

InPAs Alloys Use for Electrical Engineering in Hard-radiation Environment

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Abstract — Effective functioning of electronics in high-radiation environment requires developing of novel semiconductor systems with radiation-tolerant properties. In given work, in search of semiconductor materials with immunity to radiation, investigations have been focused on $\text{InP}_x\text{As}_{1-x}$ alloys. Investigating of electrical and optical characteristics and physical processes, flowing in heavily irradiated $\text{InP}_x\text{As}_{1-x}$ alloys under high fluences of high-energy electrons and fast neutrons, let us create new generation of radiation-resistant semiconductor materials for electrical engineering application in hard-radiation environment.

Index Terms — Semiconductor alloys, current carriers' concentrations, electronics, radiation defects.

I. INTRODUCTION

The semiconductor electronics represent the main basis of the scientific and technological revolution realized in the XXI century. Therefore, there is a growing interest in electronic materials and devices due to their huge potential in many applications of modern technique. Unfortunately, the most important parameters of devices dramatically worsen under radiation. At the same time radiation-resistant, semiconductor devices are irreplaceable elements for investigations in Space (artificial Earth satellite, interplanetary spacecraft, probes, rockets) and for investigation of elementary particles on accelerators, for atomic power stations, nuclear reactors, robots, operating at radiation heavily contaminated territories.

Protection against radiation is significantly difficult. A reasonable estimation of radiation fields, and properly selected technology (shielding of devices against damaging action of radiation, matching the optimal design topology of circuits and architecture of devices) can only expand a scope of semiconductor devices. The mitigation technique

of radiation protection is not always sufficient and effective. However, the base of all constituent units of semiconductor devices and the determining element in the device's operation is a semiconductor material itself. The basic materials for modern electronic engineering Si and GaAs, due to the features of the band structure, rapidly develop high electrical resistance under radiation and there always appear radiation centers, grasping current carriers. Fig.1 (for GaAs) and Fig. 2 (for Si) show, that the current carriers' concentration and the electrical conductivity in GaAs and Si can reduce in five-six orders under the irradiation. As a result, semiconductors turn into semi-insulator and approach to the dielectric state.

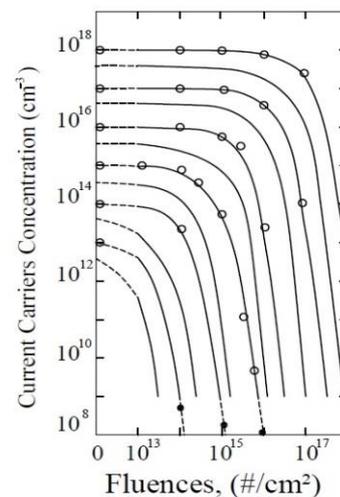


Fig. 1. The dependence of the current carriers' concentration on the fluences of fast neutrons for GaAs samples with different initial concentration of electrons: \circ - experiment, \bullet - extrapolation [1].

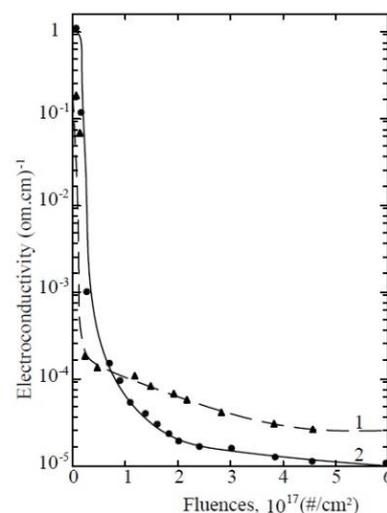


Fig. 2. The dependence of the electrical conductivity on the fluences of fast

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neutrons for *p*-type (curve 1) and *n*-type (curve 2) Si samples [2].

Today requirements to existing materials exceed their possibilities. Therefore, one of the problems of electronics industry is looking for the other materials with improved radiation characteristics and developing their technology for obtaining semiconductor materials tolerant to hard radiation. Investigations in search of radiation-resistant semiconductor materials should be focused on binary, ternary, and quaternary complex semiconductor materials on the base of III-V compounds.

The unique radiation properties of InAs, which are strictly opposed to InP according [3]-[6] in terms of formation of radiation defects, have led us to the idea of creating electrical and optical radiation-tolerant semiconductor materials on the base of $\text{InP}_x\text{As}_{1-x}$ alloys.

The key parameters, which determine the stability of functioning and the efficiency of almost all semiconductor devices, are the electrical properties and band gap of semiconductor material. Therefore, the main goal of our presentation is creating of radiation-resistant materials for high-efficient use in devices, in which electrical properties and band gap do not change even after the irradiation by high fluences of radiation of high-energy electrons ($E=50\text{MeV}$, $\Phi=6.0 \cdot 10^{17}$ electrons/cm²) and fast neutrons ($\Phi=2 \cdot 10^{18}$ neutrons/cm²).

II. EXPERIMENTAL

Bulk single crystals of $\text{InP}_x\text{As}_{1-x}$ alloys with impurity content in the range of $1 \cdot 10^{16}$ - $2 \cdot 10^{19}$ cm⁻³ have been synthesized and grown from stoichiometric melt in quartz ampoules by the method of horizontal zone fusion on three zones equipment of growing decomposing III-V semiconducting compounds. Doping has been implemented by Te and Zn. Bulk single crystals of $\text{InP}_x\text{As}_{1-x}$ alloys with impurity content in the range of $1 \cdot 10^{16}$ - $2 \cdot 10^{19}$ cm⁻³ have been synthesized and grown from stoichiometric melt in quartz ampoules by the method of horizontal zone fusion on three zones equipment of growing decomposing III-V semiconducting compounds. Doping has been implemented by Te and Zn. The obtained samples were *n*-type. The homogeneity of the samples for measurements has been determined by dispersive X-ray spectroscopy. Researching samples have been irradiated in the vertical channels of a reactor. For weakening of thermal and resonance neutrons fluences the samples were wrapped up in an indium foil or placed into indium container and then—into the cadmic case. The measurements of electrical and optical properties were implemented before and after irradiation. For induced radioactivity decay the investigation of irradiated samples was carried out after their soaking at 300K during half a year.

III. RESULTS AND DISCUSSION

Under severe radiation condition extremely complex processes are developed in the crystal lattice of semiconductors, among them III-V type compounds, as the

result of the collision of high-energy nuclear particles with atoms. There appears multitude of various types of crystal lattice defects: point types defects, vacancies, their associations with each other and impurities, clusters.

In the case of hard irradiation large defects and disordered regions appear simultaneously too. The picture is even more complicated in the case of multicomponent alloys. Even lattice amorphization is possible under the extreme large doses of radiation. The introduction of defects and their associations under radiation is the reason of appearance of local levels in the band gap and accordingly changes in electrical and optical properties of semiconductor materials.

A. Electrical Properties

Radiation causes changes of both current carriers' mobility and current carriers' concentration. Usually, the significant changes are observed for charge carrier's concentration. It is known, that in InAs, like other semiconductors and diamond group of III-V compounds, radiation introduces defects as a donor and an acceptor type. But in [4]-[6] it is shown unique radiation property of InAs crystals: radiation creates defects mainly of donor type and electrons concentration increases at any conditions of irradiation. Fermi level stabilizes at the bottom of the conductivity zone. This takes place both at irradiation with fast neutrons, protons, ions, electrons (relatively low—1MeV, 3MeV, 4MeV, and high—50MeV energy), and at the change of radiation temperature, independently of the degree, type, and quantity of preliminary doping. This phenomenon is in contrast to other materials behavior under radiation (including InP, Si and GaAs), in which irradiation always creates radiation centers, trapping electrons.

Our investigations of the dependence of the electron's concentration on the fluences of high-energy electrons and fast neutrons have revealed preservation of unique radiation properties of InAs in InAs-rich $\text{InP}_x\text{As}_{1-x}$ alloys. Fig.3 shows the typical results of investigations of $\text{InP}_x\text{As}_{1-x}$ alloys under high-energy electrons radiation.

Current carrier's concentration increases with the increase of fluencies of high-energy electrons in InAs-rich $\text{InP}_x\text{As}_{1-x}$ alloys for compositions up to $x=0.2$ (Fig. 3, curve 1).

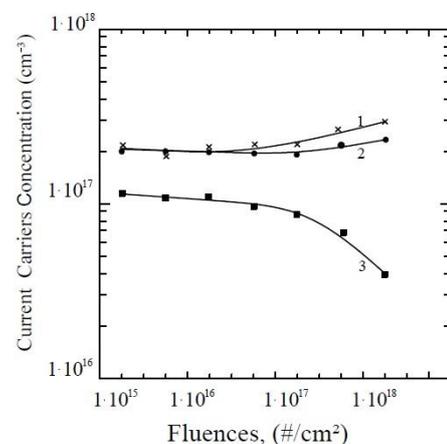


Fig. 3. The dependence of the current carriers' concentration on the fluences of high-energy electrons for $\text{InP}_x\text{As}_{1-x}$ alloys at x : 1-0.2; 2-0.3; 3-0.5.

The results obtained for InAs-rich $\text{InP}_x\text{As}_{1-x}$ alloys at

$x=0.2$ (curve 1) are strictly different from one for $\text{InP}_x\text{As}_{1-x}$ alloys at $x=0.5$ (curve 3), namely, electrons concentration decreases under radiation. That reflects the phenomenon, that the basic electrical properties of the irradiated InP compound are preserved in $\text{InP}_x\text{As}_{1-x}$ alloys at $x \geq 0.5$. The radiation properties of InP are strictly opposed to the unique radiation properties of InAs (radiation causes a decrease in the concentration of charge carriers of both electrons and holes).

Fig. 3 (curve 2) shows, that at $x=0.3$ in $\text{InP}_x\text{As}_{1-x}$ alloys the current carriers' concentration does not change at any dose of radiation. It indicates the existence of two opposite radiation processes: mutual compensation of radiation donors and acceptors in heavily irradiated $\text{InP}_x\text{As}_{1-x}$ alloys at $0.3 \leq x \leq 0.4$ composition. So, in this region of $\text{InP}_x\text{As}_{1-x}$ alloys compositions, equilibrium of two oppositely directed processes of the change of the current carriers' concentration under radiation is established. It means that in the $0.3 \leq x \leq 0.4$ area of compositions there takes place "self-recovery" of the electric characteristics of $\text{InP}_x\text{As}_{1-x}$ alloys at irradiation.

Investigation of crystals of $\text{InP}_x\text{As}_{1-x}$ alloys system with nearly the same charge carriers' concentration $n \sim 10^{16} \text{cm}^{-3}$ shows, that after irradiation mobility decreases weakly and at $x=0.3$ it even increases. Based on a detailed qualitative and quantitative analysis of electrons mobility, the physical essence of the observed phenomenon was elucidated.

There has been established that, regardless of the existence of such a complex picture, point and other types of defects in the crystal lattice play the most important role. Under conditions of severe irradiation and mutual compensation, the charged radiation donors, and acceptors approach to close enough distances to each other; the Coulomb interaction attracts them strongly and create closely spaced dipoles. So, this system of scattering ionized radiation centers may be considered as system of dipoles. As a result, instead of strongly scattering of current carriers by positively and negatively charged radiation defects, there appeared closely located dipoles. Consequently, the scattering effect of charge carriers on them sharply decreases (possibly by several orders), which gives rise to mobility at $x=0.3$.

So $\text{InP}_x\text{As}_{1-x}$ alloys, forming continuous solid solutions, allow to combine properties of InAs and InP compounds and prevent influence of formation of lattice damages under radiation and, as a result, thereby enable to improve radically radiation resistance at certain compositions. Similar results are also obtained after radiation of $\text{InP}_x\text{As}_{1-x}$ alloys by fast neutrons too.

B. Optical Properties

It is known, that long-wave part of the fundamental edge (edge tail) of semiconductors is extremely sensitive to radiation. Therefore, edge tail stabilization is an important task at operation of devices under radiation. The investigation of the spectral dependence of the optical absorption coefficient of InAs, InP and $\text{InP}_x\text{As}_{1-x}$ alloys near the fundamental edge has been the second step to identify the behavior of $\text{InP}_x\text{As}_{1-x}$ alloys under hard radiation conditions. The measurements of the optical properties

have revealed in InAs and InAs-rich $\text{InP}_x\text{As}_{1-x}$ alloys the shift of the curves of the spectral dependence of the optical absorption coefficient, and accordingly the fundamental optical absorption edge to higher energy under radiation. Fig. 4 shows the typical spectral dependence of the optical absorption coefficient for $\text{InP}_x\text{As}_{1-x}$ alloy at $x=0.1$. The movement of the fundamental optical absorption edge in $\text{InP}_{0.1}\text{As}_{0.9}$ alloy is smaller, than in InAs.

[7] explains the widening of the energy gap for special materials in the case of highly dopant content. According to [7] a phenomenon of which the band gap of a semiconductor is increased as the absorption edge is pushed to higher energies because of some states close to the conduction band being fulfilled.

So, the above-mentioned observed phenomenon of the shift of the fundamental optical absorption edge to higher energy in irradiated InAs and InAs-rich $\text{InP}_x\text{As}_{1-x}$ alloys is caused by the Burstein effect [7]. Formation by radiation exposure predominantly donors and thus the increase of the concentration of free electrons are the reason of widening of the energy gap in the investigated crystals.

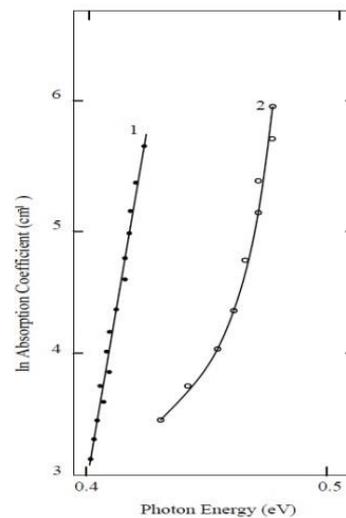


Fig. 4. The spectral dependence of the optical absorption coefficient of the crystal of $\text{InP}_{0.1}\text{As}_{0.9}$ alloy with $n_0=3.5 \cdot 10^{16} \text{cm}^{-3}$ at 300K: 1-before irradiation, 2-after irradiation by high energy electrons with the fluences of $\Phi=2 \cdot 10^{17} \text{e/cm}^2$.

Fig. 5 shows the results of the measurements of the spectral dependences of the optical absorption coefficient of InP and InP-rich $\text{InP}_x\text{As}_{1-x}$ alloys. There has been revealed the shift of the curves of the spectral dependence of the optical absorption coefficient to lower energy under radiation.

The movement of the curves weakens with decrease of phosphorus content in $\text{InP}_x\text{As}_{1-x}$ alloys. At composition of $\text{InP}_{0.5}\text{As}_{0.5}$ the movement is 10 times smaller than for InP. Analysis has shown that this phenomenon may be well explained on the basis of the developed in [6] concept of "radiation tails" of the density of states in the band gap under radiation. "Radiation tails" are caused by a fluctuation of the charged radiation defects concentration, which leads to a certain "narrowing" of the width of the forbidden band.

So, at the different sides of $\text{InP}_x\text{As}_{1-x}$ alloys system under radiation two different mutually opposite compensated

processes have been revealed in optical properties. The final result depends on the ratio of "radiation tails" of the density of states effect and the Burstein effect in the band gap.

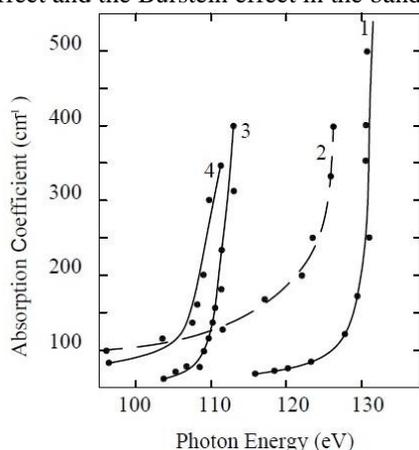


Fig. 5. The spectral dependence of the optical absorption coefficient of the crystals of InP ($n_0=1.1 \cdot 10^{16} \text{ cm}^{-3}$) and $\text{InP}_{0.8}\text{As}_{0.2}$ ($n_0=3.8 \cdot 10^{16} \text{ cm}^{-3}$) at $T=300\text{K}$: 1, 3 before irradiation, 2, 4-after irradiation by electrons with the fluences of $\Phi=2 \cdot 10^{17} \text{ e/cm}^2$.

It is clear, that the degree of compensation of displacements of the optical absorption edge by mutually opposite processes under irradiation depends on the initial concentration of electrons and the composition of alloys. For certain compositions ($0.1 \leq x \leq 0.5$) of $\text{InP}_x\text{As}_{1-x}$ alloys, at high doses of irradiation there is established equilibrium of two oppositely directed radiation processes. So, in the irradiated $\text{InP}_x\text{As}_{1-x}$ alloys there takes place "self-recovery" of the position of the edge of fundamental absorption. It means that the radiation-resistant optical materials, withstanding high doses of high-energy electrons, have been obtained.

The similar processes were detected in crystals irradiated by fast neutrons ($\Phi=2 \cdot 10^{18} \text{ n/cm}^2$).

Preservation in $\text{InP}_x\text{As}_{1-x}$ alloys of the qualitative law of optical absorption behavior under radiation, revealed in InAs and InP, at the corresponding sides of the alloys system is explained by conservation of some certain individual properties of sublattices of InAs and InP in $\text{InP}_x\text{As}_{1-x}$ alloys.

C. Microstructural Analyses

The retention of individuality of sublattices of InAs and InP in $\text{InP}_x\text{As}_{1-x}$ alloys, revealed in electrical and optical properties, have been confirmed by microstructural investigations. The images of dislocation structure of InAs, InP and $\text{InP}_x\text{As}_{1-x}$ alloys single crystals of composition from the middle of alloys system, presented in the Fig.6, clearly show, that InAs and InP sublattices retain their identity in $\text{InP}_x\text{As}_{1-x}$ alloys. The preservation of individuality of sublattices of InAs and InP in $\text{InP}_x\text{As}_{1-x}$ alloys, has been also shown in [8].

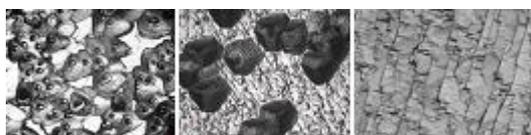


Fig. 6. Dislocation structure of single crystals on the (111) plane (x250) for: a) InAs; b) $\text{InP}_x\text{As}_{1-x}$; c) InP.

The revealed effect of radiation on the electrical and optical properties of alloys maintains at both room temperature and lower temperatures, and at the change of electrons concentration in the material. At the same time material retains the crystal structure without amorphous inclusions and metallic phases.

Thus, $\text{InP}_x\text{As}_{1-x}$ alloys make possibly create electrical and optical materials with radiation immunity, which may be regulated by the level of doping and composition of the $\text{InP}_x\text{As}_{1-x}$ alloys.

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