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Structural changes in heteroepitaxial InSb films after impact to high-energy Kr ions

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Abstract. The paper studies structural changes in heteroepitaxial InSb films on a single-crystal GaAs (100) base after irradiation with krypton ions with an energy of 145 MeV and fluences of 10^{12} and $5{\cdot}10^{12}$ cm^{-2}. Such a film system is the basis of a Hall transducer, which is used in a wide range of microelectronic devices for space and nuclear industry applications due to its high resistance to low temperatures and radiation absorption doses. Structural changes were determined using a high-resolution method of rocking curves of X-ray diffractometry. It was found that after irradiation with krypton ions, significant macro- and microstresses arise in the films with an increase in the fluence of krypton ions, reaching, respectively, values by modulus 4 and 0.1 GPa. Based on the calculated data of the work and literature, it was revealed that the reason for the emerging high values of macro- and microstresses, krypton irradiation is the formation of track defects of krypton ions in the heteroepitaxial indium antimonide film.

Keywords impact to high-energy Kr ions, heteroepitaxial InSb films, structural changes.

1. Introduction

The development of radiation materials science for use in the space industry and nuclear energy places increased demands on the radiation resistance of semiconductor materials used in measuring instruments, microcircuits and other electronic components. High doses of ionizing radiation lead to the generation of radiation defects, structural changes and other effects that have a negative impact on the performance properties of semiconductor devices. It is known that a wide range of sensors and microelectronic devices based on a Hall transducer made of heteroepitaxial InSb film on a single-crystal GaAs base have unique resistance to ultra-low temperatures of outer space. As shown in the literature [1, 2], when exposed to high-energy electrons, γ-quanta, protons, the electrophysical properties of films exhibit a certain radiation resistance, which corresponds to operational dose loads in the range of 100–500 krad for spacecraft in low-Earth orbit. However, these works do not consider the structural state of films after irradiation.

It is promising to study the properties of heteroepitaxial InSb films under the influence of higher radiation absorption doses to extend the operating time of microelectronic devices with InSb films on GaAs in space and the nuclear industry. To create high dose loads of ion influence on structural changes in heteroepitaxial InSb films, this work used irradiation with krypton ions with an energy of 145 MeV and fluences of 10^{12} and $5{\cdot}10^{12}$ Kr^{+}/cm^{2}. Irradiation with krypton ions was carried out at room temperature on a linear accelerator of heavy ions DC-60 (Institute of Nuclear Physics, Astana, Kazakhstan). Thus, the goal of the work to study structural changes in these films at significant radiation absorption doses after exposure to high-energy Kr ions is an urgent scientific task.

2. Experimental details

The objects of study in this work were heteroepitaxial InSb films on single-crystal GaAs (100) wafers, obtained by explosive thermal evaporation at two deposition temperatures 375 and 430 °C, which are the boundaries of the temperature range for obtaining high-quality heteroepitaxial InSb films. [3]. The main diffraction line of the InSb film with high intensity from the (100) plane corresponds to GaAs (100). The film thickness measured using a profilometer was $d = (2.0{\pm}0.1)$ μm.

Structural changes in InSb films after ion irradiation with Kr ions were studied using the rocking X-ray diffractometry method (diffractometer Rigaky Ultima IV, Japan). The use of the rocking curve method of X-ray diffractometry makes it possible to determine structural changes in epitaxial semiconductor films with higher accuracy than under standard X-ray diffraction conditions. The structural parameters were determined from the shift in position and broadening of the (100) diffraction peak of InSb after irradiation on the rocking curves relative to the unirradiated InSb film. Note that the (100) interplanar spacing value of the non-irradiated InSb film was very close to the reference value from the ICDD-PDF2 database. In general, the full width of the diffraction peak at half maximum (β) is determined by the microstresses in the microcrystallites, the size of the microcrystallites of the film under study, and the instrumental broadening of the device. The instrumental broadening of the device in the studied range of diffraction angles was determined by recording the rocking curves of a GaAs single crystal. In further calculations, the instrumental broadening was subtracted from the experimental diffraction peaks according to the Lorentz model, and further in the calculations, diffraction peaks "pure" from the instrumental broadening were used.

Note that atomic force microscopy data showed that there was no significant change in the size of the film microcrystallites under the influence of the applied ion irradiation with krypton. Then, the change in the full width of the diffraction peak at half maximum is determined by the microstresses of the film crystallites, which was calculated from the relation (1):

$$\varepsilon = \frac{\Delta \mathrm{d}}{\mathrm{d}} = \frac{\beta(2\Theta)}{4tg\Theta}, \tag{1}$$

where β – is the integral width of the diffraction reflection at half maximum associated with microstress; Δd is the maximum deviation of the interplanar distance for a given diffraction line of InSb (100) from the center of gravity of the experimental interplanar distance d; $\Delta d/d$ or ε is the relative microstress or deformation of crystallites. To obtain film microstresses in Pa, the value of relative microstresses was multiplied by the literature value of Young's modulus.

The magnitude of the residual macrostresses (σ) arising in the InSb film under the ionic influence of krypton was determined from the relation:

$$\sigma = -\frac{E}{\nu}\frac{d-d_0}{d_0}, \tag{2}$$

where d – is the interplanar spacing of InSb (100) of the irradiated sample; d_0 is the interplanar spacing of InSb (100) of the original sample; E is Young's modulus; ν is Poisson's ratio. To estimate micro- and macrostresses, literature data were used [4], for the value of Young's modulus and Poisson's ratio of InSb ($E = 4.09 \cdot 10^{10}$ Pa, ν = 0.35).

3. Results

The results of the study of heteroepitaxial InSb (100) films on single-crystal GaAs (100) substrates depending on the film deposition temperature of 375 °C; 430 °C and the effect of krypton ions with an energy of 145 MeV and fluences of 10^{12} and $5 \cdot 10^{12}$ $\mathrm{Kr}^+/\mathrm{cm}^2$ using the rocking curve method of X-ray diffractometry are presented in Figs. 1 and 2.

The calculated data from the rocking curves of micro- and macrostresses of the heteroepitaxial InSb (100) film after exposure to krypton ions in accordance with the method described above are presented in Table 1.

The data presented in Figs. 1 and 2 and the table 1 show the occurrence of high values of macrostress (compressive) and microstress with increasing fluence of krypton irradiation of InSb films. It is unlikely that the cause of such significant structural changes in the films is associated with the accumulation of point defects or their complexes, which arise as a result of atomic displacements during nuclear losses. Literary experimental and calculated data on the effect of krypton ions with energies greater than 100 MeV on various types of materials (Si, ionic crystals) indicate a significant excess of electron energy losses over nuclear ones at depths of these materials of tens of microns. The calculation of the energy losses of krypton ions in a film 2 μm thick carried out in the work using the SRIM program showed that the dissipation of the energy of krypton ions with an energy of 145 MeV and a fluence of $5 \cdot 10^{12}$ Kr^+/cm^2 in InSb occurs predominantly on the electron subsystem (Fig. 3), since they exceed nuclear losses by more than 400 times.

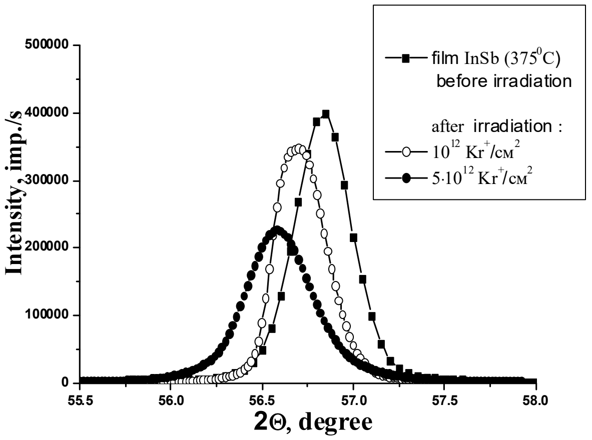

Fig. 1. Rocking curves of X-ray diffractometry of heteroepitaxial InSb (100) films deposited at a temperature of 375 °C on single-crystal GaAs substrates depending on the fluences of 10^{12} and $5 \cdot 10^{12}$ Kr^+/cm^2 of exposure to krypton ions with an energy of 145 MeV

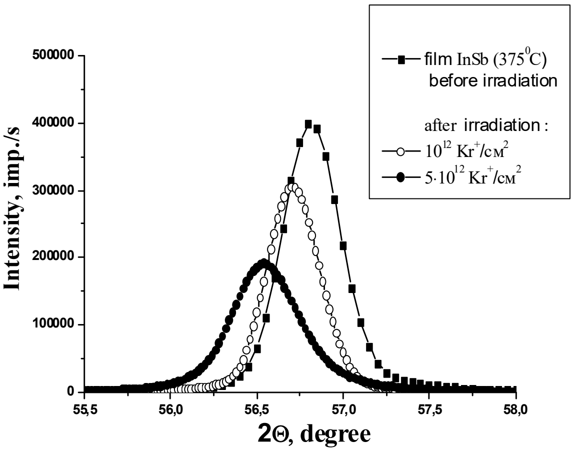

Fig. 2. Rocking curves of X-ray diffractometry of heteroepitaxial InSb (100) films deposited at a temperature of 430 °C on single-crystal GaAs substrates depending on the fluences of 10^{12} and $5 \cdot 10^{12}$ Kr^+/cm^2 of exposure to krypton ions with an energy of 145 MeV

Table 1. Change in macro- and microstresses in heteroepitaxial InSb (100) films on GaAs substrates depending on the film deposition temperature of 375 °C; 430 °C and the fluence of 10^{12} and $5 \cdot 10^{12}$ Kr^+/cm^2 of exposure to krypton ions with an energy of 145 MeV.

Temperature of InS film deposition, °C	Fluence of krypton ions with energy of 145 MeV, (cm^{-2})	Macrostress, GPa	Microstress, GPa
375	10^{12}	–0.1	0.096
	$5 \cdot 10^{12}$	–3.3	0.127
430	10^{12}	–0.1	0.096
	$5 \cdot 10^{12}$	–4.1	0.127

It is known that the SRIM program does not take into account the temperature of the electron subsystem of the material and therefore the calculations do not take into account the occurrence of such defects as tracks along the passage of high-energy ions. In the calculation work [5] with similar conditions of InSb irradiation using models and programs for heating the electron subsystem, it is shown that the temperature in the middle of the ion track is $9 \cdot 10^4$ K. InSb melts, then it recrystallizes and relaxes most of the point defects in it, after which an ion track of about 5-7 nm in size is formed. It is known that inside the recrystallization track structures, the density of the material is less than outside the material. As a result of the interaction of the damaged layer in the track area and the undamaged volume of the film, significant residual macrostresses are created. Track defects during irradiation with krypton with an energy of 145 MeV penetrate the film microcrystallites as a result of which microstresses also arise in the film microcrystallites themselves.

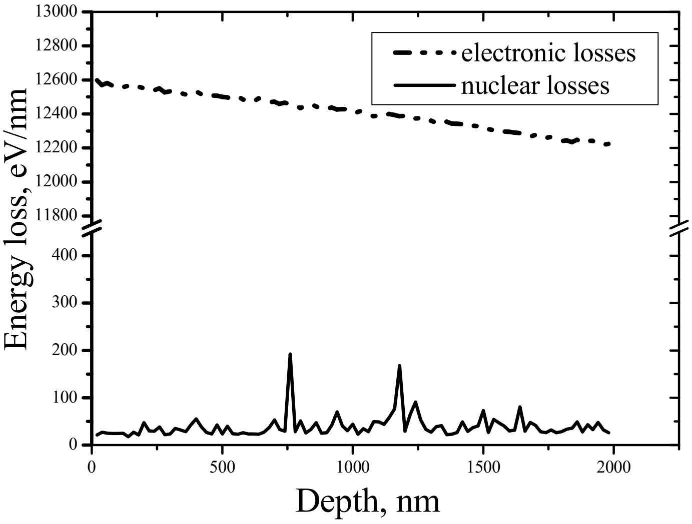

Fig. 3. Results of calculations in the SRIM program of the energy losses of krypton ions with an energy of 145 MeV and a fluence of $5\cdot10^{12}$ Kr^+/cm^2 in InSb with a thickness of 2 μm.

4. Conclusions

It has been established that after irradiation with krypton ions with an energy of 145 MeV and fluences of 10^{12} and $5\cdot10^{12}$ cm^{-2} of heteroepitaxial InSb films on single-crystal GaAs (100) wafers, significant macro- and microstresses arise in them with an increase in the krypton ion fluence, reaching, respectively, values by modulus of 4 and 0.1 GPa. The difference in the deposition temperature and the structural features of the initial heteroepitaxial films do not affect the dynamics of the accumulation of micro- and macrostresses in the films under the influence of krypton ions. Calculations using the SRIM program showed that the electron energy losses of krypton ions with an energy of 145 MeV in an InSb film 2 μm thick significantly exceed the nuclear losses. Based on the calculated data of the work and literature, it was revealed that the reason for the emerging high values of macro- and microstresses, krypton irradiation is the formation of volumetric track defects of krypton ions in the indium antimonide film.

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