SEMICONDUCTOR MATERIALS WITHSTANDING LARGE FLURNCE OF HARD IRRADIATION

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Abstract: On the basis of InAs, InP and their InP_xAs_{1-x}solid solutions the technologies were developed and materials were created where the electrons concentration and optical and thermoelectric properties do not change under the irradiation with $\Phi=2\cdot10^{18}$n/cm^2 fluences of fast neutrons high-energy electrons (50MeV, $\Phi=6\cdot10^{17}$e/cm^2) and 3MeV electrons with fluence $\Phi=3\cdot10^{18}$e/cm^2. It has been solved the problem of obtaining such material, in which under hard irradiation the mobility of the electrons does not decrease, but increases. This material is characterized by high thermal stability up to $T = 700^0\,C$. The complex process of defects formation has analyzed and shown that, despite of hard irradiation, the essential properties of investigated materials are mainly determined by point type defects.

Keywords: InAs-InP, Solid Solutions, Irradiation

I. INTRODUCTION

On the one hand, investigation of semiconductor materials exposed to radiation is really significant because it makes possible to create new materials that can be successfully used on nuclear accelerators, for robots operating on heavily radioactive contaminated areas like Chernobyl and Fukushima. Naturally, these materials will be useful also for opto- and microelectronic devices and photovoltaics operating in Space, where they are irreplaceable because of their small size and high efficiency.On the other hand, 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 their solid solutions $InP_xAs_{1-x}$are actual and important materials for opto and microelectronics and nanotechnology [1-6].

The investigation of radiation properties of mentioned materials has been implemented in many our works [7-15]. Interesting results are obtained by V.N.Brudnyi [16] and I.Bolshakova[17] and others. 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 radiation much larger amounts of new type 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 to establish the mechanisms of radiation processes and defect formation in mentioned materials. It is necessary to clarify the role of 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.

However, as it is known at the end of this year, the operation of CERN Collider will be suspended for several years and its equipment will be re-installed, including semiconductor detectors. We intend to prepare corresponding proposal.

II. EXPERIMENT

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 *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 have been studied in IR region on UR-20 spectrometer. The thermoelectric properties and thermal conductivity of investigated materials has been 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 with fluence $\Phi=3\cdot10^{18}$e/cm^2.

RESULTS AND DISCUSSIONS

3.1 Radiation resistant electrical material

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].

It may be noted that the authors have led up to the phenomenon of mutual compensation of radiation donors and acceptors and to creation of radiation-resistant materials with the help of discovered two mode behavior of InAs-InP solid solutions lattice vibrations [18], that points to the preservation of individual properties of InP and InAs sub-lattices in solid solutions. Those results were confirmed at the Oxford Clarendon Laboratory [19], at the Saclay Nuclear Research Centre [20], and in the work [21].

In the material obtained, 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. 1.Here, for comparison, the dependence for Si is presented as well.

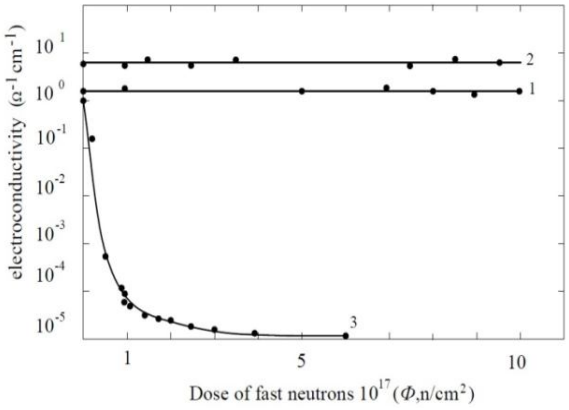

Fig.1 Specific conductivity dependence on the fluence of fast neutrons for$InP_{0.3}As_{0.7}$with $n_0=1.5\cdot10^{17}$cm^{-3}(curves1) and with $n_0=7.0\cdot10^{17}$cm^{-3}(curve2).Curve3—Si.

3.2 Radiation-resistant Optical Material

It is known that in the most of semiconductor materials, irradiation causes a decrease in the concentration of charge carriers of both electrons and holes. Similar behavior we also observe in the studying the radiation properties of InP. However, Aukerman [22] showed that under irradiation of InAs with electrons there occurs electrons concentration increase.

We have shown that InAs has unique radiation properties consisting in the fact that the radiation increases the electrons concentration in the indium arsenide at **any conditions.** Our results are confirmed by Walukievicz [23] and Gerstenberg [24]. We irradiated InAs crystals with fast neutrons, high energy electrons (50MeV) and also by electrons with energies of 3MeV and 7.5MeV. Also, there have changed fluence, conditions and temperature of irradiation and the method of crystals growth, type and degree of doping (in wide range from $1\cdot10^{16}$cm^{-3} to 10^{19}cm^{-3}). We invariably discovered that in the result of irradiation in InAs crystals mainly radiation donors are originated.

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 indium arsenide we have 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. 2, where data are presented for InAs crystals irradiated by electrons with energy of 3MeV.

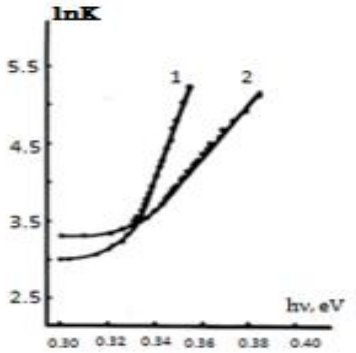

Fig.2. The frequency dependence of the optical absorption coefficient in the region of the edge for InAs crystals with an initial electron concentration $n_0= 2.7\cdot10^{17}$cm^{-3}, 1-before and 2-after irradiation with electrons $\Phi=7\cdot10^{17}$e/cm^2.

As noted above in a solid solution, the InAs sub-lattice retains its individual properties in InAs-InP solid solution. 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.3).

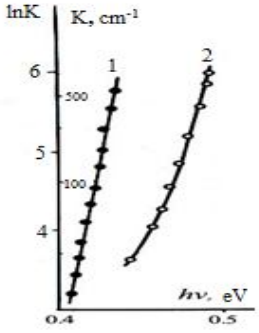

Fig.3 The frequency dependence of the optical absorption coefficient in the region of the edge of crystals of the solid solution $InP_{0.1}As_{0.9}$with n_0=3.5·10^{16}cm^{-3}.1-before irradiation, 2-after irradiation with electrons with the flux Φ= 2·10^{18}e/cm^2.

Fig.4 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.

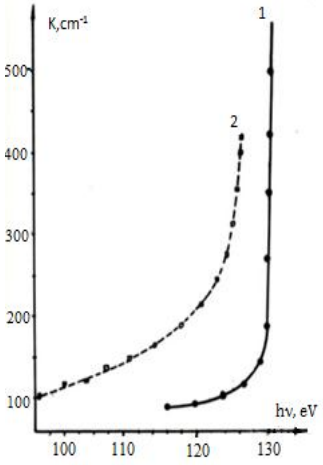

Fig.4. The frequency dependence of the optical absorption coefficient in the region of the edge of n-InP crystals with n_0= 1.1·10^{16} cm^{-3},1-before irradiation, 2 -after irradiation with electrons (Φ = 5.9·10^{17} e/cm^2).

It can be seen from the figure that in this case the opposite effect is realized: 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 indium arsenide, the indium phosphide sub-lattice retains its properties in a solid solution. In indium phosphide -rich alloys we also observe displacement of the curves into the region of low energy. Shift of curves weakens with 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 high-energy electrons with an energy 50 MeV and fast neutrons with a flux Φ= 2·10^{18}n/cm^2. By selecting the composition of the solid solution and the initial concentration of the doping donors, there was obtained optical radiation resistant material. The optical absorption near the age did not shift after irradiation in this material. Thus, radiation-resistant optical material was created.

3.3 Radiation-resistant Thermoelectric Material

As it is well known the thermoelectric efficiency of materials *Z* is given by relationship:

$$Z=\alpha^2\sigma/\eta,$$

Where σ is the electrical conductivity, α is the thermoelectric power, and η is the thermal conductivity. Thermoelectric power (as well as *Z*) of InP, GaAs, InAs, their solid solutions and of more other semiconductors decreases sharply after their irradiation.

Noted clearly is demonstrated in the Fig.5, where curves1a and 1b relate to indium phosphide before and after irradiation with fast neutrons (Φ=2·10^{18}n/cm^2).

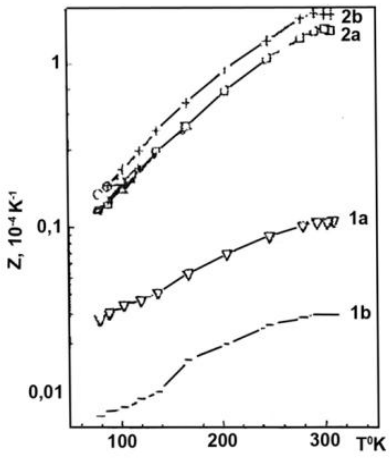

Fig. 5. Dependence of thermoelectrical efficiency of InP_xAs_{1-x} solid solutions on temperature. (a) before radiation, (b) after irradiation with fast neutrons.

(a) Curves: 1a, 1b-InP, 2a, 2b- InP_xAs_{1-x}.

However, there were developed the technology and created InP_xAs_{1-x} solid solutions of defined composition in which, as a result of irradiation with fast neutrons, the value of *Z* does not reduce. As it was noted at irradiation, there are formed large and small size defects on which intense phonons scattering occurs. In turn, this causes thermal conductivity reduction and, accordingly, thermoelectric efficiency growth. Simultaneously, in noted InP_xAs_{1-x} solid solution, the electrical conductivity grows. As a result, the increase in value of σ/æ significantly exceeds the fall in the value of α^2 and ultimately the value of thermoelectric efficiency does not decrease but increases significantly. Marked is shown in Fig. 5 (curves 2a,2b).

Thus through introduction of radiation defects into the semiconductors it is possible to increase the value of thermoelectric efficiency.

So there was developed InP_xAs_{1-x}solid solutions efficiently converting thermal energy into electrical energy in high radiation conditions. The latter is important for their application in Space at atomic power stations, and nuclear reactors.

3.4. The Stabilisation and Increase of Mobility of Electrons

It is clear, that creation of radiation-resistant optical, thermoelectric and electrical materials is important. However, this is always accompanied by a serious problem. Under any irradiation conditions, a radiation defect always arises, creating additional scattering centers for the charge carriers. This, in turn, causes the mobility decrease, which is an undesirable phenomenon. On the basis of the phenomenon of mutual compensation of radiation donors and acceptors revealed by us in heavily irradiated InAs-InP solid solutions and the development of an appropriate technology, there has been created such semiconductor material, in which the hard irradiation not only does not reduce mobility, but increases it.

Measurements of the electric properties of $InP_{0.3}As_{0.7}$material subjected to irradiation of high flux of fast neutrons $\Phi=2\cdot10^{18}$n/cm^{2}discussed in paragraph 3.1 showed that while in the solid solution of the mentioned composition mobility of electrons should have been:

$$u_1=3500\text{cm}^2/\text{V.sec},$$

Actually, mobility has increased to:

$$u_2=12000\text{cm}^2/\text{V.sec}$$

The effect of mobility growth is undoubted because growth was also revealed at low temperatures and after irradiation with electrons of 3MeV energy with $\Phi=5\cdot10^{17}$n/cm^2. Based on a detailed qualitative and quantitative analysis of electron mobility, the physical essence of the observed phenomenon was elucidated. It is known that in semiconductors, among them III-V type compounds, after the irradiation large number of defects of various types appears in them: interstitial atoms and their vacancies, their associations with one another and impurities. In this case of hard irradiation large defects and disordered regions appear simultaneously. The picture is even more complicated in our case where multi component solid solutions are considered. We have established that, regardless of the existence of such a complex picture, point 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 one another; the Coulomb interaction attracts them strongly and creates closely spaced dipoles. As a result, instead of strong scattering by positively and negatively charged defects, we obtain closely located dipoles, the carriers scattering effect of which sharply decreases (possibly by several orders), leading to mobility rise.

Regardless of the fact that radiation donors appear in the InAs sub-lattice, and in the InP lattice – radiation acceptors, they are much more mobile and can approach to much closer distances than typical impurity donors and acceptors located at the sites of the crystal lattice. As a result, there is a sharp increase in mobility during irradiation.

A quantitative analysis of the electron mobility was carried out, and it confirms the above considerations. It is natural to assume that closely spaced dipole pairs represent a system of very high stability. Indeed, it was confirmed by experiment.

Experiment shows, that irradiated with fast neutrons $InP_{0.3}As_{0.7}$ materials has high level of thermal stability: In irradiated samples charge carriers concentration not change even up to 700°C thermal treatment.

From the above it is possible to conclude that, based on the obtained materials, it is possible to create such highly radiation-resistant and thermo stable devices that can function at high temperatures, which is today a great need. It is interesting to note that such devices will make it possible to study the radiation of the sun on condition to maximum approximation to it.

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