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Peculiarities of the track formation in InP and GaAs crystals

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Abstract

Track formation processes in InP and GaAs crystals irradiated with swift Bi and U ions to fluences in the range 5×10^{10}–$1\times10^{12}\,cm^{-2}$ have been investigated by means of selective chemical etching (SCE), atomic force microscopy (AFM) and computer simulation. SCE data on the InP crystals show the formation of the two-layer system of tracks differing by the matrix disorder degree under the Bi ion irradiation. Transition from an individual track embedded in an unchanged solid (single tracks) to a modified solid (consisting of partial overlapping tracks) is observed at the fluence of 1×10^{12} Bi/cm^2. Ion tracks in GaAs samples irradiated with U and Bi ions to the fluence of $5\times10^{10}\,cm^{-2}$ were registered by means of AFM and SCE. The density of the tracks obtained from AFM data coincides well with the irradiation fluence. Fluence growth up to $1\times10^{12}\,cm^{-2}$ leads to the annealing of the tracks formed in GaAs on the early stages of irradiation. The results of the computer simulation of the track formation processes in InP and GaAs crystals are also presented. Simulation was based on the modified thermal spike model, including thermal dependencies of thermophysical properties and containing no free parameters. Calculated diameters of molten regions near the surface of the crystal are 20.6 and 17.4 nm for InP and GaAs crystals, respectively, irradiated with 710 MeV Bi ions. The comparison of the calculation results with the experimental data has been made.
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Keywords: InP and GaAs crystals; Heavy ion irradiation; Tracks; Selective chemical etching; Atomic force microscopy; Modified thermal spike model

1. Introduction

Swift heavy ion irradiation is a promising technique for nanostructuring of solids. The outstanding characteristic of high-energy ion irradiation is the high level of electronic excitations arising from ion inelastic collisions in solids.

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Under these conditions each single projectile produces a track in the form of narrow cylinder or nanometer cluster chain with modified structure embedded into undamaged matrix. Such tracks have been revealed in dielectrics, metals, polymers and ionic crystals [1–5]. The effects of electronic excitations for semiconductor crystals have been found to be more complicated in comparison with other materials. Until now, irradiation conditions leading to track formation, and track formation mechanisms are not elucidated in detail.

In our previous works, we observed track formation after the irradiation with swift Xe ions by means of transmission electron microscopy (TEM) and selective chemical etching (SCE) for InP crystals, but not for GaAs crystals [6,7]. Colder et al. [8] registered amorphous tracks in GaAs crystals irradiated with swift carbon clusters C_{60}. Those tracks recrystallized in the microscope under the electron beam. Instability under the influence of electron beams complicates the tracks investigation by means of TEM and forces to look for other detection methods.

In the present work, we present the results of the investigations of track formation in InP and GaAs crystals by means of computer simulation, atomic force microscopy (AFM) and SCE. SCE gives evidence of the presence of the tracks, though does not allow the characterization of the nature of the defects in the track region. SCE of cross-sections allows in getting information on damage distribution along the whole ion trajectory in one experiment.

2. Experimental

2.1. Irradiation

(1 0 0)-oriented GaAs and InP crystals were implanted with 710 MeV Bi ions to fluences of 5×10^{10}, 1×10^{11}, $1\times10^{12}\,\mathrm{cm}^{-2}$ at the Joint Institute for Nuclear Research (Dubna, Russia). U ions with an energy of 1300 MeV were implanted into GaAs crystals on UNILAC accelerator complex (Darmstadt, Germany). To avoid sample heating, the ion flux was kept at $2\times10^{8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Projected ranges R_p for bismuth ions, calculated by means of program TRIM'98, are 33.4 and 30.6 μm, respectively.

2.2. Atomic force microscopy and selective chemical etching

The surfaces of the implanted GaAs samples were investigated by the AFM Nanoscope IIIa using the standard silicon cantilever and program "Femtoscan online" (MSU Center of Perspective Technologies). Radiation damage was revealed by the treatment of the crystals cleaved perpendicular to the surface in AB etchant (CrO_3:H_2O:HF:$AgNO_3$) [9]. Fresh cleaves were etched for 10–20 s at room temperature (GaAs) and for 3–5 min at 60–70 °C (InP). Then the samples were studied by the optical microscope Leica INM-100. The layers with thicknesses of ~0.2–0.3 μm (GaAs) and 3–4 μm (InP) were dissolved during the etching.

2.3. Results

Fig. 1 represents the cleaves of the irradiated InP crystals after etching. For the sample irradiated to a fluence of $5\times10^{10}\,\mathrm{cm}^{-2}$, two regions with track-related etch figures were revealed. These are regions of the high-contrast etch figures like conic tubes in the depth region from the surface to 7–12 μm and the underlying regions of less contrast etch figures in the form of cylinders with non-equal thickness segments extending almost to the end of the ion range. The end of the ion range is marked by a narrow stripe of dark or bright contrast at a depth of ~30 μm and coincides well with the R_p value (taking into account the material removed during etching). The difference in the contrast of the two types of track-related etch figures reflects different degrees of matrix damage in track regions. The same etch pattern is observed for the sample irradiated to a fluence of $1\times10^{11}\,\mathrm{cm}^{-2}$ (not shown in the figure). With the fluence increasing up to $1\times10^{12}\,\mathrm{cm}^{-2}$, the track-related etch figures overlap forming the zone of the strong disorder in the depth region from the surface down to ~17 μm. According to the TEM data, track diameters in the crystalline InP are 7–15 nm [6]. If every ion forms a track, partial overlapping of the tracks can be observed at

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