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Defect Transformations in Ion Bombarded InGaAsP

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Damage buildup and defect transformations at temperatures ranging from 15 K to 300 K in ion bombarded InGaAsP epitaxial layers on InP were studied by *in situ* Rutherford backscattering/channeling measurements using 1.4 MeV ^{4}He ions. Ion bombardment was performed using 150 keV N ions and 580 keV As ions to fluences ranging from 5×10^{12} to 6×10^{14} at./cm^2. Damage distributions were determined using the McChasy Monte Carlo simulation code assuming that they consist of randomly displaced lattice atoms and extended defects producing bending of atomic planes. Steep damage buildup up to amorphisation with increasing ion fluence was observed. Defect production rate increases with the ion mass and decreases with the implantation temperature. Parameters of damage buildup were evaluated in the frame of the multi-step damage accumulation model. Following ion bombardment at 15 K defect transformations upon warming up to 300 K have also been studied. Defect migration beginning above 100 K was revealed leading to a broad defect recovery stage with the activation energy of 0.1 eV for randomly displaced atoms and 0.15 eV for bent channels defects.

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1. Introduction

The InGaAsP/InP semiconductor system has attained much interest for optoelectronic devices in the 0.95–1.65 μm wavelength region. Especially InGaAsP/InP buried heterostructure (BH) laser diodes have considerable potential for the use in a long distance and high capacity optical fiber communication systems due to their low threshold current, high quantum efficiency, and stable lateral-mode operation at high temperatures. Such photodevices can also be applied in a radiation environment, typical for the space or nuclear plants.

Modification of semiconductor properties by ion implantation is a well-established technological process. For structures based on compound semiconductors it is used for electrical doping, compositional mixing of quantum wells and formation of isolation regions. Point defects and their complexes determine optical and electrical properties of semiconductors, diffusion of impurities as well as the recovery of crystalline lattice after ion bombardment and subsequent annealing. Broad recovery stage at low temperatures exists for III–V semiconductor compounds [1–4]. It is located between 100 K and 400 K and is attributed to the recombination or reconfiguration of a variety of defects with different activation energy. Thus, the investigation of thermally activated processes can be decisive for identification of defects. On the other hand, defect mobility at 300 K (RT) can lead to important defect transformation after RT implantation and subsequent storage. Hence, structure and distribution of radiation defects are of great scientific and technological interest and their reproducible control is crucial for electrical and structural properties of implanted materials.

In this paper we review the results of the study of defect buildup and recovery in InGaAsP compound after 150 keV N-ion and 580 keV As-ion bombardment at temperatures below 15 K (LT) and subsequent warming up to RT. This process was monitored by *in situ* Rutherford backscattering/channeling (RBS/c) measurements. Since the objective of this work was to elucidate the properties of point defects and their complexes different ion bombardment was applied. N-ions produce principally diluted binary collision cascades and are well suited for the study of simple defects. On the other hand, As-ions produce more dense collision cascades, which lead to the formation of extended defects.

2. Experimental

$In_{0.82}Ga_{0.18}As_{0.52}P_{0.48}$ epitaxial layers were grown on (001) InP substrates using the metal-organic vapor phase epitaxy (MOVPE) technique in the Aixtron AIX200RD reactor at the Institute of Electronic Materials Technology, Warsaw. In order to prevent decomposition of the surface all structures were capped with 50 nm thick InP layers. Epitaxial layers of $In_{0.82}Ga_{0.18}As_{0.52}P_{0.48}$ composition are lattice matched to InP substrates and consequently they are not strained due to the pseudomorphic growth.

Experiments were carried out using the Romeo and Julia two beam facility at Institute of Solid State Physics, Friedrich Schiller University Jena (Germany). The

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beams delivered by the ion implanter Romeo were used to produce defects, while the tandem accelerator Julia equipped with a 3-axis goniometer was applied for *in situ* ion-channeling (RBS/c) measurements. Virgin and implanted samples were analyzed with RBS/c using 1.4 MeV ^{4}He-ions. The experiments were carried out following two schemes:

(i) Epitaxial layer was implanted to increasing fluences of 150 keV N-ions or 580 keV As-ions until amorphisation was attained; damage buildup was monitored by *in situ* RBS/c measurements. This procedure was performed at two temperatures: 15 K and RT. In order to avoid sample heating upon ion implantation beam current density was kept below 1 μA/cm^2.

(ii) Epitaxial layers were implanted at 15 K and subsequently analyzed *in situ* by RBS/c and stepwise warmed up to RT. At each selected temperature the sample was stored for 10 min and then cooled up to 15 K where aligned RBS/c spectra were measured. Next, the sample was warmed to the higher preset temperature and the whole procedure was repeated. Such a procedure allows the analysis of channeling data without the necessity of taking into account changes of thermal vibration amplitudes of crystal atoms at different temperatures.

The Monte Carlo computer code McChasy described in detail elsewhere [5] was used for the purpose. A new function, the *bent channel model* [6] in the Monte Carlo simulations for channeling in single crystals containing extended defects such as: clusters, dislocations, loops, stacking faults, etc. was used. It allows quantitative separation of contributions from direct scattering (randomly displaced atoms, RDA) and dechanneling by extended defects (bent channels, BC).

3. Results

Figure 1 shows the random and (001) aligned spectra for InGaAsP, epitaxial layer taken at 15 K prior to and after ion bombardment to different fluences of 150 keV N-ions. The solid line shows the results of MC simulations performed for a best fit to the damage peak located in the energy interval 950–1200 keV assuming RDA and BC defects. Damage buildup curves for these two types of defects are shown in Fig. 2a and b. They show the amorphous fraction defined as the ratio of damage content in a given depth interval to the corresponding random yield, n_d (a), and the normalized BC defect concentration, n_v (b), as a function of ion fluence. In order to be able to compare the irradiation effects of different mass and energy ions the ion fluence was expressed in units of displacements per atom (dpa) [7]. 1 dpa corresponds to each atom in the lattice being displaced 1 time on average, at the peak damage depth of the material. The number of dpa of a material serves as its quantitative measure: dpa $= \frac{C_i \Phi}{A}$ where C_i is the number of displacements per ion per unit depth in the sample thickness as calculated using the Monte Carlo computer code SRIM [8], A is the atomic density of the target and Φ is the ion fluence. Value of dpa = 0 indicates a perfectly crystalline material whereas dpa = 1 indicates a completely amorphous material.

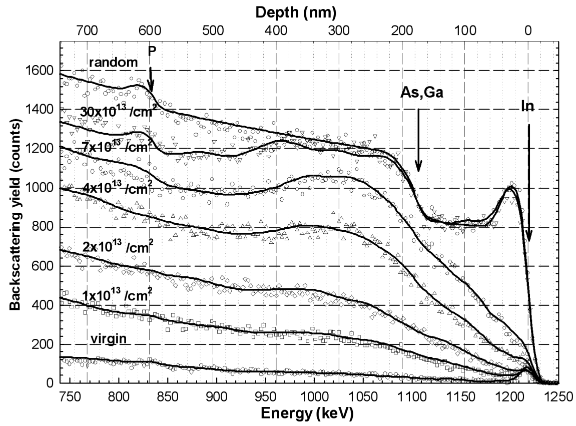

Fig. 1. Random and aligned RBS spectra for (100) InGaAsP epitaxial layers bombarded at 15 K to different fluences of 150 keV N-ions.

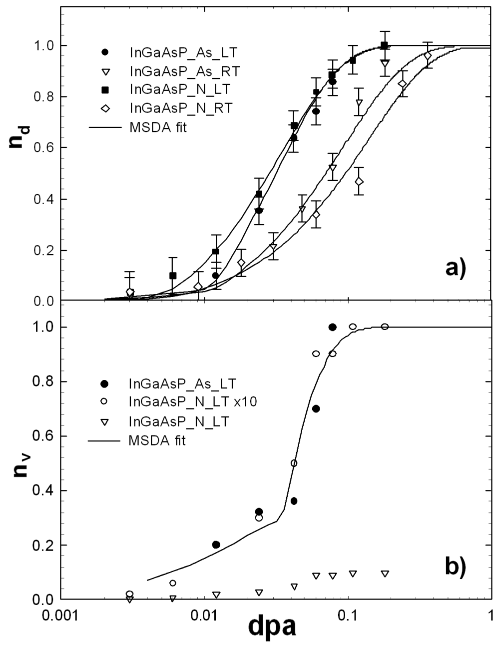

Fig. 2. Accumulated damage in InGaAsP epitaxial layers bombarded with 150 keV N-ions and 580 keV As--ions. Solid lines are fits to RBS/channeling data using the MSDA model.

Surprisingly, a rather small difference was observed in defect production efficiency at LT between As- and N-ion bombardment. Damage ingrowth is much slower for ion bombardment at RT. Temperature dependence of defect production efficiency is a strong indication that important defect transformations occur at RT or even at lower temperatures. Concentration of BC defects for As-ion bombardment at LT is about ten times larger than that produced by N-ions. Apparently the reason is the differences in the density of produced collision cascades. Furthermore, it has been observed that BC defects produced by N-ion bombardment disappear after warming to RT, whereas those due to As-ion bombardment remain unchanged. Here again this can be related to the size of formed defect clusters. Much denser collision cascades produced by As-ion bombardment lead to the formation of defects of much higher binding energy. The multi-step damage accumulation (MSDA) model has been applied for data analysis [9, 10]. The best fit has been attained assuming a two-step process.

Figure 3 shows aligned spectra for InGaAsP epitaxial layer bombarded at 15 K with 1.8×10^{13} N/cm^2, which corresponds to 0.13 dpa [7] and subsequently warmed up to RT. Here a typical damage peak was formed although the bombarded fluence was quite small. No changes of the damage peak were observed until a temperature of above 100 K was reached. Continuous decrease of the defect concentration with increasing temperature is clearly visible. The damage peak does not disappear completely at RT. Similar set of spectra was measured for samples implanted with 580 keV As-ions to the fluence of 1.0×10^{12} at./cm. Dpa value for this case was somewhat smaller i.e. 0.07. In both cases the ion fluence was small enough to avoid subsequent cascade overlap.

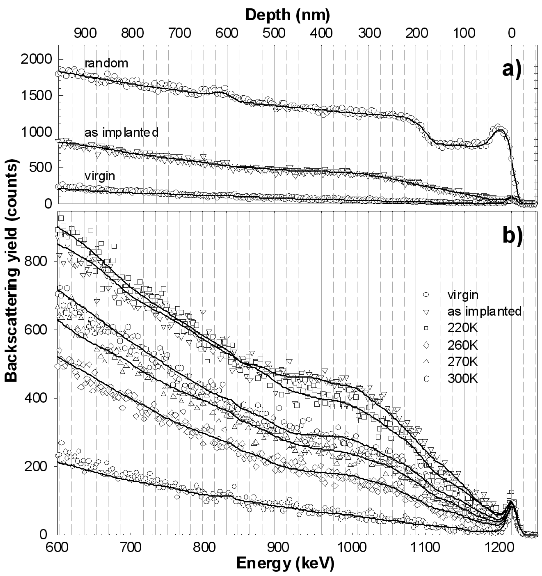

Fig. 3. (a) Random and aligned (virgin and implanted) RBS/c spectra for InGaAsP epitaxial layer bombarded at 15 K with 150 keV N ions to the fluence of 1.8×10^{13} at/cm^2, (b) evolution of aligned RBS/c spectrum for implanted layer shown in (a) during warming to RT.

Figures 4a and b show damage recovery curves calculated from spectra shown in Fig. 3 for RDA and BC defects, respectively. The broad recovery stage begins at approximately 150 K for RDA and above 200 K for BC defects. The solid line presents the fit to Arrhenius equation $n = 1 - a\mathrm{e}^{-(\frac{E_\mathrm{a}}{kT})}$, where n is normalized defect content, E_a is the activation energy and a is normalization factor. Activation energies estimated from plots in Fig. 4 were listed in Table.

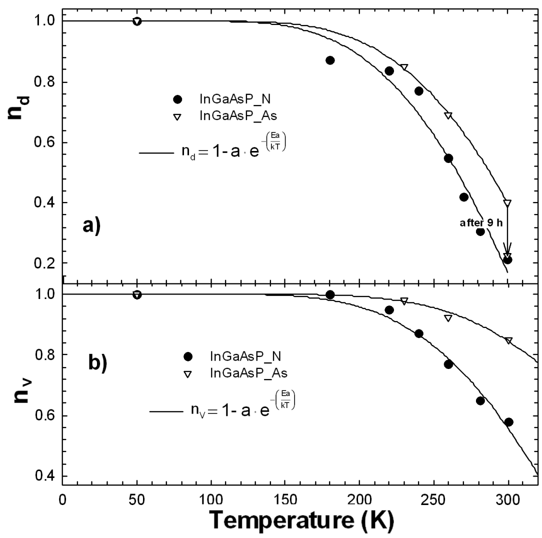

Fig. 4. Damage recovery curves calculated for RDA (a) and BC (b) defects in N- and As-ion implanted InGaAsP epitaxial layers during the warming from 15 K to 300 K. The solid lines show the fit to the Arrhenius equation.

TABLE

Activation energies for defect recovery in InGaAsP.

E_a [eV]			
RDA_N	RDA_As	BC_N	BC_As
0.103	0.115	0.130	0.160

The used experimental setup does not allow direct measurements above RT, however, the prolonged storage at RT after warming up leads to the further reduction of defect content, thus indicating that the recovery stage extends above RT.

4. Discussion and conclusions

Although ion bombardment processes in compound semiconductors have been studied quite extensively over the few last decades, a lack of understanding remains on the fundamental mechanism of dynamic annealing that controls the damage buildup and amorphization of these materials. In contrast to the usually applied Gibbons model [11], in which a continuous growth of amorphous damage clusters has been assumed, the MSDA model is based on the fact that at a specific fluence phase transformations in bombarded crystals occur, which are visualized as steps in the defect buildup curve.

In the case of InGaAsP a two-step process has been revealed. This is especially clear for the BC type of defects. Our previous research has indicated that ion bombardment of InP [12] as well as InGaAs [13] induces decrease of the lattice parameter leading to a compressive stress. The same effect should be also effective in the case of InGaAsP. Hence, in the first stage of defect accumulation defects are formed that in spite of the fact that they produce biaxial stress along (100) are hardly visible by RBS/c. Such defects can be (100) stacking faults. When the critical value of stress has been attained, at the beginning of stage two crystalline layers collapse to a structure containing large concentrations of a variety of extended defects and defect clusters.

Damage recovery of RDA in InGaAsP at low temperatures did not reveal important differences between As- and N-ion bombardments. Since simple defects are immobilized at 15 K and the vast majority of them can neither cluster nor form extend defects. Karsten and Ehrhart [4] observed in electron irradiated InP no change of lattice parameter with radiation damage buildup and concluded that lattice displacements introduced by interstitial atoms and vacancies are of the same magnitude leading to the strain compensation. In-interstitials are mobile at RT and can be easily trapped by other defects, most probably antisites, forming stable complexes [14]. According to Törnquist et al. [15] vacancies become mobile at temperatures above 450 K, hence no vacancy clusters should be formed at RT.

Recovery curve for BC defects follows the same function as that for RDA. Dissolution of BC defects begins at above 200 K by letting free simple defects, which can migrate and recombine in the same manner as RDA's. As a consequence the activation energy for BC defects is given by $E_{\mathrm{a}} = E_{\mathrm{b}} + E_{\mathrm{m}}$, where E_{b} is the binding energy of defect cluster and E_{m} is the migration energy. The later is approximately equal to the E_{a} for RDA.

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