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Features of gettering during irradiation of Cr /4*H*-SiC photodetectors with argon ions

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The paper presents the results of the effect of stepwise irradiation 7 times with argon (Ar) ions with an energy of 53 MeV and a fluence of $1 \cdot 10^{10}\,\text{cm}^{-2}$ (total fluence $7 \cdot 10^{10}\,\text{cm}^{-2}$) on the structural and optical characteristics of ultraviolet Cr/4*H*-SiC photodetectors. It is shown that the features of the spectral characteristics in the range of 200−400 nm are determined by gettering of simple radiation defects of vacancy nature by cluster formations in 4*H*-SiC. The cyclic nature of the gettering effect was confirmed during successive seven-fold irradiation of Cr/4*H*-SiC photodetectors with argon ions with a fluence of $7 \cdot 10^{10}\,\text{cm}^{-2}$, which was first observed with proton irradiation.

Keywords: Silicon carbide, irradiation, argon, gettering, external quantum efficiency, X-ray.

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Introduction

Concentrations of background impurities and defects in semiconductors have an adverse impact on the electrophysical and functional characteristics of devices. The development and use of techniques in semiconductor technology that prevent or significantly reduce the negative effects of impurity or defective compounds is referred to as „gettering“. These techniques are very diverse, and they can be applied to purify the volume of semiconductors using various process operations: heat treatment in inert or chemically active media, application of various films to the surface, and the introduction of a getter during cultivation or subsequent diffusion [1–4]. In addition, clearing the semiconductor structures from impurities and defects, as well as changing the electrophysical characteristics of devices may be implemented using disturbed homo-phase or hetero-phase regions existing within the semiconductor itself — the so-called internal gettering“ [5,6]. Special focus is made on purification of the source material during growth and the improvement of the instrument structures quality by the introduction of rare earth elements Yb, Gd, Sm, Nd, Er [7–11]. One of the effective methods of creating an internal getter is irradiation with high-energy light ions [12,13]. In 4*H*-SiC the gettering was first used during formation of ion-doped Al p^+-n-transitions during studies with various methods: SEM, EBIC, SIMS, XPS, CCL, BAX. Improvement of the quality of initial epitaxial 4*H*-SiC-layer grown by method of chemical vapor deposition (CVD), due to gettering the defects by the implanted Al p^+-layer was proved by XRD-, LCL-, CL- and TEM-measurements which resulted in higher lifetime of the nonequilibrium carriers in 2−2.5 times [14–16].

Ultraviolet (UV) photodetectors based on 4*H*-SiC with Schottky barriers are widely used in the diagnosis of outer space, the study of planetary atmospheres, and the study of „ozone holes “. Wide application UV 4*H*-SiC detectors are explained by the unique electrophysical properties of the semiconductor: band gap (3.23 eV), low values of generation currents, high thermal conductivity. These properties make it possible to create high-temperature „visible-blind“ detectors with a low threshold of photosensitivity due to which even weak UV signals may be registered. The radiation resistance of 4*H*-SiC devices has been confirmed by irradiation with various high-energy particles. Moreover, radiation at elevated temperatures up to 500 °C results in higher radiation and longer time for 4*H*-SiC devices due to the annealing of some radiation defects [17]. Detectors with Schottky barriers Cr/4*H*-SiC are capable of operating up to 200 °C with no deterioration in optical performance [18]. The processes of radiation defect gettering were studied under proton irradiation of Cr/4*H*-SiC UV photodetectors. Upon a stepwise 7-times irradiation with protons with an energy of 150 MeV and a fluence of $1 \cdot 10^{12}\,\text{cm}^{-2}$ (total fluence of $7 \cdot 10^{12}\,\text{cm}^{-2}$), the cyclic nature of the gettering effect was revealed for the first time [19].

This paper examines the effect of a stepwise irradiation with Ar ions seven times by fluence $1 \cdot 10^{10}\,\text{cm}^{-2}$ (total fluence $7 \cdot 10^{10}\,\text{cm}^{-2}$) with an energy of 53 MeV on the structural and optical characteristics of Cr/4*H*-SiC UV photodetectors. The limiting fluence of Ar ion irradiation has been determined, leading to degradation of the detector with a concentration of uncompensated donors $(1-3) \cdot 10^{15}\,\text{cm}^{-3}$ in 4*H*-SiC-epitaxial CVD-layer.

Sample

UV photodetectors Cr/4*H*-SiC were formed based on the structures made of n^+-substrates of 4*H*-SiC with a thickness of 400 μm with concentration of the non-compensated donors $N_d-N_a = 3 \cdot 10^{18}\,\text{cm}^{-3}$ and epitaxial layers of n-4H-SiC, grown by CVD-method $5\,\mu$m thick with concentration of the non-compensated donors $N_d{-}N_a = (1{-}3)\cdot 10^{15}\,\text{cm}^{-3}$. The Cr/Al base contacts on the substrate side, as well as Cr Schottky barriers with a diameter of 8 mm and a thickness of $< 0.1\,\mu$m on CVD layers, were formed by thermal evaporation in vacuum. The same photodiode structures were irradiated seven times successively with 8-charge Ar ions with energy of 53 MeV at room temperature with fluence $1\cdot 10^{10}\,\text{cm}^{-2}$. Since SiC has a cumulative effect of radiation, the total fluence after the seventh irradiation was $7\cdot 10^{10}\,\text{cm}^{-2}$. The uniform density of radiation defects formed on the surface of samples (not worse than 7%) was ensured by scanning a beam of Ar ions focused in a line when scanning along a coordinate perpendicular to this line.

Research methods

Structural changes in 4H-SiC after each irradiation with Ar ions were studied using X-ray diffraction analysis (X-ray). The intensity distribution patterns near the reciprocal lattice site on the reflection of (0008) CuK_α were obtained by measurements in two scanning modes ω and 2ω on a two-crystal spectrometer assembled using an industrial diffractometer DRON-3. The details of the measurement procedure are described in detail in this paper [19]. The penetration depth of X-rays on reflection (0008)4H-SiC, calculated according to dynamic theory, is $17\,\mu$m, the average projected path of argon ions is approximately $8.3\,\mu$m [20]. The greatest structural changes occur in the region of ion deceleration at a depth of about 10 mm, however, these changes are also noticeable near the surface of CVD layer, which is reflected in optical measurements.

The spectral characteristics of Cr/4H-SiC photodetectors sensitivity in the wavelength range of 200−400 nm were measured by comparison with the readings of a calibrated silicon photodiode FDUK-100UT. The measurements were carried out under illumination with a DDS-30 deuterium lamp using an SF-16 monochromator, the beam area was $5\,\text{mm}^2$. The sensitivity measurement error was 10% for the range of wavelengths 210−240 nm and 6% for the wavelengths 240−400 nm. To register the current signals from Cr/4H-SiC-photodetector and calibrated silicon photodiode the picoammeter Keithley 6487 was used. The dark currents of the initial photodetector Cr/4H-SiC and after irradiation by Ar ions didn't exceed 10^{-13} A.

Results and discussion

X-ray measurements

As mentioned earlier [21,22], the structure of the initial sample with a concentration of $N_d{-}N_a = (1{-}3)\cdot 10^{15}\,\text{cm}^{-3}$ was already imperfect (Fig. 1, initial). In it, along with the matrix (at $2\omega = 0$), there was a region with negative deformation (on the side of large angles at $2\omega = 60$ arcsec), and on the side of smaller 2ωcorners, an extended intense reflection region was observed (up to $2\omega = -60$ arcsec). The coexistence of these two regions in the matrix structure made the structure initially tense. In the process of the first irradiation with Ar ions by $1\cdot 10^{10}\,\text{cm}^{-2}$ fluence, simple radiation defects (mainly of the vacancy type) migrate under stress towards a localized monocrystalline region with negative deformation (at $2\omega = 60$ arcsec), making it more powerful (Fig. 1, 1D). It is this region that serves as a drain for simple radiation defects of the vacancy type that occur during 1st irradiation, being itself an internal getter. Along with this, the length of the region from the side of the smaller 2ω rises up to $2\omega = -100$ arcsec, which indicates the formation of interstitial defects during the 1st irradiation. Apparently, the stresses in the structure at this stage already reach critical values, and the existence of such a configuration becomes energetically unprofitable. Therefore, during the second irradiation with Ar ions with total fluence $2\cdot 10^{10}\,\text{cm}^{-2}$, partial stress relief occurs due to the destruction of a single crystal cluster supersaturated with vacancies, through the formation and enlargement of dislocation loops and their transformation into extended-type defects [23]. A similar effect was observed in case of irradiation with protons [18]. At the same time, as in the case of proton irradiation, the density of extended defects in the structure rises (compared to the initial sample). However, since the mass of Ar ion is several tens of times greater than the mass of a proton, then, during irradiation with Ar ions, along with the formation of a large number of vacancy-type defects, a noticeable formation of interstitial atoms occurs (Fig. 1, 2D). The structure at this stage is a coexistence of 3 single crystal regions: a matrix and regions with both negative and positive deformation. Elastic stresses in such a structure cause migration of radiation defects in opposite directions, i.e. both regions behave as internal getters for both vacancy-type defects and interstitial atoms. Such structure is apparently nonequilibrium, and during the 3rd irradiation with total fluence $3\cdot 10^{10}\,\text{cm}^{-2}$, the gettering regions are destroyed with the simultaneous predominant formation of simple vacancy-type defects (Fig. 1, 3D). The next 4th irradiation again leads to the formation of a single crystal region with negative deformation, which acts as a getter for vacancy defects (Fig. 1, 4D). During the 5th irradiation, the gettering region with negative deformation is destroyed again. All stresses stimulating the migration of fine radiation-induced defects vanish (Fig. 1, 5D). As a result of the 2nd irradiation, the single crystal region with negative deformation is destructed along with formation of the linear defects in its structure and further degradation of the structural perfection of the initial structure. 6th irradiation with total fluence $6\cdot 10^{10}\,\text{cm}^{-2}$ leads to the predominant formation of interstitial atoms with a clear tendency to form a single-crystal complex (Fig. 1, 6D). After the 7th irradiation, there is an almost uniform expansion of regions saturated with simple radiation defects of both types (Fig. 1, 7D). Summing up the results obtained during X-raystudies with a stepwise irradiation of 4H-SiC by Ar ions with energy 53 MeV

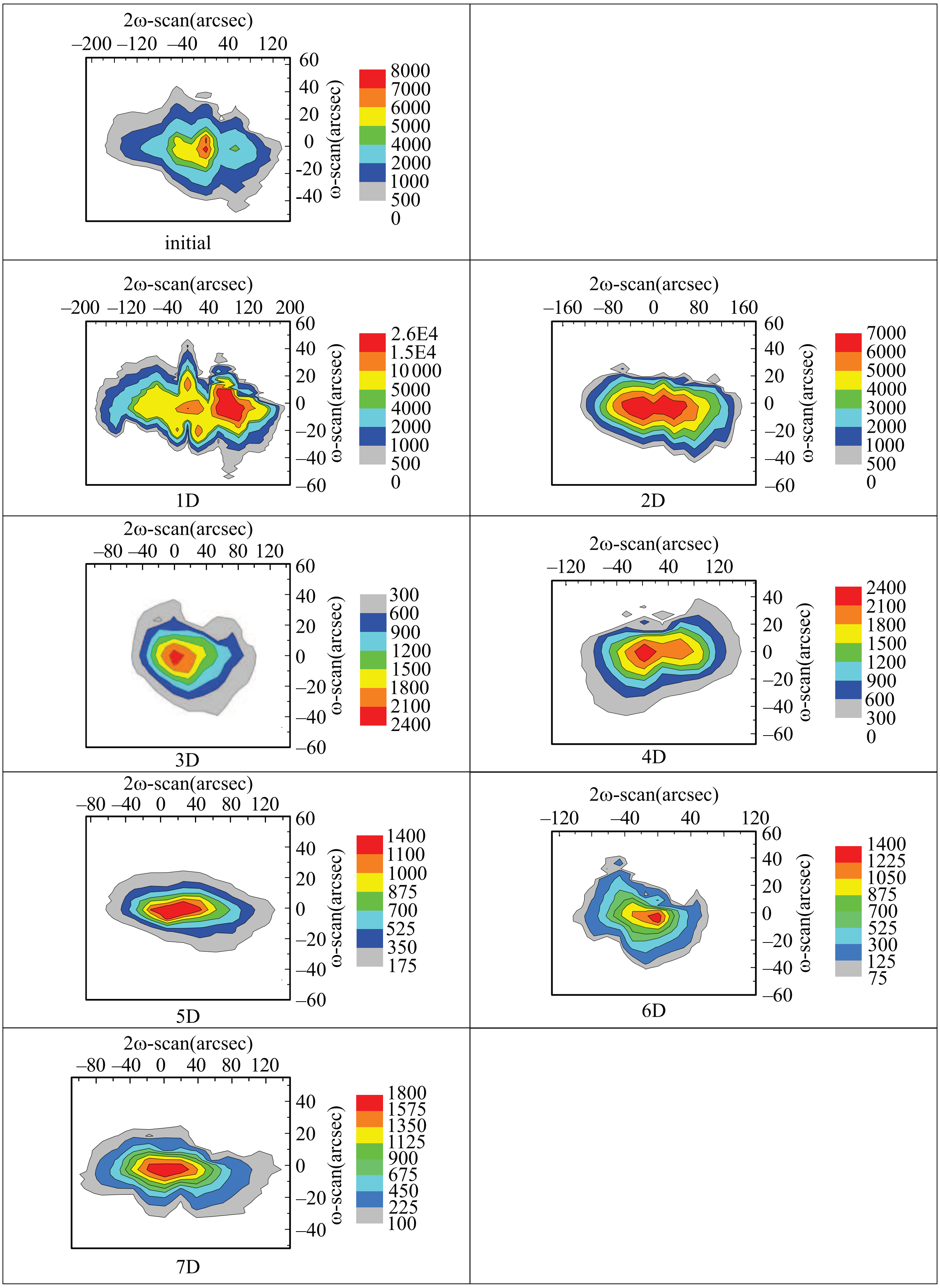

Figure 1. Distribution of intensity on reflection (0008) in the initial sample of 4*H*-SiC with concentration $N_d - N_a = (1-3) \cdot 10^{15}\,\mathrm{cm}^{-3}$ in the epitaxial CVD-layer (initial) and after each of 7 irradiations by Ar ions with an energy of 53 MeV and fluence $(\cdot 10^{10}\,\mathrm{cm}^{-2})$: 1 (1D), 2 (2D), 3 (3D), 4 (4D), 5 (5D), 6 (6D), 7 (7D).

and fluence $1 \cdot 10^{10}\,\text{cm}^{-2}$, we may ascertain that there's a cyclical effect of simple radiation defects internal gettering due to the formation of large clusters enriched in both vacancies (with negative deformation) and interstitial atoms (with positive deformation) during irradiation, and their subsequent destruction at different stages of irradiation. Optical measurements proved this type of structure transformation.

Spectral measurements

The structural rearrangements in epitaxial CVD layers of 4*H*-SiC observed during X-ray studies after a stepwise irradiation with Ar ions with energy of 53 MeV and various fluences, manifested themselves in the spectra of the external quantum efficiency (QE) of Cr/4*H*-SiC-photodetectors (Fig. 2). After the first irradiation with Ar ions with fluence $1 \cdot 10^{10}\,\text{cm}^{-2}$ the QE in the maximum remained practically the same due to migration of simple radiation defects under the influence of stresses towards a localized single-crystal region with negative deformation already existing in the initial sample (Fig. 2, curve 1D). The observed effect contributed to the lower number of radiation defects of a vacancy kind, higher lifetime of nonequilibrium current carriers, and, as a consequence, to the values of QE for Cr/4*H*-SiC-photodetectors equivalent to the that of initial samples. A significant decrease in QE after the second irradiation with general fluence $2 \cdot 10^{10}\,\text{cm}^{-2}$ is caused, according to X-ray measurements, by a general disordering of the CVD layer structure (Fig. 2, curve 2D). The destruction of the gettering regions during the third irradiation, with the simultaneous predominant formation of single vacancy-type defects, led to a further decrease in the lifetime of nonequilibrium charge carriers jcite24,25 and, as a result, to a decrease in QE of Cr/4*H*-SiC photodetectors (Fig. 2, curve 3D). The next 4th irradiation again was accompanied with formation of a single crystal region with negative deformation, which acts as a getter for vacancy defects in 4*H*-SiC-layer (Fig. 1, 4D), and QE increased again (Fig. 2, curve 4D). After 5-th irradiation with Ar ions with a total fluence $5 \cdot 10^{10}\,\text{cm}^{-2}$ the single-crystal gettering region in CVD-layer 4*H*-SiC was destructed again (Fig. 1, 5D). The destruction of the single-crystal region was accompanied by a degradation in the structural perfection of the initial structure, as a result of which the QE of Cr/4*H*-SiC photodetector sharply decreased (Fig. 2, curve 5D). According to X-ray measurements, the 6th irradiation of 4*H*-SiC structure with Ar ions by the total fluence $6 \cdot 10^{10}\,\text{cm}^{-2}$ led to the prevailing formation of interstitial atoms with a tendency to form a single-crystal complex with positive deformation, playing the role of a getter (Fig., 1, 6D). Growth was again observed in QE spectrum (Fig. 2, curve 6D). After the 7th irradiation with Ar ions having the total fluence $7 \cdot 10^{10}\,\text{cm}^{-2}$, an irreversible increase in the dark current was observed by orders of magnitude and it was impossible to register a photocurrent at the same time, which was interpreted as a destruction of 4*H*-SiC structure, leading to complete degradation of Cr/4*H*-SiC-photodetectors.

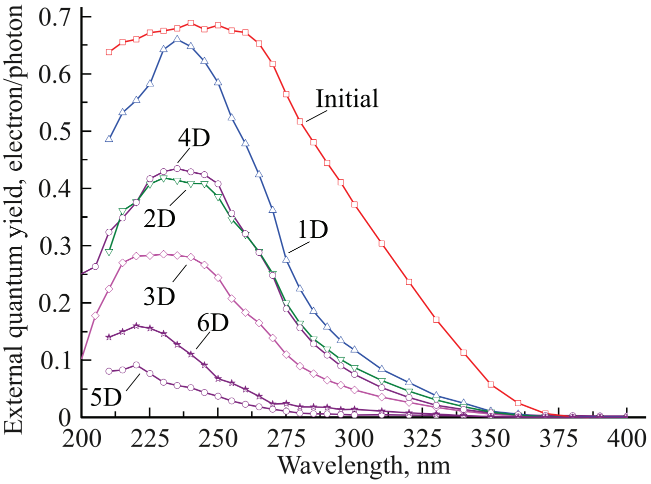

Figure 2. QE spectra of Cr/4*H*-SiC-photodetectors with a concentration of $N_d - N_a = (1-3) \cdot 10^{15}\,\text{cm}^{-3}$ in the epitaxial CVD-layer (initial) after irradiation with Ar ions with an energy of 53 MeV and fluence ($\cdot 10^{10}\,\text{cm}^{-2}$): 1 (1D), 2 (2D), 3 (3D), 4 (4D), 5 (5D), 6 (6D).

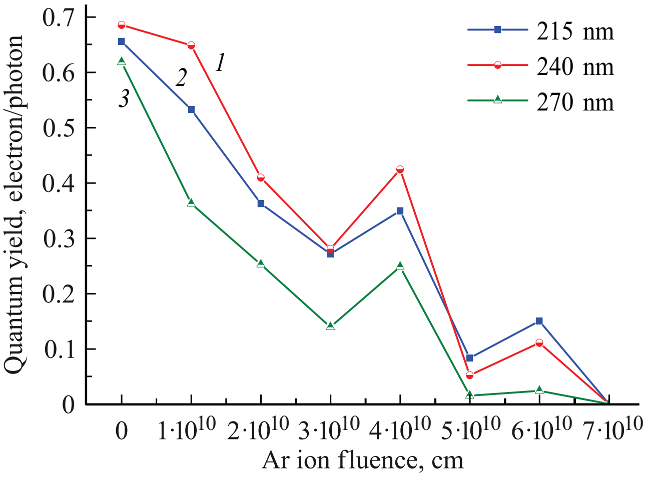

Figure 3. QE spectra of Cr/4*H*-SiC-detector with doping level $N_d - N_a = (1-3) \cdot 10^{15}\,\text{cm}^{-3}$ in CVD-layer versus Ar irradiation fluence for the wavelengths: *1* — 240 nm, *2* — 215 nm, *3* — 270 nm.

The dependence of QE of Cr/4*H*-SiC photodetectors differs significantly for the regions of long-wave and short-wave photoelectric effects. At wavelengths $\lambda < 380$ nm (photon energy $h\nu > 3.2$ eV), QE grows slowly, since this region is determined by indirect optical transitions between the valence band at Γ-point of the Brillouin zone and the bottom of the conduction band near the point Mk-space. With the energy of photons $h\nu = 4.9$ eV a direct optical transition into 4*H*-SiC occurs with the maximum in QE-spectrum (240–250 nm). A drastic decline in QE spectra in the short-wavelength region at photon energies exceeding 5 eV is explained by the formation of a hot exciton binding an electron and a hole during the photoelectric effect and its behavior in a contact electric field [26,27].

The correlation between structural changes in 4H-SiC and QE spectra of Cr/4H-SiC photodetectors during their stepwise irradiation 7 times with Ar ions is well observed when plotting the spectra for three wavelengths: 240 nm (direct transition), 215 and 270 nm (indirect transitions) (Fig. 3). The values of QE for Cr/4H-SiC-detectors varied in synchrony with the formation and further destruction of the clustered formations in 4H-SiC according to X-ray-examination. The cyclicity of these processes confirms the cyclical process of radiation defect gettering during a stepwise irradiation of Cr/4H-SiC detectors with Ar ions seven times with $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$ fluence (total fluence $7 \cdot 10^{10}\,\mathrm{cm}^{-2}$).

Conclusions

A 7-times irradiation of 4H-SiC detector with Ar ions with an energy of 53 MeV and fluence $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$ (total fluence $7 \cdot 10^{10}\,\mathrm{cm}^{-2}$) leads to complex structural changes. According to X-ray examination, as a result of irradiation with a set of fluences, periodic formation and destruction of cluster formations in 4H-SiC occur, enriched in both vacancies and interstitial atoms.

1. Cluster formations in 4H-SiC serve as drains for simple defects, playing the role of their getters. The observed gettering effect after the first irradiation with Ar ions having fluence $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$ ensures the QE values of Cr/4H-SiC UV detectors at the level of the initial samples.
2. The cyclic nature of the gettering effect was confirmed upon a stepwise irradiation of 4H-SiC with Ar ions having fluence $1 \cdot 10^{10}\,\mathrm{cm}^{-2}$.
3. The fluence of Ar ions was identified resulting in degradation of Cr/4H-SiC UV detectors with the doping level of $N_d - N_a = (1-3) \cdot 10^{15}\,\mathrm{cm}^{-3}$ in CVD-layer making $7 \cdot 10^{10}\,\mathrm{cm}^{-2}$.

Conflict of interest

The authors declare that they have no conflict of interest.

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