiated 4 times with a total dose: $D1=1\cdot 10^{10}\,\mathrm{cm}^{-2}$, $D5=5\cdot 10^{10}\,\mathrm{cm}^{-2}$, $D6=6\cdot 10^{10}\,\mathrm{cm}^{-2}$ and $D7=7\cdot 10^{10}\,\mathrm{cm}^{-2}$. IV$s$ was measured before irradiation ($D0$) and after each irradiation at room temperature using a pressure probe with Keithley 6485 picoammeter in the current range of $10^{-12}-2\cdot 10^{-2}$ A. The series differential resistance R_s in the initial and irradiated diodes was determined at room temperature from IVs with a forward bias and (unless otherwise specified) maximum measured currents (10–20 mA) or voltages (10 V).

3. Results and discussion

Prior to irradiation with forward bias diodes on the epitaxial layer #585 are characterized by an exponential (up to the area of influence of R_s diode) dependence of current on voltage $I = I_0 \exp(qV/nkT)$, with an ideality coefficient of $n = 1.1-1.5$ (Figure 1, *a*). IVs with one exception are noticeably shifted relative to each other (up to 0.2 V in voltage or up to 3 orders of magnitude in current). All diodes before irradiation are within 20–30 ohms with relatively high currents R_s. In this area of currents, IVs are also noticeably shifted relative to each other, while the nature of the shift does not correspond to (and even opposes) the nature of the shift at low currents (Figure 1, *a*, see box). The current-voltage dependence at low currents remains close to exponential as a result of irradiation, n after irradiation is $n = 2.4-3$, IVs are shifted towards high voltages (Figure 1, *b*). Irradiation also leads to an increase of R_s of diodes, however, the nature of the dependence of R_s on the radiation dose is not monotonous (Figure 1, *b*, see insert). R_s has the largest magnitude ($\sim 3 \cdot 10^4$ ohms) after the minimum radiation dose ($D1$) and, for example, is one hundred times higher than R_s ($\sim 3.6 \cdot 10^2$ ohms) at a dose of $D3$. Repeated irradiation with a dose of $D1$ of diodes #20, 12 and 33 on the layer #585 (initially irradiated with doses of $D1$, D2 and $D5$) has practically no effect on the value of R_s of these diodes, and diode #1 (initially irradiated with a dose of $D3$) increased from $R_s \sim 3.6 \cdot 10^2$ ohms to $R_s \sim 1.5 \cdot 10^4$ ohms.

The values R_s shown above are calculated from the results of the first (test, with a relatively large voltage step) or second (with a small step) measurements of IVs with forward bias of the diode. In practice, the number of measurements of IVs turns out to be significantly large. So, in addition to measurements with forward bias, all diodes are characterized with reverse bias, and with varying values of the maximum reverse voltage. In addition, it is of interest to study IVs both with forward and reverse displacement when illuminated by various light sources, in some cases it is desirable to control IVs depending on the clamping force of the probe or the location of the probe on the metal surface, etc. Thus, the total number of measurements of IVs of one diode can reach 10–20 and more measurements. IVs are well reproduced in some cases, but not always. For example, the current during the measurement began to sharply decrease when measuring the IVs of diode #1 (irradiated with a dose of $D3 + D1$) with a reverse bias of about 80 V. Repeated measurement of the reverse IV characteristic showed that, for example, the current decreased from 1 mA to 1.5 nA at a reverse voltage of 30 V. Measurement of forward IVs after this showed that the characteristic changed little at low voltages, the current decreased at high voltages and R_s increased from $R_s \sim 1.5 \cdot 10^4$ ohms (see above) up to $R_s \sim 3 \cdot 10^6$ ohms at 10 V. Another example of this kind is shown in Figure 2, *a* for the diode N33, initially irradiated with a dose of $D5$ and then re-irradiated with a dose of $D1$, i.e., it received a total dose of $D6$ ($D6 = 6 \cdot 10^{10}\,\mathrm{cm}^{-2}$). Five consecutive measurements of the forward IV characteristic $D6(1-5)$ (and six measurements of the reverse IV characteristic before -10 V) were reproducible (and, in

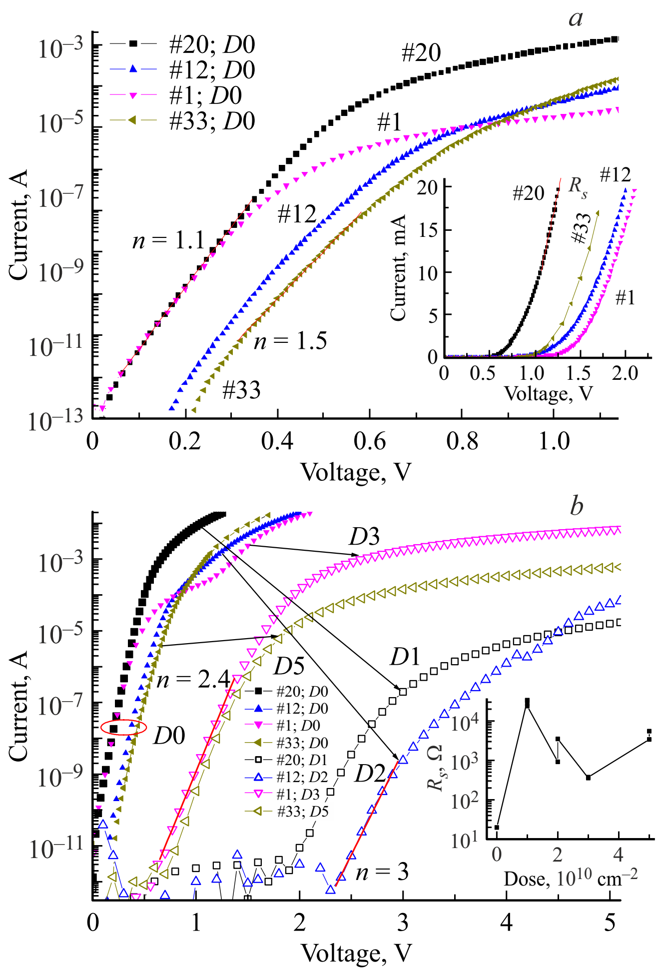

Figure 1. Forward IV characteristics of 4 Schottky diodes (#1, 12, 20, 33) on the #585 layer before irradiation ($D0$) (*a*) and after irradiation by Ar^{8+} with doses of $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$ ($D1$), $2 \cdot 10^{10}\,\mathrm{cm}^{-2}$ ($D2$), $3 \cdot 10^{10}\,\mathrm{cm}^{-2}$ ($D3$), $5 \cdot 10^{10}\,\mathrm{cm}^{-2}$ ($D5$) (*b*). Inserts shows IV characteristics on a linear scale (*a*), the dependence of the series resistance R_s on the radiation dose (*b*). (The colored version of the figure is available on-line).

particular, showed that R_s does not change after irradiation with $D5$ and $D6$), however, the sixth measurement of the forward IV characteristics ($D6(6)$) showed that the characteristic not only changed at low voltages (up to 4 V), but also changed forwardly during the sixth measurement at voltages of 8–10 V (marked with (X): the forward current decreased by ~ 4 order in several stages). Subsequent measurements of forward IV characteristics (seventh measurement $D6(7)$ and tenth measurement $D6(10)$) showed that the characteristic relatively stabilized and the value R_s amounted to $\sim 10^8$ ohms.

Irradiation of a diode #26 formed on the surface of a highly doped epitaxial layer #729-15, showed that irradiation leads to a monotonous increase of R_s from 4 ohms before irradiation ($D0$) to ~ 600 ohms after the first radiation dose ($D1$) and then up to $\sim 10^9-5 \cdot 10^{10}$ ohms at high radiation doses (Figure 2, *b*). The dependence of R_s

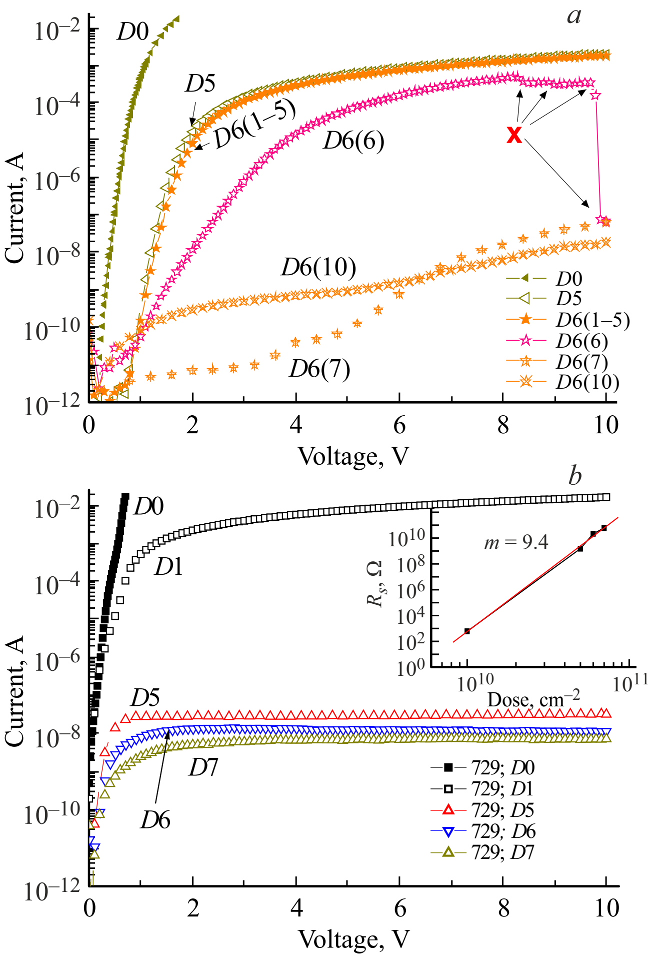

Figure 2. Forward IV characteristics of the Schottky diode (#33) on the #585 layer before irradiation ($D0$) and after irradiation by Ar^{8+} with doses of $5 \cdot 10^{10}\,cm^{-2}$ ($D5$) and $6 \cdot 10^{10}\,cm^{-2}$ ($D6$) (measurement numbers are indicated in brackets; the (X) indicates the voltages at which instability with an irreversible decrease in current was observed) (a) and Schottky diode (#26) on layer #72915 before irradiation ($D0$) and after irradiation by Ar^{8+} with doses of $1 \cdot 10^{10}\,cm^{-2}$ ($D1$), $5 \cdot 10^{10}\,cm^{-2}$ ($D5$), $6 \cdot 10^{10}\,cm^{-2}$ ($D6$) and $7 \cdot 10^{10}\,cm^{-2}$ ($D7$) (b). The insert b shows the dependence of the series resistance R_s of diode #72915-26 on the radiation dose.

on the dose can be represented as a power-law dependence $R_s \sim D^m$ with an exponent of $m \sim 9-10$ (Figure 2, b, see insert). It should be noted that in some cases, the forward IV characteristic exhibits a more or less pronounced N-shapedness (Figure 2, b, curve $D6$; in this case, the diode resistance was determined not as differential but by dividing the voltage by current at 10 V).

The effects observed in diodes before irradiation at low currents are similar to the effects that were apparently first presented in 1996 in two papers, namely: 1 — spread of IVs of identical Schottky diodes and 2 — shunt of the main diode with a parasitic one (see [4] and references therein). Later, parasitic shunting of the main diode was also observed in Ref. [5–9] (see also references in Ref. [4]). Both of these effects are observed in this paper (effects 1 and 2 according to classification [4]), as well as the transition of 1 effect to 2, taking into account the data at high currents (Figure 1, a). IVs almost did not change at low currents in the region of the exponential dependence of current on voltage both in $p-n$-structures [1] and in Schottky diodes [2] (see also [10–14]), unlike the effects observed in diodes based on layer #585 in this paper. This fact, as well as the spread (instead of monotonous growth) of R_s of identical diodes on layer #585 after irradiation (the effect 4 in Ref. [4]) indicate the manifestation of semiconductor defects in IVs diodes (see Ref. [2,4]). The instability of IVs found in this paper (see effect 3 in Ref. [4]) is probably caused by partial degradation of parasitic diodes shunting the main diode. R_s increases monotonously starting from the dose of $\sim 6 \cdot 10^9\,cm^{-2}$ in a diode based on a highly doped layer #72915. It should be noted that the series resistance has a value of $R_s \sim 10^{12}$ ohms in diodes on layer #585 for diodes #20 and 12 after irradiation with even minimal doses of $D1$ and $D2$, if we evaluate R_s not at 10 V, but at $U < 2$ V, i.e., before the appearance of excess currents, apparently caused by defects (Figure 1, b).

Thus, the dose of $\sim 6 \cdot 10^9\,cm^{-2}$ in this experiment can be taken as an upper estimate of the threshold dose of irradiation D_{th} of SiC-based Schottky diodes with a doping level of $\sim 10^{14}-10^{15}\,cm^{-3}$ by Ar^{8+} ions with an energy of 53 MeV.

4. Conclusion

A study of the IV characteristics of Schottky diodes Cr/SiC(4H) with a diameter of 8 mm with the level of doping of the epitaxial layer $\sim 10^{14}-3 \cdot 10^{15}\,cm^{-3}$ and the effect of irradiation with argon ions with an energy of 53 MeV revealed a significant spread of IVs of the diodes both before and after irradiation which is probably caused by defects in the epitaxial layer, which makes it difficult to interpret the results and assess the radiation resistance of the diodes. An upper estimate of the threshold radiation dose of irradiation D_{th} ($\sim 6 \cdot 10^9\,cm^{-2}$) by Ar^{8+} ions with an energy of 53 MeV is given.

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Conflict of interest

The authors declare that they have no conflict of interest.

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