Structure and electrical properties of heteroepitaxial InSb films after exposure to high-energy krypton ions

V. V. Uglov[1)], *A. K. Kuleshov*[1)], *S.V. Zlotski*[1)], *D. P. Rusalsky*[1)]

[1)] Belarusian State University, 4 Nezavisimosty ave., Minsk, 220030, Belarus

tel. +375172096257, e-mail: kuleshak@bsu.by

Abstract. The paper studies changes in the structure and electrical properties of InSb heteroepitaxial films on a single-crystal (100) GaAs base after irradiation with krypton ions with an energy of 145 MeV and fluences of 10^{12} and 5×10^{12} ion/cm^2. It is found that after irradiation with krypton ions, significant macro- and microstresses arise in the films, reaching values of 4.0 and 0.1 GPa in absolute value respectively. Based on the calculated data of the paper and the literature, it is assumed that the reason of the arising macro- and microstresses is the formation of track defects in the film. At the maximum fluence of krypton ions irradiation with 5×10^{12} ion/cm^2, the change in the electrical properties of the InSb heteroepitaxial film consists in an increase of resistivity and carrier concentration in more than 10 times. The mobility of charge carriers, the Hall constant and sensitivity to a magnetic field are significantly reduced.

Key words: epitaxial films, indium antimonide, radiation resistance, krypton ions, residual mechanical stresses, track defects, Hall constant, carrier concentration.

Introduction

Studies of the resistance of semiconductor materials to radiation effects are of great scientific and practical importance for expanding knowledge in the field of radiation materials science and their application in the space industry, nuclear power engineering, and other areas associated with ionizing radiation. High doses of ionizing radiation lead to the generation of radiation defects, structural changes, and other effects that have a negative impact on the properties of semiconductor materials and devices based on them. The narrow-band semiconductor of the $A^{III}B^{V}$ group – indium antimonide has wide practical application in solid-state microelectronics. This is due to the record high electron mobility in it in relation to other semiconductor compounds. At present, the technological capabilities of deposition of heteroepitaxial film structures of indium antimonide on gallium arsenide substrates make it possible to obtain properties similar to single crystals. The temperature of the GaAs substrate during indium antimonide deposition is the most important parameter determining the condensation mechanism, growth and degree of structural homogeneity and epitaxial perfection of InSb thin films. It has been shown in the literature that at temperature of GaAs plate in the temperature range of (375 – 430) °C, a InSb film with high-perfection heteroepitaxial structure is formed during explosive thermal deposition (Zhang et al., 2004; Taher et al., 2018; Debnath et al., 2004; Uglov et al., 2021).

It is known that a wide range of microelectronic sensors and 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 (Kamenskaya, 2007; Kolesnikova et al., 2021), when exposed to high-energy electrons, ɣ-quanta, protons, the electrophysical properties of the films exhibit radiation resistance that corresponds to operational dose loads in the range of 100 – 500 krad for spacecraft in near-earth orbit. It is promising to study the properties of heteroepitaxial InSb films under the action of higher radiation absorption doses to know the maximum operating time of microelectronic devices with InSb films on GaAs both in space and in other industrial applications. To create high dose loads of ion impact on structural changes in heteroepitaxial InSb films, irradiation with krypton ions with an energy of 145 MeV and fluences of 10^{12} and 5×10^{12} ion/cm^2 was used in this work. The impact of high-energy ions can lead to various types of radiation damage in the heteroepitaxial film, including the generation of point radiation defects, their accumulation, etc. The formation of volume defects in the film in the form of "tracks" has the strongest effect on the electrical properties. Tracks are formed as a result of rapid intense radiation heating and melting in the region of passage of a high-energy ion (Gaiduk, 2009) accompanied by processes of ultrafast crystallization and the formation of a volume defective region with a density lower than that of the undamaged material (Suvorova et al., 2022). As a result of track formation, mechanical stresses may arise, the concentration and mobility of charge carriers in the film may change, and other effects may occur.

Thus, the aim of the work is to study structural changes in the heteroepitaxial InSb film associated with mechanical stresses, changes in the complex of electrical properties in a magnetic field (concentration, mobility of charge carriers, Hall constant, etc.) after exposure to high-energy Kr ions with an energy of 145 MeV and fluences of 10^{12} and 5×10^{12} ion/cm^2.

Materials and experimental details

The objects of study in this work were heteroepitaxial InSb films on single-crystal (100) GaAs wafers obtained by explosive thermal evaporation. To obtain high-quality heteroepitaxial InSb films, the deposition temperature was 375 °C (Uglov et al., 2021). The film thickness measured with a profilometer was (2,0 ± 0,1) μm. The methods for measuring the electrical properties of films in a magnetic field are described in (Uglov et al., 2021). Irradiation with krypton ions was carried out at the Institute of Nuclear Physics of the National Nuclear Center, Almaty, Kazakhstan. When irradiated with krypton ions, the film sample was mounted on a water-cooled holder with a temperature of 20°C. The current of the beam of Kr ions with an energy of 145 MeV was about 500 nA for the entire irradiation area 16 cm^2. Thermal imaging data taken immediately after irradiation showed a temperature on the film sample in the range of 30-40°C.

Structural changes in InSb films after ion irradiation with Kr ions were investigated using the rocking curves X-ray diffractometry method. The use of the rocking curves X-ray diffractometry method allows one to determine structural changes in epitaxial semiconductor films with a higher accuracy than under standard X-ray diffraction method conditions. The structural parameters were determined by the shift in the position and broadening of the diffraction peak (100) of InSb after irradiation on the rocking curves relative to the unirradiated InSb film. Note that the value of the interplanar distance of (100) InSb of the unirradiated film was very close to the reference value from the ICDD-PDF2 database. In the general case, the full width of the diffraction peak at half maximum (β) is determined by microstresses in microcrystallites, the size of 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 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 then in the work, diffraction peaks "clean" from the instrumental broadening were used in the calculations.

The surface morphology and roughness of indium antimonide films obtained on single-crystal gallium arsenide substrates before and after krypton irradiation were studied by atomic force microscopy (AFM) using a Solver P47 PRO scanning probe microscope. The surface morphology was studied by the constant force method in the amplitude modulation mode using contactless silicon cantilevers with a tip curvature radius of 10 nm.

The data of atomic force microscopy showed in Table 1 show that there was no change in the size of the average roughness (S_a), This means that there was no change in the size of the film microcrystallites under the action of the applied krypton ion irradiation.

Table 1. The average roughness (Sa), the skewness factor (S_{sk}) and the kurtosis factor (S_{ka}) before and after exposure to krypton ions with 145 MeV Kr ions up to a fluence of 5×10^{12} cm^{-2}.

Fluence of krypton ions with energy of 145 MeV, ion/cm^2	S_a, nm	S_{sk}	S_{ka}
Initial InSb film	5.0	1.5	13.6
5×10^{12}	5.2	1.6	12.1

The data of atomic force microscopy showed in Table 1 show that there was no change in the size of the average roughness (Sa), This means that there was no change in the size of the film microcrystallites under the action of the applied krypton ion irradiation.

Then, the change in the full width of the diffraction peak at half-maximum is determined by the microstresses of the film crystallites, which were calculated using the known relationship (Bowen et al., 2002):

$$\varepsilon = \frac{\beta}{4tg\theta},$$

where β is the integral width of the diffraction reflection at half-maximum associated with the microstress, $\varepsilon=\Delta d/d$ is the relative microstress or deformation of the crystallites, Δd is the maximum deviation of the interplanar distance for a given (100) InSb diffraction line from the value of the center of gravity of the experimental interplanar distance d, θ is the angular value of incidence of X-rays determined for the experimental film corresponding to InSb (100). To obtain the film microstress in Pa, the value of the relative microstress was multiplied by the literature value of Young's modulus.

The magnitude of residual macrostresses (σ) arising under the influence of krypton ion action in the InSb film was determined using the relation (Bowen et al., 2002):

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

where d is the interplanar distance of (100) InSb of the irradiated sample, d_0 is the interplanar distance of the original (100) InSb, E is Young's modulus, ν is Poisson's ratio. Literature data were used for the values of Young's modulus and Poisson's ratio of InSb: E = 4.09×10^{10} Pa, ν = 0.35).

Result and discussions

The results of the study of heteroepitaxial (100) InSb films on single-crystal (100) GaAs substrates and the effect of krypton ions with an energy of 145 MeV and total fluences of 10^{12} and 5×10^{12} ion/cm^2 using the rocking curve method of X-ray diffractometry are presented in Fig. 1.

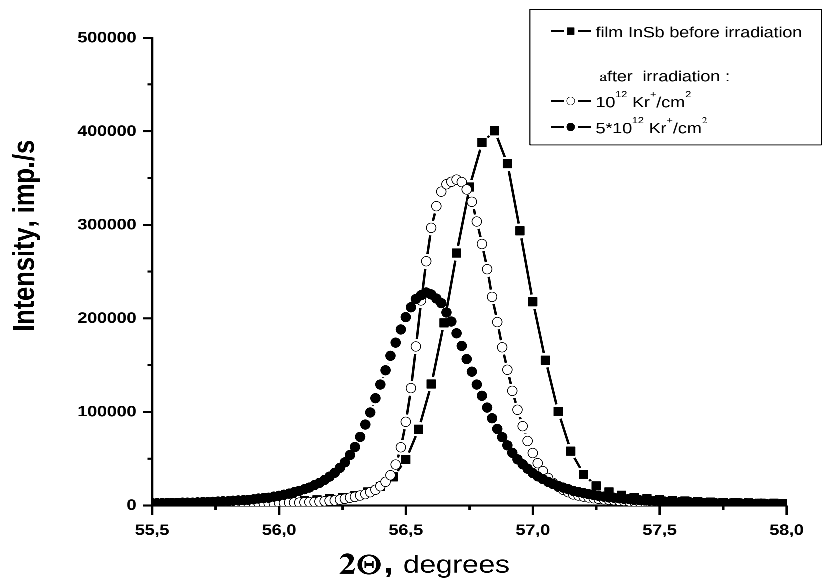


Figure 1. Rocking curves of X-ray diffractometry of heteroepitaxial (100) InSb films deposited at a temperature of 375 °C on single-crystal GaAs substrates irradiated by krypton ions with an energy of 145 MeV and fluences of 10^{12} and 5×10^{12} ion/cm^2

The calculated data from the rocking curves of micro- and macrostresses of the heteroepitaxial (100) InSb film after exposure to krypton ions in accordance with the method described above are presented in Table 2.

Table 2. Changes in macro- and microstresses in heteroepitaxial (100) InSb films on GaAs substrates depending on the fluence of krypton ion irradiation with an energy of 145 MeV

Fluence of krypton ions with energy of 145 MeV, ion/cm^2	Macrostress, GPa	Microstress, GPa
10^{12}	– 0.1	0.096
5×10^{12}	– 4.0	0.127

The data presented in Fig. 1 and the Table 2 show the occurrence of macrostresses (compressive) and microstresses with increasing krypton irradiation fluence of InSb films. It is unlikely that the cause of such structural changes in the films is associated with the accumulation of point defects that arise as a result of atomic displacements during nuclear losses.

The calculation of the energy losses of krypton ions in a 2 μm thick film 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 5×10^{12} ion/cm^2 in InSb occurs predominantly on the electron subsystem, since electron losses exceed nuclear losses by more than 400 times.

It is known that the SRIM program does not take into account the change in temperature of the electronic subsystem of the material and therefore the calculations do not take into account the occurrence of melting regions along the passage of high-energy ions.

To discuss and evaluate the possibility of track formation at high electron losses under the action of 145 MeV krypton ions on indium antimonide, previously published calculation data (Teterukov et al., 2023) were used, in which models and programs for heating the electron subsystem were used taking into account the data of electron losses calculated by the SRIM program. It was shown that the heating temperature of the electron subsystem reaches the melting temperature of InSb, i.e. “tracks” or areas of radiation melting with a diameter of several nm are created. We assume that as a result of the formation of a track region with a density lower than before irradiation, residual macrostresses are created in the entire film. Track defects are also formed in the film microcrystallites, which leads to the formation of microstresses.

As a result of the passage of krypton ions with an energy of 145 MeV, areas of "track" defects are created in the indium antimonide film. That is, in the track area, the material was melted and crystallized very quickly. The density of the material in such "track" quickly remelted areas is significantly less than in the volume of the film material. As a result, compressive mechanical stresses arise in the film.

Table 2 presents the results of changes in electrical properties (sensitivity of the Hall voltage to the magnetic field (γ), concentration (n), and carrier mobility (μ)) before and after irradiation with krypton ions at room temperature.

Table 2. Hall sensitivity (γ), carrier concentration (n), carrier mobility (μ) of heteroepitaxial indium antimonide films, depending on the krypton ion irradiation fluence

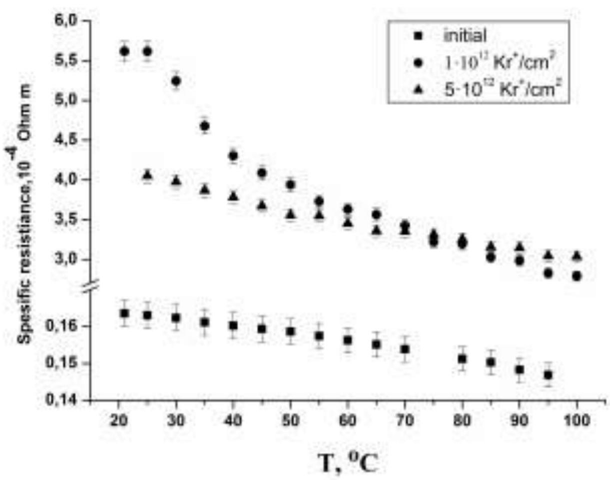
Krypton ion fluence, ion/cm^2	γ, mV×T^{-1}	n, cm^{-3}	μ, cm^2×V^{-1}×s^{-1}
initial	127.5	$(2.23 \pm 0.15) \times 10^{17}$	$(17.2 \pm 1.2) \times 10^3$
10^{12}	518.4	$(5.47 \pm 0.38) \times 10^{16}$	$(2.03 \pm 0.14) \times 10^3$
5×10^{12}	11.8	$(2.40 \pm 0.17) \times 10^{18}$	642 ± 4.5

It follows from the data in the Table 2 that with an increase in the irradiation fluence of krypton ions, the mobility of charge carriers and the Hall sensitivity decrease significantly, and the concentration of carriers at the maximum irradiation fluence increases significantly.

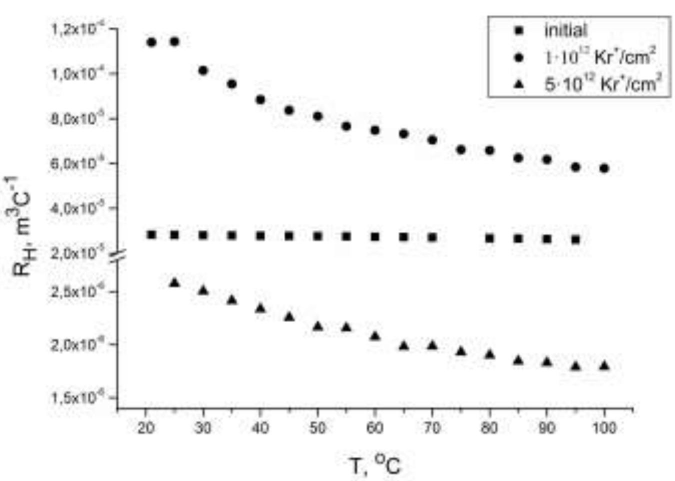
It is assumed that the observed changes occur as a result of the formation of acceptor-type defects (at a fluence of 10^{12} ion/cm^2) or donor-type defects (at a fluence of 5×10^{12} ion/cm^2) that change the position of the Fermi level in the irradiated film relative to the “reference” Fermi level of the original film.

The results of the studies of resistivity and the Hall coefficient of the initial and krypton ion-irradiated heteroepitaxial indium antimonide films in the temperature range from room temperature to 100 °C are presented in Fig. 2.

It follows from the obtained data that the resistivity and Hall constant of heteroepitaxial indium antimonide films increase at a krypton ion irradiation dose of 10^{12} ion/cm^2 to 5.61×10^{-4} Ω×m. A further increase in the krypton ion irradiation dose to 5×10^{12} ion/cm^2 leads to a decrease in the resistivity of the films to 4.1×10^{-4} Ω×m at room temperature. The concentrations and nature of radiation defects created by krypton ion irradiation in the indium antimonide film determine changes in the resistance and Hall constant, as well as the mobility and concentration of carriers.



a



b

Figure 2. Temperature dependences of the resistivity (a) and Hall coefficient (b) of heteroepitaxial indium

antimonide films before and after irradiation with krypton ions with an energy of 145 MeV with fluences of 10^{12} and 5×10^{12} ion/cm^2

According to the amphoteric defect model (Kamenskaya, 2007; Brudny, 2005), the type of dominant defects is determined by the position of the "defect" Fermi level relative to the position of the standard Fermi level. It is known that in undoped InSb, antimony vacancies act as a donor, and indium vacancies act as an acceptor. Based on this model, experimental dependences of changes in electrical properties are explained. It is assumed that acceptor-type defects (indium vacancies) are formed in the film when irradiated with krypton ions with an energy of 145 MeV and a fluence of 10^{12} ion/cm^2. An increase in fluence to 5×10^{12} ion/cm^2 when irradiated with krypton ions leads to a shift of the "defect" Fermi level below the standard level. In this case, the formation of more energetically favorable defects in the form of donor complexes of antimony vacancies is possible, resulting in an increase in the concentration of charge carriers and a decrease in the electrical resistivity at the maximum irradiation fluence of 5×10^{12} ion/cm^2.

Conclusions

It has been established that after irradiation by krypton ions with an energy of 145 MeV and fluences of 10^{12} and 5×10^{12} ion/cm^2 in heteroepitaxial InSb films on single-crystal (100) GaAs plates, macro- and microstresses arise, reaching values of 4.0 and 0.1 GPa in absolute value respectively. Based on the calculated and literature data, it is assumed that the reason for the arising stresses is high ionization losses of krypton ions leading to melting of the material volume along the trajectory of krypton ions and the formation of "tracks"– defective areas with a reduced density during crystallization.

At the maximum fluence of 5×10^{12} ion/cm^2 of krypton irradiation, the electrical properties of the InSb heteroepitaxial film change as follows: the resistance and carrier concentration increase; the mobility of charge carriers, the Hall constant, and the sensitivity to the magnetic field decrease. This probably occurs as a result of the formation of both track defects and the formation of vacancy complexes of donor-type antimony defects.

This work was carried out within the framework of the state scientific project of the Republic of Belarus “Radiation-resistant heteroepitaxial structures of indium antimonide on gallium arsenide substrates”.

References

Zhang T., Clowes S. K., Debnath M., Bennett A., Roberts C., Harris J. J., Stradling R. A., High-mobility thin InSb films grown by molecular beam epitaxy. *Applied Physics Letters*. Vol. 84 (22), pp. 4463–4465, 2004.

Taher Md. Abu., Effect of substrate temperature on the properties of vacuum evaporated thin InSb films. *DIU Journal of science and technology*. Vol. 13 (1), pp. 39−43, 2018.

Debnath M.C., Zhang T., Roberts C., Cohen L.F., Stradling R.A., High-mobility InSb thin films on GaAs (001) substrate grown by the two-step growth process. *Journal of Crystal Growth*. Vol. 267, pp. 17-21, 2004.

Uglov V.V., Drapezo A.P., Kuleshov A.K., Rusalsky D.P., Kolesnikova E.A., Effect of explosive thermal evaporation conditions on the phase composition, crystallite orientation, electrical and magnetic properties of heteroepitaxial InSb films on semi-insulating GaAs (100). *High Temperature Material Processes*. Vol. 25 (1), pp. 71−80, 2021.

Kamenskaya I.V. *Electrophysical and tensoelectric properties of InSb and GaSb irradiated with electrons, protons and neutrons*: Abstract of Cand. Sci. (phys.-math.) diss., Siberian Institute of Physics and Technology; Tomsk State Pedagogical University Tomsk, pp. 23, 2007. (in Russian).

Kolesnikova E. A., Uglov V. V., Kuleshov A. K., Rusalsky D. P., Gurinovich V. A., Radiation stability of sensors made on the basis of n-InSb-i-GaAs. *Interaction of radiation with a solid body: materials of the 14th International Conference*. BSU, Minsk, pp. 530–533, 2021. (in Russian).

Gaiduk P. I. Formation and annealing of track defects in thin layers of Si0.5 Ge0.5 alloy. *BSU Bulletin*. Ser. 1., № 1, pp. 37-41, 2009. (in Russian).

Suvorova E. I., Degtyarenko P. N., Ovcharov A. V., Vasiliev A. L., Influence of the structure of ion tracks in YBCO on the superconducting properties of composite wires. *Surface. X-ray, synchrotron and neutron studies*. №. 2, pp. 26–32, 2022. (in Russian).

Bowen D. K., Tanner B. K., *High-resolution X-ray diffractometry and topography: monograph*. Moscow: Nauka, pp. 256, 2002. (in Russian).

Teterukov E.V., Uglov V.V., Kuleshov A.K., Kolesnikova E.A., Rusalsky D.P., Modeling of temperature fields and track formation in indium antimonide during irradiation with high-energy krypton ions. *Proc. of the 15th International Conference*. Minsk, Belarus, pp.136-138, 2023.

Brudny V. N., Radiation effects in semiconductors. *Bulletin of Tomsk State University*. № 285, pp. 96-102, 2005. (in Russian).