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Low-temperature luminescence study of the formation of radiation defects in $4H$-SiC Schottky diodes

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The effect of electron and proton irradiation temperature on the formation of radiation defects in $4H$-SiC Schottky diodes was studied using low-temperature photoluminescence spectroscopy. It has been established that the temperature at which irradiation is carried out significantly affects the formation of radiation defects in the base layer of n-$4H$-SiC diodes. This observation is in good agreement with the results of changes in the electrical properties of the same samples under the influence of proton and electron irradiation.

Keywords: $4H$-SiC Schottky diode, proton irradiation, electron irradiation, photoluminescence, electrical properties.

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The effect of irradiation on the properties of semiconductors and semiconductor devices is important both from an applied point of view and from the point of view of studying fundamental physical processes of defect formation. Previously papers [1,2] studied the effect of electron and proton irradiation temperature at formation of radiation-induced defects in n-$4H$-SiC. These studies used such methods as non-stationary capacitance spectroscopy, measurements of current-voltage and capacity-voltage characteristics etc. Such studies make it possible to conclude on the characteristics of the defects introduced as a result of irradiation from the measurement of integral parameters in the studied objects. Micro-photoluminescent (μ-PL) studies are the effective method to analyze the local structure of the radiation-induced defects introduced into $4H$-SiC. The objective of this paper was to obtain new information using low-temperature μ-PL in the spectrum of defects generated in $4H$-SiC Schottky barrier diodes and created by high-energy protons and electrons in the wide range of the irradiation temperatures.

$4H$-SiC Schottky barrier diodes JBSCPW3-1700-S010B were studied with a blocking voltage of 1700 V, initial concentration of electrons in the base $n_0 \approx 3.4 \cdot 10^{15}\,\mathrm{cm}^{-3}$ and the thickness of the base of $W \approx 20$ mkm. The specimens were irradiated with protons of 15 MeV energy with dose of $1.0 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at four temperatures: 23, 150, 300 and 500°C on an isochronous cyclotron MGTs-20 and electrons with energy of 0.9 MeV with dose of $1.3 \cdot 10^{17}\,\mathrm{cm}^{-2}$ at three temperatures: 23, 100 and 200°C on electron accelerator RTE-1V in the Peter the Great St. Petersburg Polytechnic University. μ-PL measurements were carried out at $T = 5$ K using spectrometer LabRAM HREvo UV-VIS-NIR-Open (Horiba, France), equipped with a closed-loop cryostat system RC-102 (Cryo Inc., USA). To excite μ-PL spectra, the line $\lambda = 325$ nm (3.81 eV) of He−Cd-laser was used. A laser beam was focused by a mirror lens into a spot with diameter of ~ 4 mkm on the specimen surface. Excitation density changed in a range from 1 to 50 kW/cm^2. Spectral resolution of the spectrometer was not below 0.3 meV in all spectral ranges. Depth of irradiation penetration in $4H$-SiC on the used wavelength at $T = 5$ K was approximately 8.6 mkm [3]. Our experimental results to measure μ-PL are related to this particular depth of the basic layer in a $4H$-SiC Schottky barrier diode, the full thickness of which was $W \approx 20$ mkm.

Figure 1 presents an μ-PL spectrum of a non-irradiated $4H$-SiC Schottky barrier diode (*#5*) in the energy region of 3.26−3.13 eV (380−396 nm), where the lines are presented, which are caused by recombination of free ($I_{76.4}$) and impurity-bound (Q_0) excitons near the edge of the $4H$-SiC bandgap. Their presence indicates good quality of the basic $4H$-SiC layer. The same figure presents the spectra measured in the samples irradiated with protons with dose of $1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at various temperatures: 25°C (*#1*), 150°C (*#2*), 300°C (*#3*), 500°C (*#4*). One can see well that the strongest changes in the intensity and form of the spectral lines occurred in the SiC spectrum of the specimen irradiated at 25°C. This indicates that the irradiation at room temperature provides for the strongest radiation effect at $4H$-SiC parameters. Irradiation at higher temperatures causes substantially weaker changes in the spectra of studied specimens, and, accordingly, indicates weaker radiation-induced damage. From the data presented in Figure 1 it follows that the specimen irradiated with protons at temperature 300°C was subjected to the least radiation effect.

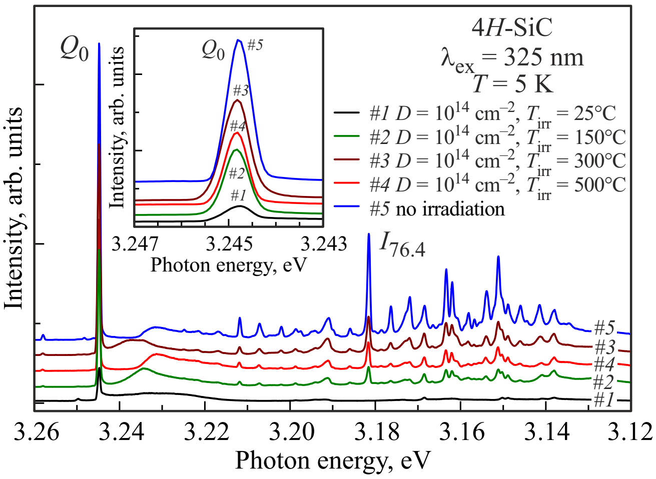

Figure 1. μ-PL spectrum near the edge of the intrinsic absorption of basic layer in non-irradiated 4*H*-SiC Schottky barrier diode (*#5*) and evolution of μ-PL spectra of 4*H*-SiC Schottky barrier diodes exposed to proton irradiation with dose of $D = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at temperatures T_{irr}, °C: 25 (*#1*), 150 (*#2*), 300 (*#3*), 500 (*#4*). The insert shows transformation of line Q_0, which is due to recombination of exciton related to a neutral nitrogen donor in the cubic environment.

SiC spectra of the studied specimens in the energy range of 2.92–2.83 eV (424–438 nm) are presented in Figure 2. For the non-irradiated specimen (*#5*) this part of the spectrum shows no features. However, multiple narrow lines appear in the spectra of the irradiated specimens, the number and intensity of these lines being dependent on the irradiation conditions. These features in the 4*H*-SiC spectra are caused by the recombination of excitons on the structural defects created under irradiation exposure (interstitial defects, vacancies, divacancies, antisites). The literature has assigned the name of „alphabet lines" there to [4]. In the corresponding spectra we may clearly distinguish 12 luminescent peaks, which should be referred to series *b*–*g* of „alphabet lines". From the data shown in Figure 2 it follows that the basic layer of the Schottky barrier diode irradiated at the room temperature was subjected to the highest radiation effect. Irradiation at higher temperatures causes substantially lower radiation-induced damage. In general, these conclusions match the conclusions made previously from the analysis of the spectra shown in Figure 1. From the data shown in Figure 2 it follows that the fewest structural defects responsible for appearance of „alphabet lines" in SiC spectra 4*H*-SiC occurred at irradiation temperature 500°C, which matches well with the results of the studies of proton-irradiated diode electrical characteristics [2].

Figure 3 presents SiC spectra in the wide energy range of 3.0–1.7 eV. As one can see from the figure, the spectrum of the non-irradiated Schottky barrier diode includes a wide band with maximum near 2.2 eV (565 nm), which is typical for SiC polytypes and is caused by the presence of deep defect centers [5]. After irradiation by protons, a new wide band appears with peak of 2.6 eV (477 nm), the nature of which depends on the irradiating recombination with the participation of the donor level of nitrogen and acceptor center arising in the process of irradiation [6]. The results of the studies on this band available in the literature indicate

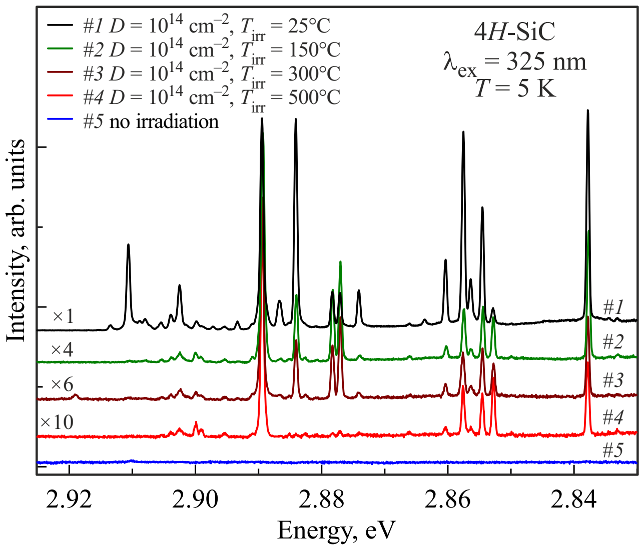

Figure 2. μ-PL spectra of basic layer in 4*H*-SiC Schottky barrier diodes measured at temperature 5 K in the area of „alphabet lines" without (*#5*) and with proton irradiation with dose of $D = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at temperatures T_{irr}, °C: 25 (*#1*), 150 (*#2*), 300 (*#3*), 500 (*#4*). For convenience of analysis the background formed by the part of the wide band with maximum ~ 2.6 eV, is subtracted in this spectral area, and the spectra are normalized to the intensity of line ~ 2.89 eV with the specification of the corresponding normalization coefficients.

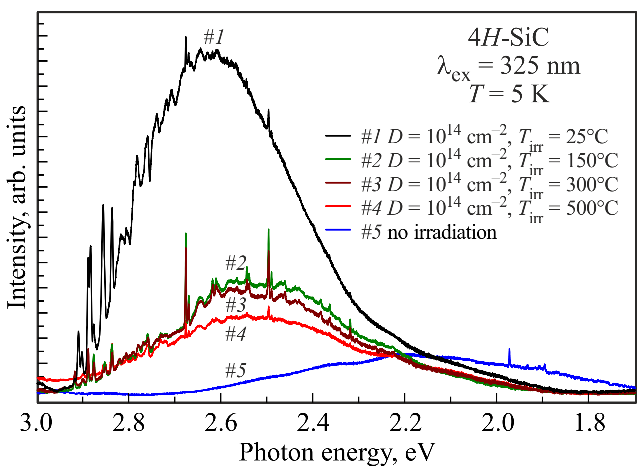

Figure 3. μ-PL spectra of basic layer in non-irradiated Schottky barrier diode (*#5*) and Schottky barrier diodes irradiated with protons with dose of $D = 1 \cdot 10^{14}\,\mathrm{cm}^{-2}$ at temperatures T_{irr}, °C: 25 (*#1*), 150 (*#2*), 300 (*#3*), 500 (*#4*). The wide band with maximum ~ 2.6 eV was due to the irradiating recombination with the participation of the donor level of nitrogen and acceptor center arising in the process of irradiation.

the increase of its intensity with increase of the radiation exposure intensity. With this consideration in mind, from the data shown in Figure 3 one can conclude that the basic layer of the Schottky barrier diode irradiated at $T_{irr} = 25°$C was subjected to the highest radiation-induced effect.

The analysis of the similar spectra for the 4H-SiC Schottky barrier diodes irradiated with electrons (not presented in this paper) indicated that the specimens irradiated at the room temperature are also subjected to the maximum radiation-induced effect. It was found that the temperature of proton and electron irradiation substantially impacts the process of radiation-induced defects formation. This observation is in good agreement with the results presented in papers [1,2]. However, one should note the substantial differences in the formation of radiation-induced defects under electron and proton irradiation manifesting themselves in μ-PL spectra. They are especially visible in the area of „alphabet lines", and also in the degree of exposure for line Q_0, provided for by recombination of the exciton bound with the neutral nitrogen donor in the cubic environment. The studies of the polarized SiC spectra in the spectral region 1.45–1.30 eV, where zero-phonon lines V_1–1.440 eV (V_1'–1.444 eV) and V_2–1.354 eV appear, being provided for by the presence of two types of isolated silicon vacancies in 4H-SiC, also found a considerable difference in the development of such radiation-induced defects by different types of irradiation. It was found that the electron irradiation causes only one type of vacancies — cubic, characterized by lines $V_1(V_1')$, while the proton irradiation causes both types of vacancies — cubic and hexagonal, which is indicated by the appearance of lines $V_1(V_1')$ and V_2, accordingly. Detailed studies were made on the temperature dependence of intensities of zero-phonon lines $V_1(V_1')$ and V_2 in the temperature range of 5–300 K. It was found that the homogeneity of the introduced defects under electron irradiation is much higher than under proton irradiation. Detailed description of the results of the studies for the specimens subjected to the electron irradiation will be presented in the more detailed publication.

Changes in the electric properties of 4H-SiC under the proton irradiation correlate well with the results of the optic measurements presented in Figures 1–3. At one and the same dose of the proton irradiation $D = 1.0 \cdot 10^{14}\,\mathrm{cm}^{-2}$ the change in conductivity is maximum when irradiated at temperature $T_{irr} = 25°$C and monotonously decrease with the growth of the irradiation temperature. As the irradiation temperature increases, the concentration of electrons in the conduction band n_p monotonously rises and makes $\sim 10^8\,\mathrm{cm}^{-3}$ at $T_{irr} = 23°$C, $\sim 10^{11}\,\mathrm{cm}^{-3}$ at $T_{irr} = 300°$C, and $\sim 10^{13}\,\mathrm{cm}^{-3}$ at $T_{irr} = 500°$C.

It should also be noted that the proton irradiation completed at all the above values T_{irr}, causes appearance of long-term conductivity relaxation in the irradiated specimens. The similar phenomenon was observed in a whole range of semiconductors. However, all previously published papers established stationary conductivity as the result of monotonous decrease in current after applying direct voltage impulse to the specimens. We observed a fundamentally different time dependence for the first time: when the direct voltage impulse is applied, the current first decreases with time, and then starts rising. The range of time constants characterizing both processes is within the dozens and hundreds of milliseconds up to hundreds of seconds. This result indicates appearance of not one, but two impurity zones in the prohibited area as a result of proton irradiation. The analysis of the potential effect from the appearance of the second impurity zone at the optical spectra is an important and an interesting objective.

The electron irradiation also decreases conductivity 4H-SiC. Besides, the speed of carrier recession under the electron irradiation is 200–300 times less than under the proton irradiation. As in the case of the proton irradiation, the concentration of electrons in the basic layer after the electron irradiation, n_e, is the higher, the higher is the irradiation temperature T_{irr}. However, it should be noted that under no conditions the electron irradiation would cause the long-term relaxation of conductivity. This indicates that the electron irradiation causes no impurity zones in the prohibited area of the semiconductor. The electron irradiation creates only local levels in the prohibited area.

Summarizing the above, one may conclude that the serial comparison of the results on the change of the local optical and integral electrical characteristics of 4H-SiC exposed to the proton and electron irradiation may effectively assist in finding out the nature of the defects occurring as a result of radiation effect.

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Conflict of interest

The authors declare that they have no conflict of interest.

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