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Physics

Characteristics of some Radiation Defects of 3-5 Semiconductor Compounds

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ABSTRACT. The effects of irradiation with fast neutrons, high energy electrons (50MeV) and 3MeV and 7.5MeV energies electrons on the electrical and optical properties of *n*-type InAs have been studied. The influence of fast neutron irradiation on the electrical and optical properties of *n*-type InP_xAs_{1-x} solid solutions is also investigated. Detailed investigation confirmed the unique radiation properties of InAs. Regardless of the conditions and temperature of irradiation and the method of crystals growth, the type and degree of doping ($1\cdot10^{16}cm^{-3}\div10^{19}cm^{-3}$), mainly the radiation donors are originated in InAs crystals. It has been revealed that InAs-rich InP_xAs_{1-x} solid solutions retain the basic electrical and optical properties of InAs samples. The mechanisms of radiation processes and defect formation in InAs and the InP_xAs_{1-x} solid solutions are considered. On the basis of the results of investigations obtained, the role of point and other types of defects in the considered transport phenomena in InAs and InP_xAs_{1-x} solid solutions is revealed. By selecting the composition of the InP_xAs_{1-x} solid solutions and the initial doping impurities, electrical and optical radiation-resistant material is possible to obtain. *© 2019 Bull. Georg. Natl. Acad. Sci.*

Key words: radiation effects, InAs, InP, solid solutions, irradiation

The list of suitable semiconductor materials with immunity to hard irradiation is limited. For a long time, Si and GaAs were prevailing selected semiconductors and at present they are one of the basic materials in modern electronic engineering. Reliable operation of devices under extreme outer conditions is impossible in case of Si, and in spite of the fact that GaAs is accepted as radiation-resistant material, solar elements on its base do not withstand great doses of irradiation. Si and GaAs rapidly develop high electrical resistance and the current carriers' concentration can reduce in five, six order radiation, and material approaches to the dielectric state (Fig.1, Fig. 2).

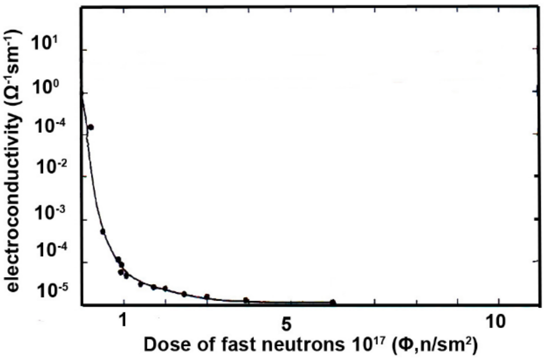

Fig. 1. Dependence of electro conductivity of Si on the fluence of fast neutrons.

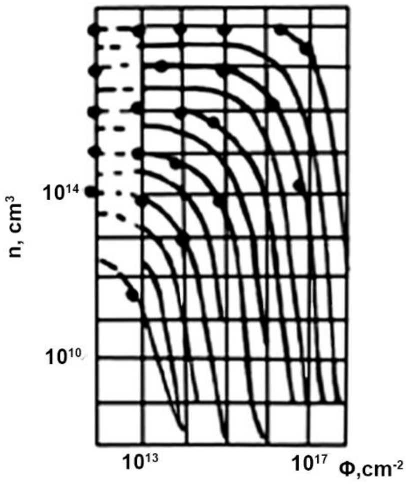

Fig. 2. Dependence of charge carriers concentration of GaAs on the fluencies of fast neutrons.

Devices on the base of Si and GaAs quickly get out of action at hard irradiation. That is why, the main goal of our investigation is to create manufacturable generation of radiation-resistant materials for efficient use in devices.

Investigations in search of radiation-resistant semiconductor materials should be focused on binary, ternary and quaternary complex semiconductor III-V compounds. The reason is that they have short lifetime of the minor current carriers and consequently may possess a higher radiation resistance in comparison with the elemental semiconductors. These materials can perform important role in creation of radiation-resistant semiconductor devices. During irradiation very complex processes occur in crystals whose regularity must be established to solve the problems of solid-state physics.

Semiconductor compounds InAs, InP and InP_xAs_{1-x} solid solutions are important for opto and microelectronics and nanotechnology [1-6]. The investigation of radiation properties of InP, InAs and InP_xAs_{1-x} is implemented in many works by authors [7–15]. Interesting results are obtained by Brudnyi [16] and Bolshakova [17]. The investigation of the radiation properties in the direction of InAs and InP of binary and especially triple materials in comparison with silicon is associated with additional difficulties, because under irradiation, much larger amounts of new types of defects appear in them. It is well known that in the mentioned materials severe irradiation can create many types of point defects and their small and large associations, both, among themselves and with chemical impurities, as well as large-scale defects of the so-called disordered regions and the other. As a result, we got a very complex picture, a correct analysis of which, and even more so, quantitative, is associated with great difficulties. At the same time, research in the marked direction provides a good opportunity to elucidate new physical processes and solve applied problems on its basis. The purpose of this paper is also to establish the mechanisms of radiation processes and the defect formation in the mentioned materials. It is necessary to clarify the role of the point-type defects in the noted complicated and multifaceted situation and, on the basis of the studies carried out, to develop a technology and create radiation-resistant compounds that withstand high doses of hard radiation.

Experiments

Experimental samples of InAs, InP and InP_xAs_{1-x} solid solutions were grown from stoichiometric melt by the horizontal zone melting method with three zones. The data of electrical properties are obtained by the measurements of Hall Effect and electric conductivity with compensation circuit at the direct current. The obtained samples were of *n*-(doping by Te) and *p*-type (doping by Zn). High degree of homogeneity of InP-InAs solid solutions was confirmed by several methods, among which the most important are X-ray micro analysis and performance of Vegard law. The optical properties of investigated materials were studied in IR region on UR-20 spectrometer. The thermoelectric properties and thermal conductivity of investigated materials were measured on the equipment constructed and made by us.

The crystals were irradiated with fast neutrons to fluencies of $\Phi=2\cdot10^{18}$n/cm^2 and high-energy electrons 50MeV ($\Phi=6\cdot10^{17}$e/cm^2) and 3MeV electrons ($\Phi=3\cdot10^{18}$e/cm^2).

Results and Discussions

A. Electrical phenomenon. As a result of detailed investigation of InAs compounds we established that InAs has unique radiation properties, in difference of other materials (Si, GaAs, InP etc.). As a result of irradiation, InAs always creates radiation donors.

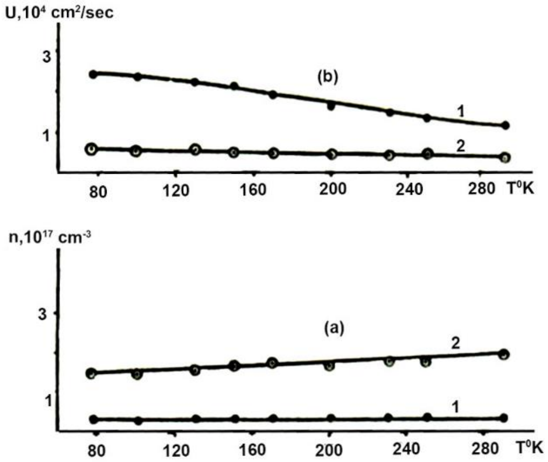

Fig. 3. Temperature dependence of electron concentration (a) and mobility (b) of charge carriers in the $InP_{0,1}As_{0,9}$ solid solutions ($n_0=3.5\cdot10^{16}$cm^{-3}) before and after irradiation with fast neutrons $\Phi=2\cdot10^{18}$n/cm^{-2}.

We irradiated InAs crystals with fast neutrons, high energy electrons (50MeV) and also by electrons with energies of 3MeV and 7.5MeV. Also, we changed fluencies of neutrons, conditions and temperature of irradiation and the method of crystals growth, type and degree of doping (in wide range $1\cdot10^{16}$cm^{-3} $\div10^{19}$cm^{-3}). We invariably discovered that as a result of irradiation mainly radiation donors are originated in InAs crystals.

After irradiation, electron concentration increases, which indicates that the $InP_{0,1}As_{0,9}$ solid solution retains the basic electrical properties of InAs samples. At the same time, the electron mobility significantly reduces, which is a consequence of the introduction of a large number of radiation defects.

Fig. 4 presents the analogical result for $InP_{0,2}As_{0,8}$ solid solution. It is shown that up to x=0.2, the basic electrical properties of the InAs are preserved.

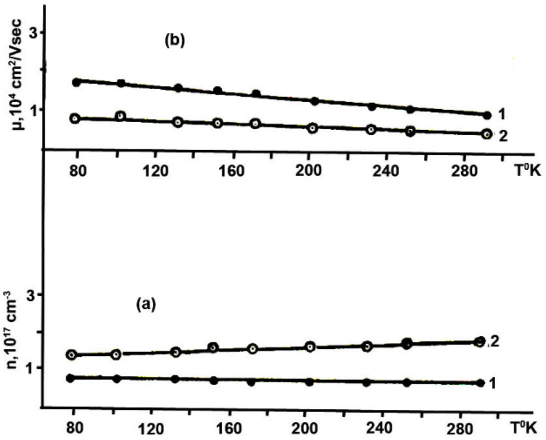

Fig. 4. Temperature dependence of electrons concentration (a) and mobility (b) of charge carriers in the $InP_{0,2}As_{0,8}$ before and after irradiation with fast neutrons $\Phi=2\cdot10^{18}$n/cm^{-2}, ($n_0=8.4\cdot10^{16}$cm^{-3}). 1 – before irradiation, 2 – after irradiation.

In irradiated InAs-InP solid solutions the phenomenon of mutual compensation of radiation donors and acceptors was discovered and on the basis of this phenomenon the radiation-resistant $InP_{0.3}As_{0.7}$ material was created [7, 8, 10].

In material, the electron concentration remains constant even after irradiation with a large flux of fast neutrons $\Phi=2\cdot10^{18}$n/cm^2. Conductivity dependence on the fluence of fast neutrons for InP_xAs_{1-x} at x=0.3 are shown in Fig. 5. Here, for comparison, the dependence for Si is presented as well.

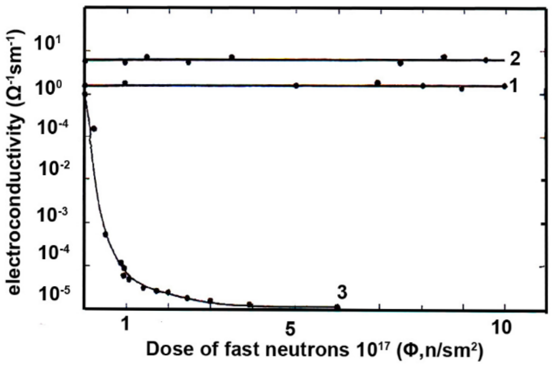

Fig. 5. Specific conductivity dependence on the fluence of fast neutrons for $InP_{0.3}As_{0.7}$ with n_0=1.5·10^{17}cm^{-3} (curve 1) and with n_0=7.0·10^{17}cm^{-3} (curve 2). Curve 3-Si.

B. Optical phenomenon. In the most of semiconductor materials, irradiation causes a decrease in the concentration of charge carriers of both electrons and holes. Similar behavior was observed during studying the radiation properties of InP. However, Aukerman [18] showed that the carrier concentration of n-type InAs increases during irradiation.

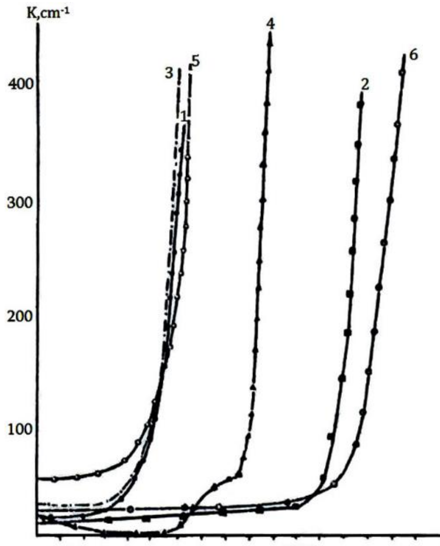

Fig. 6. Dependence of the optical absorption coefficient on the photon energy in InAs n_0=2.66·10^{17}cm^{-3}: 1, 2 before irradiation; T=300K and T=80K respectively. 3, 4 after irradiation Φ=1.0·10^{17}e/cm^2, at T=300K and T=80K respectively; 5, 6 after annealing at T=500^{0}C, t=3hours, measurements at T=300K and T=80K, respectively.

Curves presented in Fig. 6 are exponential optical absorption near the fundamental edge of InAs, before and after irradiation. It is seen that as a result of the irradiation, the curves shift sharply toward higher energies. This is due to the fact that irradiation in crystals causes an increase in the concentration of charge carriers. After annealing at $T = 500^0C$, the curves are restored.

We investigated the frequency dependence of the optical absorption coefficient of InAs near the fundamental edge. It is important that unlike the fundamental edge, its long-wave part (edge tail) is extremely sensitive to radiation. Therefore, tail stabilization is an important task.

In irradiated InAs we observed the manifestation of the Burstein effect, i.e., the displacement of the spectral curves toward higher energies. The noted phenomenon is shown in Fig. 7, where data are presented for InAs crystals irradiated by electrons with energy of 3MeV.

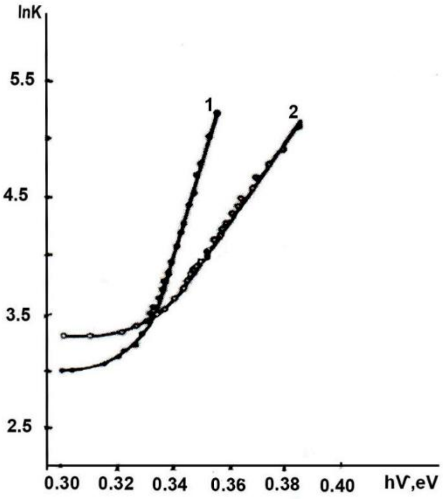

Fig. 7. The frequency dependence of the optical absorption coefficient in the region of the edge for InAs crystals with an initial electron concentration n_0=2.7·10^{17}cm^{-3}, 1-before and 2-after irradiation with electrons Φ=7·10^{17}e/cm^2.

In a solid solution, the InAs sub-lattice retains its individual properties in InAs-InP. So irradiation causes a shift of curves of the optical absorption to higher energies, but the shift is smaller in solid solutions, than in indium arsenide (Fig. 8).

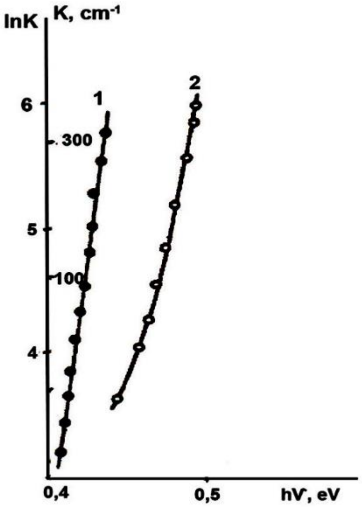

Fig. 8. The frequency dependence of the optical absorption coefficient in the region of the edge of crystals of the solid solution $InP_{0.1}As_{0.9}$ with n_0=3.5·10^{16}cm^{-3}. 1 – before radiation, 2 – after irradiation with electrons with the flux Φ=2·10^{18}e/cm.

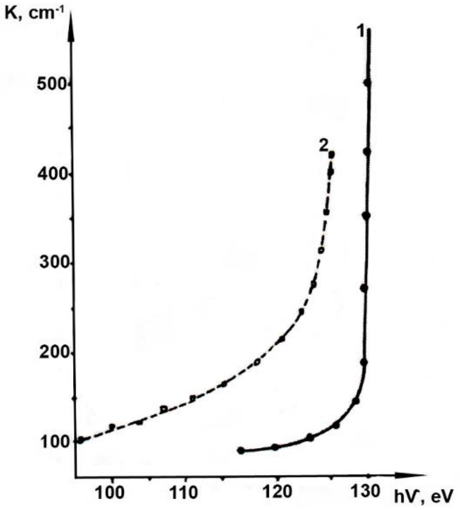

Fig. 9. The frequency dependence of the optical absorption coefficient in the edge region of n-InP crystals (n_0=1.1·10^{16}cm^{-3}), 1 – before irradiation, 2 – after irradiation with electrons (Φ=5.9·10^{17}e/cm^2).

Fig. 9 shows the dependence of the optical absorption coefficient in the edge region on the photon energy before and after irradiation of the indium phosphide crystal. It can be seen from the figure that in this case, the opposite effect is obtained: the radiation causes the curve shifts toward the low energy side. This phenomenon is caused by a fluctuation of the charged radiation defects, leading to the appearance of fluctuations tails of the density of the state and to a certain "narrowing" of the width of the forbidden band.

As in the case of InAs, the InP sub-lattice retains its properties in a solid solution. In InP-rich alloys we also observe displacement of the curves into the region of low energy.

Shift of curves weakens with the decrease of phosphorus content in a solid solution decreases. Displacement depends on the initial concentration of electrons in the material. The same processes were detected in crystals irradiated with 50MeV and Φ=2·10^{18}n/cm^2.

By selecting the composition of the solid solution and the initial concentration of the doping donors, optical radiation resistant material was obtained. The optical absorption near the age did not shift after irradiation in this material. Thus, radiation-resistant optical material was created.

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ფიზიკა

ზოგიერთი რადიაციული დეფექტის დახასიათება III-V ნახევარგამტარულ შენაერთებში

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შესწავლილია ჩქარი ნეიტრონებით, მაღალი ენერგიის (50MeV) ელექტრონებით და 3MeV და 7,5MeV ენერგიების ელექტრონებით დასხივების ეფექტი n-ტიპის InAs-ის ელექტრულ და ოპტიკურ თვისებებზე. ასევე გამოკვლეულ იქნა ჩქარი ნეიტრონებით დასხივების ზეგავლენა n-ტიპის InPxAs$_{1-x}$ მყარ ხსნარებზე. დეტალურმა კვლევებმა დაადასტურა InAs-ის უნიკალური რადიაციული თვისებები. დასხივების პირობების, ტემპერატურის და კრისტალების გაზრდის მეთოდისგან და ლეგირების (1·10^{16} სმ$^{-3}$÷10^{19}სმ$^{-3}$) ტიპის და ხარისხისგან დამოუკიდებლად, InAs-ის კრისტალებში ძირითადად წარმოიქმნება რადიაციული დონორები. დადგენილია, რომ InAs-ით მდიდარ InPxAs$_{1-x}$ მყარი ხსნარები ინარჩუნებენ InAs-ის ნიმუშების ძირითად ელექტრულ და ოპტიკურ თვისებებს. განხილულია რადიაციული პროცესები და დეფექტთწარმოქმნის მექანიზმები InAs-ში და InPxAs$_{1-x}$ მყარ ხსნარებში. კვლევის შედეგად მიღებული მონაცემების საფუძველზე დადგენილია წერტილოვანი და სხვა ტიპის დეფექტების როლი. InPxAs$_{1-x}$ მყარი სხნარების შემადგენლობის და საწყისი მალეგირებელი მინარევების შერჩევით შესაძლებელია რადიაციულად მდგრადი ელექტრული და ოპტიკური მასალის მიღება.

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