1. INTRODUCTION

Silicon carbide is one of the most radiation-resistant semiconductors and is attractive for use in harsh environments, including strong radiation, high temperature, and chemical activity. SiC finds application in space electronics, various nuclear-power setups, in the control of fissionable materials, and as promising material for inert matrix fuel host. Moreover, long-term radiation control detectors are required for physical experiments with intensive radiation, which are being planned for the next generation of accelerators such as the Large Hadron Collider and its modification SLHC at the European Organization for Nuclear Research (CERN). Considering the vast potential for the use of such radiation-resistant equipment, it is necessary to study in detail the effect of various high-energy particles on the structural, electrical, and optical properties of silicon carbide.

The results of numerous experiments have shown that electron, proton, and neutron irradiation lead to similar kinds of radiation damage and change in the SiC structure (see, e.g., [1–4]). In contrast to such conventional radiation, the effect of high-energy heavy ions on SiC properties has not been studied in detail yet. At the same time, the study of the mechanism of defect formation in SiC subjected to irradiation by heavy ions with mass and energy more then 80 and 100 MeV, respectively, is of great interest for simulation of structural damage induced by fission fragments. Under conditions of high and superhigh ionization energy loss and high rate of generation of radiation defects, there is a possibility of the formation of point and extended radiation defects, as well as latent tracks.

The first studies of the structural, optical, and electrical properties of n- and p-6H-SiC crystals irradiated by high-energy heavy ions were carried out using Xe ions with energy of 124 MeV [5, 6] and 5.5 GeV [7, 8]. It was concluded that xenon ions created radiation defects which were similar to those induced by light particles. For example, the formation of point defects, which due to their high mobility, especially under annealing, easily formed extended defects such as vacancies and their complexes, was observed. These defects were produced via elastic scattering. No specific lattice damage which could be associated with electronic stopping was observed up to specific ionization loss level of $Se = 21.9$ keV/nm. A similar conclusion was made when n-6H-SiC crystals were irradiated by I ions with energy of 72 MeV [9] and by Kr ions with the energy of 246 MeV [10]. The absence of latent tracks at $Se = 34$ keV/nm was noted in the first works on irradiation of n-6H-SiC crystals by 710 MeV Bi ions, which shows the high radiation resistance of SiC [11]. Further optical and electro-physical studies of defect formation in high-purity high-resistivity n-6H-SiC CVD epitaxial layers irradiated by Bi ions with 710 MeV energy in the $10^{9}$–$5 \times 10^{10}$ cm$^{-2}$ fluence range made it possible to reveal the formation of a wide spec-
trum of radiation defects. Their parameters were similar to those of defects which occurred in SiC subjected to irradiation by electrons, neutrons, and light ions [12, 13]. In addition, it was shown that heating of irradiated samples up to 500°C led to partial recovery of the characteristics of the device structures, which had degraded after irradiation by Bi ions [13].

The aim of this work is to study the structural and luminescence characteristics of pure n-type 4H-SiC CVD epitaxial layers subjected to irradiation by high-energy Bi ions followed by post-irradiation thermal treatment. Such experiments allow for revealing the contribution of radiation defects to the recombination processes which take place in irradiated epitaxial layers and device structures based on them.

2. EXPERIMENTAL

The 26-µm thick 4H-SiC epitaxial layers with concentration of uncompensated donors 5 × 10^{18} cm^{-3} were grown CVD on commercial 4H-SiC wafers with N_{D} = N_{A} = 10^{19} cm^{-3}. Before the growth of the CVD layers, thin (~0.1 µm) n-type 4H-SiC layers with N_{D} - N_{A} = 10^{19} cm^{-3} were grown on the substrates using liquid-phase epitaxy (LPE). The substrates and the epitaxial layers were irradiated along the c axis by 710 MeV Bi ions with fluence ranging from 1.4 × 10^{10} up to 5 × 10^{10} cm^{-2}.

The thickness of the LPE and CVD epitaxial layers, as well as their structure before and after irradiation, were determined on freshly cleaved edges of the samples in a scanning electron microscope (SEM) with the beam energy of 20 keV. The structural characteristics of the n-type 4H-SiC substrates and the epitaxial layers before and after irradiation were studied using X-ray topography (XRT) and X-ray diffractometry (XRD). The topographs were taken using CuKal radiation in the (1128) reflection, where the thickness of the layer, with formed reflection of structural defects, was ~25 µm. Diffraction curves were recorded in double-crystal mode using CuKα1 radiation for two symmetrical reflections (0004) and (0008), where the estimated depths of reflected beam formation were ~5 µm and ~25 µm, respectively. Distribution of radiation-induced defects along the track of implanted Bi ions, as well as the structure and transformation of the defects during annealing, was studied with the use of transmission electron microscopy (TEM). To study the formation of radiation-induced defects at the depth of the CVD epitaxial layer in detail, step-by-step lapping down to the thickness of ~5 µm was used. TEM measurements were carried out near the surface and at the depth of the CVD layer, as well as in the area which was close to the epitaxial layer–substrate interface. The acquired data were compared with the results of photo- and cathodoluminescence (PL, CL). PL (80 K) was excited by a He–Cd laser (20 mW) at 325 nm with laser beam filtered by an UFC-1 filter. CL (300 K) measurements were carried out along the depth of the CVD layer using angle lapping, with the exposition of 0.1 s and electron beam current and energy of 30 nA and 10 keV, respectively. The diameter of the electron beam was ~1 µm, so the generation region was estimated as 1 to 3 µm.

3. RESULTS AND DISCUSSION

The projected range of 710 MeV Bi ions in SiC, according to SRIM 2000 code calculation is 28.8 µm (see Fig. 1). Therefore, considering the fact that the thickness of the CVD epitaxial layer was 26 µm, we can assume that the data acquired during the study of the effect of ion irradiation represent two processes which took place in the epitaxial layer.

According to the SEM data, the initial CVD epitaxial layers had a high degree of structural perfection, which was due to the presence of a thin buffer LPE layer that is well seen at the interface between the CVD layer and the substrate. The LPE layer hindered the penetration of defects from the substrate into the CVD layer [14]. After the irradiation by Bi ions with 5 × 10^{10} cm^{-2} fluence, the formation of a thin subsurface damaged layer with the thickness ≤1 µm, as well as accumulation of radiation defects in the CVD layer, was observed. These defects were produced in the region with the thickness of 3–4 µm, which was close to the interface with the substrate (Fig. 1).

High structural perfection of the initial epitaxial layers was also confirmed by the analysis of X-ray topograms. The presence of basal dislocations was found in