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Radiation Effects and Defects in InAs, InP Compounds and Their Solid Solutions InP_xAs_{1-x}

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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 electron 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 (50 MeV, $\Phi = 6\cdot10^{17}$ e/cm^2) and 3 MeV electrons with fluence $\Phi = 3\cdot10^{18}$ e/cm^2. The problem of obtaining such material has been solved, 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 °C. The complex process of defects formation has been 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

MICRO and optoelectronic devices are irreplaceable elements for investigations in space, for accelerators, atomic power stations, and nuclear reactors and for the creation of robots operating on heavily contaminated territories like Chernobyl and Fukushima. Unfortunately, the effective functioning of semiconductor devices dramatically worsens under severe radiation. This is especially true for the charge carriers' mobility, which under large doses of hard radiation dramatically decreases. Therefore, the effective functioning of semiconductor micro and optoelectronic devices is impossible in hard radiation conditions.

The mitigation technique of radiation protection is not always sufficient and effective. A semiconductor material itself is the base of all constituent units of semiconductor devices and is the determining element in the devices operation. Therefore, today there exists urgent and serious problem of creation of radiation-resistant semiconductor materials, for producing effective micro and optoelectronic devices withstanding high doses of hard 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 basic materials for modern electronic engineering. But reliable operation of devices under extreme outer conditions is impossible in case of Si, and in spite of that GaAs is accepted as radiation-resistant material, solar elements on its base does not withstand great doses of radiation. Si and GaAs rapidly develop high electrical resistance and the current carriers' concentration can reduce in five, six order irradiation, and material approaches to the dielectric state (Figs. 1 and 2).

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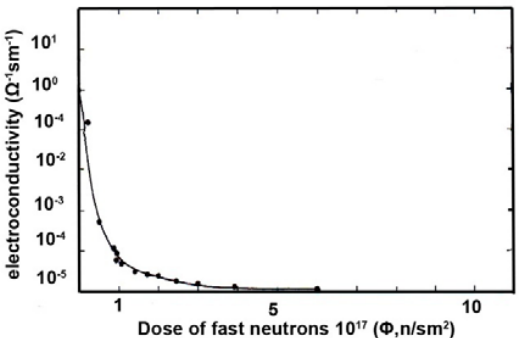

Fig. 1 Dependence of electro conductivity of Si on the fluence of fast neutrons

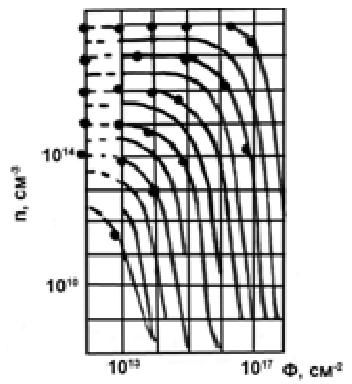

Fig. 2 Dependence of charge carriers concentration of GaAs on the fluencies of fast neutrons

So, devices on the base of Si and GaAs quickly get out of action at hard irradiation. That is why Si and GaAs do not satisfy requirements (in the part of the efficiency and radiation resistance) of the devices functioning under severe radiation. That is why one of the main problems of electronic industry is looking for other materials tolerant to hard irradiation, apart from Si and GaAs. That is why, the main goal of our investigation is creating of manufacturable generation of radiation-resistant materials for high-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 elemental semiconductors. Therefore, these materials can play important role in creation of radiation-resistant semiconductor devices on their base.

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 InP, InAs and InP_xAs_{1-x} solid solutions has been implemented in many works [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 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 also 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 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. 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 *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 have 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 (50 MeV, $\Phi=6\cdot10^{17}$ e/cm^2) and 3 MeV electrons with fluence $\Phi=3\cdot10^{18}$ e/cm^2.

III. Results and Discussions

A. Electrical Phenomenon

We have confirmed detailed investigation of InAs compounds and established that InAs has unique radiation properties, what is that unlike of other materials (Si, GaAs, InP etc.) as a resultof irradiation, InAs always creates radiation donors.

We irradiated InAs crystals with fast neutrons, high energy electrons (50 MeV) and also by electrons with energies of 3 MeV and 7.5 MeV. 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 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.

On Fig. 3 is presented temperature dependence of electrons concentration (a) and mobility (b) of $InP_{0,1}As_{0,9}$ solid solutions ($n_0=3.5\cdot10^{16}$ cm^{-3}) before (1) and after (2) irradiation with fluence of fast neutrons $\Phi=2\cdot10^{18}$n·cm^{-2}.

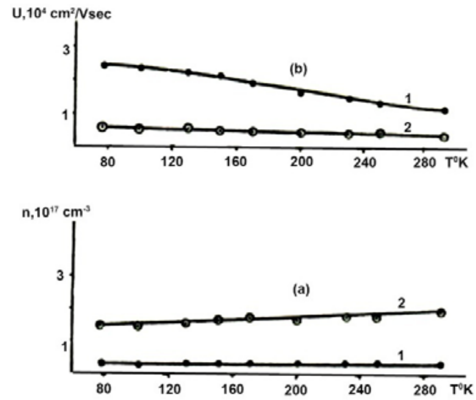

Fig. 3 Temperature dependence of electron concentration (a) and mobility (b) of charge carriers in the $InP_{0,1}As_{0,9}$ solid solutions before and after irradiation with a fast neutrons $\Phi=2\cdot10^{18}$ n·cm^{-2}

It is seen that 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.

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].

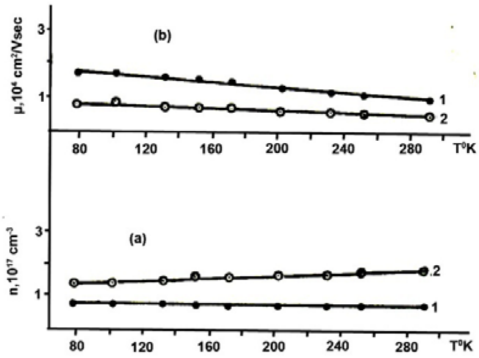

Fig. 4 Temperature dependence of electrons concentration (a) and mobility (b) of charge carriers in the $InP_{0,2}As_{0,8}$ solid solutions before and after irradiation with a fast neutrons Φ=2·10^{18}n·cm^{-2}, (n_0= 8.4·10^{16}cm^{-3}). 1-before irradiation, 2- after irradiation

In material, the electron concentration remains constant even after irradiation with a large flux of fast neutrons Φ= 2·10^{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.

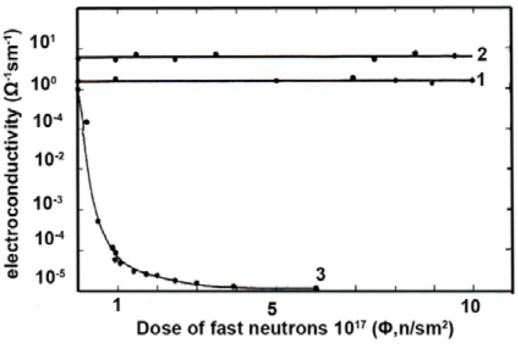

Fig. 5 Specific conductivity dependence on the fluence of fast neutrons for $InP_{0.3}As_{0.7}$ with n_0=1.5·10^{17}cm^{-3} (curve 1) and with n_0= 7.0·10^{17}cm^{-3} (curve 2). Curve 3-Si

B. Optical Phenomenon

As it was noted above 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 in the studying the radiation properties of InP. However, Aukerman [18] showed that the carrier concentration of n-type InAs increases during irradiation.

Curves presented in Fig. 6 are exponential optical absorption near the fundamental edge of indium arsenide, 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 °C, 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.

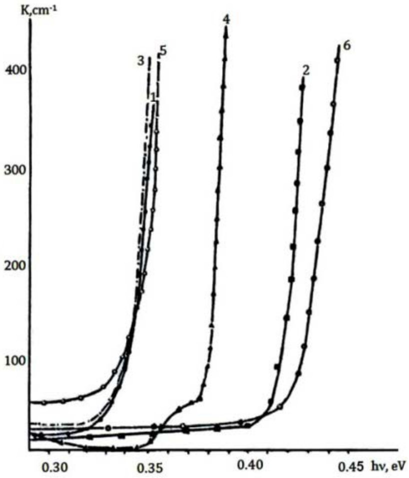

Fig. 6 Dependence of the optical absorption coefficient on the photon energy in InAs n_0=2.66·10^{17}cm^{-3}: 1, 2 before irradiation; T=300 K and T=80 K respectively. 3, 4 after irradiation Φ=1.0·10^{17}e/cm^2, at a temperature T=300 K and T=80 K respectively; 5, 6 after annealing at temperature T=500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

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. 7, where data are presented for InAs crystals irradiated by electrons with energy of 3 MeV.

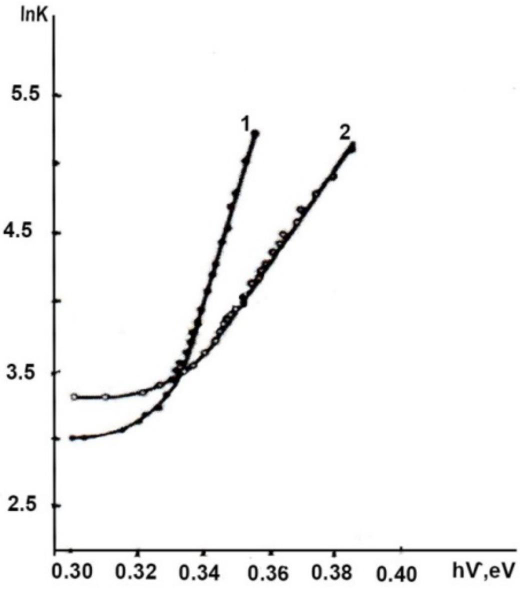

Fig. 7 The frequency dependence of the optical absorption coefficient in the region of the edge for InAs crystals with an initial electron concentration n_0= 2.7·10^{17} cm^{-3}, 1-before and 2-after irradiation with electrons Φ=7·10^{17} e/cm^2

In a solid solution, the InAs sub-lattice retains its individual properties in InAs-InP 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. 8).

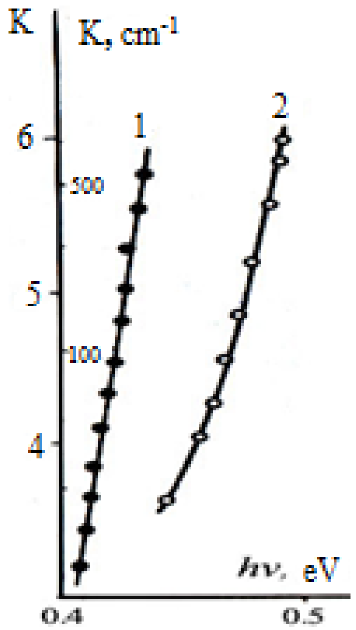

Fig. 8 The frequency dependence of the optical absorption coefficient in the region of the edge of crystals of the solid solution $InP_{0.1}As_{0.9}$ with n_0=3.5·10^{16} cm^{-3}. 1-before irradiation, 2-after irradiation with electrons with the flux Φ=2·10^{18} e/cm^2

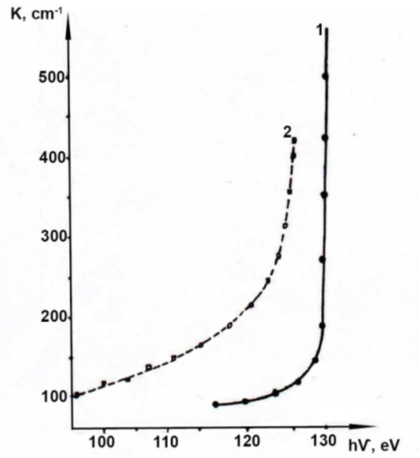

Fig. 9 The frequency dependence of the optical absorption coefficient in the edge region of n-InP crystals (n_0=1.1·10^{16} cm^{-3}), 1-before irradiation, 2-after irradiation with electrons (Φ=5.9·10^{17} e/cm^2)

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 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, 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.

C. Thermoelectrical Phenomenon

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

$$Z = \alpha^2\sigma/\eta \qquad (1)$$

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.

In Fig. 10 curves 1a and 1b relate to indium phosphide before and after irradiation with fast neutrons (Φ=2·10^{18} n/cm^2). Thus, the technology was developed and radiation-resistant solid solutions of certain compositions were created.

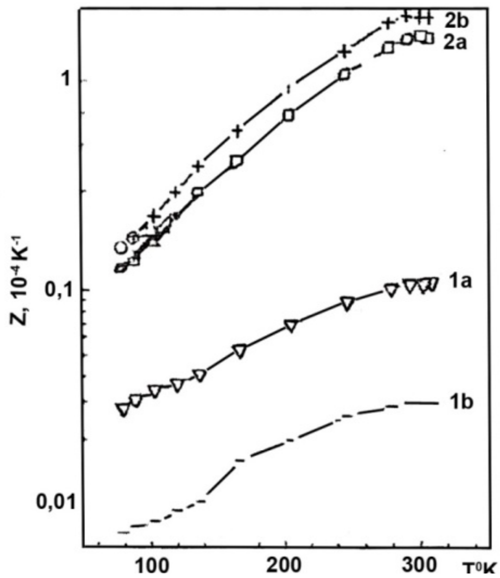

Fig. 10 Dependence of thermo electrical efficiency of InP_xAs_{1-x} solid solutions on temperature, (a) before irradiation, (b) after irradiation with fast neutrons. Curves: 1a, 1b-InP, 2a, 2b-InP_xAs_{1-x}

As can be seen from Fig. 10 (curves 2a and 2b) after irradiation of the solid solution InP_xAs_{1-x}, thermoelectric efficiency increases over the entire temperature range.

During irradiation, complex radiation processes are developing in the material. Large and small defects are formed. At the same time, all other material parameters are changed, which requires a complex analysis of processes. Thus through introduction of radiation defects into the semiconductors it is possible to increase the value of thermoelectric efficiency. So InP_xAs_{1-x} solid solutions efficiently converting thermal energy into electrical energy in high radiation conditions were developed. The latter is important for their application in space at atomic power stations, and nuclear reactors.

D. The Stabilisation and Increase of Mobility of Electrons

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 materials, in which the hand irradiation not only does not reduce mobility, but stabilizes it.

Fig. 11 shows composition dependence of the experimental values of electrons mobility (μ_{exp}) for the InAs-InP solid solutions at T=300 K, before (curve 1) and after (curve 2) irradiation with fast neutrons fluence $\Phi=2\cdot10^{18}$ n/cm^2. Investigated crystals of InP_xAs_{1-x} alloys system before irradiation had nearly the same charge carrier concentration $n\sim10^{16}$ cm^{-3}.

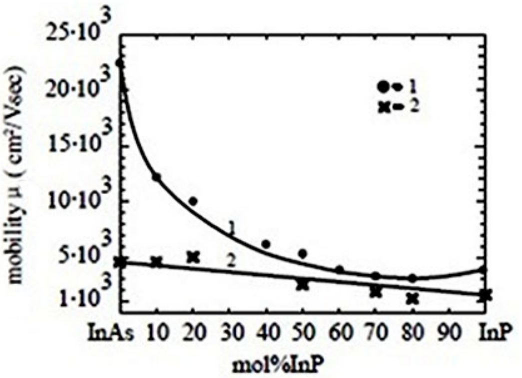

Fig. 11 Composition dependence of charge carriers mobility of InP_xAs_{1-x} alloys of experimental samples with nearly the same initial carriers concentration $n\sim10^{16}$cm^{-3}, 1- before irradiation, 2-after fast neutrons irradiation

As can be seen from Fig. 8, near the composition of solid solution x=0,2÷0.3, after irradiation mobility growth was observed. Curve 2 shows that at the composition of x=0,2÷0.3 the value of the electrons mobility should be equal to $3{,}5\cdot10^3$ cm^2/Vs. In fact the mobility has grown and has become $1.2\cdot10^4$ cm^2/Vs. The increase in the mobility of the electrons is already observed at the composition of x=0.1 and it continues to the composition of x=0.2 and terminated at x=0.4.

The effect of growth of mobility is without of doubt, because growth was also revealed at low temperatures and after irradiation with electrons of 3 MeV 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 large number of various types defects appears after the irradiation: point defects, interstitial defects and their vacancies, their associations with each other and impurities. In this case, under hard irradiation, large defects and disordered regions appear simultaneously. The picture is even more complicated in our case when 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 of radiation defects, the charged radiation donors and acceptors approach to close enough distances to each other; the Coulomb interactions attract them strongly and create closely spaced dipoles. As a result, instead of strongly scattering by positively and negatively charged defects, we obtain closely located dipoles, the scattering effect of which of carriers of free charge sharply decreases (possibly by several orders}, which gives rise to mobility.

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. The observed phenomenon is closely related with the feature of sub lattices of InAs and InP of retaining some certain individual properties in InP_xAs_{1-x} alloys.

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REFERENCES

[1] X. Jiang, Q. Xiong, S. Nam, F. Qian, Y. Li, and Ch. M. Lieber, “InAs/InP radial nanowire heterostructures as high electron mobility devices”, *Nano Lett.*, *7* (10), pp 3214–3218. 2007.
[2] L. Romeo, S. Roddaro, A. Pitani, D. Ercolani, L. Sorba, and F. Beltran, “Electrostatics spin control in InAs/InP nanowire quantum dots”, *Nano Lett.*, *12* (9), pp 4490–4494 [3], 2012.
[3] D. W. Stokes, J. H. Li, R. L. Forrest, S. L. Ammu, J. C. Lenzi, S. C. Moss, B. Z. Nosho, E. H. Aifer, B. R. Bennett, and L. J. Whitman, “Optical and structural properties of InAs/GaSb nanostructures”, Mater. Res. Soc. Symp. Proc., vol.794, T9.9, 2003.
[4] T. C. Newell, D. J. Bossert, A. Stintz, B. Fuch, K.J. Malloy, L.F. Lester. “Gain and linewidth enhance ment factor in InAs quantum-dot laser diodes”. IEEE. Phot. Technol. Lett., vol.11, issue 12, p.1527,1999.
[5] Y. Kuwahara, H. Oyanagi, Y. Takeda, H. Yamaguchi, and M. Aono, “Bond length relaxation in ultrathin $Ga_xIn_{1-x}P$ and InP_xAs_{1-x} layers on InP(100)”, Appl.Sur.Sci., vol.60/61, p.529, 1992.
[6] K. Zdansky, L. Pekarek, and P. Kacerovsky, “Evaluation of semi-insulating Ti-doped and Mn-doped InP for radiation detection”, Semicond. Sci. Technol., vol.16, p.1002, 2001.
[7] N. Kekelidze, G. Kekelidze, Patent No.89035, USSR, Moscow, 1975.
[8] N. Kekelidze, T. Jakhutashvili. “Solar energy resources and their

application perspective in Georgia". International Solar Energy Society. Proceedings of Solar World Congress-1999, Jerusalem, 1999.
[9] N. Kekelidze, G. Kekelidze, D. Kekelidze, V. Aliyev. International Conference on the Physics of Semiconductors (ICPS 2012). Zurich. AIP Conference Proceedings. v. 1566(1); p. 101-102. 2013
[10] N. Kekelidze, B. Kvirkvelia, D. Kekelidze, E. Khutsishvili, G. Kekelidze. Phenomenon of Mutual Compensation of Radiation Donors and Acceptors and Creation of Radiation-Resistant Materials. J. of Electrical Engineering (JEE), 2, #4, 187-192 (2014).
[11] Elza Khutsishvili, Bella Kvirkvelia, David Kekelidze, Vugar Aliyev, David Khomasuridze, Nodar Kekelidze. International Conference on the Physics of Semiconductors (ICPS-2012), Zurich. AIP Conference Proceedings 103-104. 2013.
[12] N. Kekelidze, J. Khubua, G. Kekelidze, D. Kekelidze, V. Aliyev, B. Kvirkvelia, E. Khutsishvili. Proceedings of the 7th International Conference "Physics in the LHC era" 2013, pp. 59-70. 2013.
[13] N. Kekelidze, E. Khutsishvili, B. Kvirkvelia, G. Urushadze, G. Kekelidze. Abstract of 32nd International Conference on the Physics of Semiconductors (ICPS 2014) Austin, USA.
[14] N. Kekelidze, E. Khutsishvili, B. Kvirkvelia, D. Kekelidze, V. Aliyev, G. Kekelidze. Transport Properties of InAs-InP Solid Solutions. J. of Electrical Engineering (JEE). 2, #5, pp. 207-212. 2014
[15] N. Kekelidze, E. Khutsishvili, Z. Kvinikadze, Z. Davitaya, D. Kekelidze, B. Kvirkvelia, K. Sadradze, L. Nadiradze, G. Kekelidze. American Journal of Nano Research and applications. 5(3-1). p.48-55. 2017.
[16] V. N. Brudnyi, S. N. Grinyaev, N. G. Kolin. Electrophysical and optical properties in electron (~2MeV) irradiated InAs: energetic structure of the intrinsic point defects. Fizika i tekhnika poluprovodnikov (Physics and Techniques of semiconductors), 2005, v. 39, # 4, pp. 409-418.
[17] I. Bolshakova, I. Vasilevskii, L. Viererbl, I. Duran, N. Kovalyova, K. Kovarik et al., Prospects of using In-containing semiconductor materials in magnetic field sensors for thermonuclear reactor magnetic diagnostics, IEEE Transactions on Magnetics 49(2013) 50-53.
[18] L. W. Aukerman, "Electron irradiation of indium arsenide", Phys.Rev., vol.115,p. 1133,1959