Chemical potential μ is very important physical magnitude. The concentration of free charge carriers in crystals depend on chemical potential. Chemical potential is in Fermi-Dirac equilibrium distribution function f_0. In the solid-state physics chemical potential is determined by neutrality equation.

REFERENCES

1. Буджак Я.С., Раренко А. І. Кінетична теорія ефекту Зеєбека в кристалах // Термоелектрика. – 1998. – № 3. – p.40-47.

2. Буджак Я.С., Фреїк Д.М., Готра О.З., Никируй Л.І., Межиловська Л.Й. До теорії кінетичних явищ у напівпровідникових кристалах // Фізика і хімія твердого тіла. – 2001. – Т.2, № 1. – С.77-85.

3. Буджак Я.С., Готра О.З., Лопатинський І.Є. Елементи теорії термодинамічних та кінетичних властивостей матеріалів. // Вісник Державного університету "Львівська політехніка", "Електроніка". – Львів: видавництво Державного університету "Львівська політехніка". – № 397. – 2000. – С.108-113.

I. Bolshakova[1], C. Leroy[2], M. Kumada[3]

[1] Magnetic Sensor Laboratory, Lviv Polytechnic National University, Lviv, Ukraine
[2] Laboratory R-J.A.-Levesque, Montreal University, Montreal, Canada
[3] National Institute of Radiological Sciences, Chiba, Japan

INVESTIGATION OF INDIUM ANTIMONIDE MICROCRYSTALS IRRADIATED WITH FAST NEUTRONS

Microcrystals of III-V semiconductor compound indium antimonide were obtained by means of complex doping in the growth process. Such compounds are stable after irradiation with fast neutron fluences up to 10^{16} n·cm^{-2}. Magnetic field microsensors developed on their base are applied in magnetic measuring systems for charged particle accelerators and in the space instrumentation building.

INTRODUCTION

Indium andimonide is known as a material for the electronics, in particular for sensors. The investigation of the behaviour of this semiconductor material under high radiation loads may contribute to the possibility of the development of radiation resistant sensors and sensor devices on its base.

This paper continues the systematic investigations we started in the last years, as to the possibility to obtain III-V microcrystals with the parameters, applicable for the manufacturing of time-stable magnetic field microsensors for operation under extreme conditions, in particular, under conditions of hard irradiation [1]. This paper presents the investigation results of the influence of the irradiation with high fast neutron fluences on the parameters of indium antimonide microcrystals, as well as technological processes for improvement of the radiation resistance of microcrystals and magnetic field sensors manufactured on their base.

TECHNOLOGY

Microcrystals of indium antimonide were obtained from the vapour phase by means of the method of chemical transport reactions with the use of halogens as transporting agents. The main reactions responsible for the transport in the iodide system are the reactions of the disproportionation of indium and stannum iodides:

$$InSb_{(к,р)}+InI_{3(г)}\leftrightarrow 3InI_{(г)}+1/2Sb_{4(г)}$$

$$SnJ_4(г) + Sn(р) \leftrightarrow 2\ SnJ_2\ (г)$$

Technological modes of InSb microcrystal growth were determined from the temperature dependence of the partial pressures. The temperature of the source zone is equal to 1080 K and temperature of the crystallization zone is equal to 780 K. Crystals were grown in the closed quartz tubes, with the growth rate of $2.5\cdot10^{-4}$ mm$\cdot$s^{-1}. The dimensions of the obtained microcrystals: length is equal to 5-10 mm, width 0.05-0.1 mm, thickness 0.01-0.02 mm. Growth forms are whiskers, and the growth direction coincides with the crystallographic axes [211] or [110]. The surfaces of the edges are specular.

To provide the radiation resistance of InSb microcrystals under high neutron fluences, the method of complex metallurgical doping in the process of crystal growth was applied. Compound impurity complexes included the main impurity with the donor character of behaviour, as well as the combination of the additional impurities. The results of investigations performed earlier [2, 3] of the influence of great number of various impurities on the radiation resistance of InSb microcrystals made it possible to limit the scope of this paper with the investigation of impurity complexes, including stannum as the main donor impurity and aluminium and chrome as additional impurities.

When selecting Sn as the main doping impurity in the irradiated samples it was taken into account, that the part of the thermal neutrons in the fast neutron flux with the energy E>1.5 MeV is usually about 10 %. Since the number of atoms of the main doping impurity is within 10^{-5} at. % to 10^{-4} at. %, one may expect the considerable change in the composition and the parameters of the semiconductor due to the radiation modification of the impurity atoms. Application of Sn allows reducing the influence of radiation modification, since In becomes the end product of the nuclear reactions as a result of the radiation transformations. Since In is the main element in InSb, it is obvious that stannum doping will not lead to the change in its electric parameters in case of the radiation modification.

Additional impurities as a part of impurity complex were selected due to the following considerations: doping by Al isovalent impurity, with the covalent radius of its atoms differing considerably from the covalent radii of the main atoms of the crystal lattice, leads to deformation of the crystal potential. The field of elastic deformations formed by the complex of such atoms leads to the formation of the drains for the radiation defects [4]. According to the previous experimental studies [3], chrome has positive influence on the time stability of the parameters. Microcrystals InSb <Sn:Cr>, InSb <Sn:Al> and InSb <Sn:Al:Cr> were considered in this work on the investigation of the influence of the high fluences.

INVESTIGATION

The radiation resistance of the doped InSb microcrystals was evaluated according to the change in the main parameters: the charge carrier concentration, their sensitivity and a resistivity after the fast neutron irradiation. All the investigations – irradiation and measurements, were performed at the temperature close to the room temperature, as all the investigated microcrystals had to be used for the manufacturing of the sensors, which later became the developed base of the magnetic measurement system for magnetic field monitoring in charged particle accelerators at 25±1°C. Such temperature is available, for example, at CMS in CERN.

The measurement of microcrystal parameters before and after irradiation was performed at the specially developed precise measuring bench, which allows one to determine the change in these parameters with the high accuracy of 0.1 %. Such accuracy is achieved due to the use of thermostatic control of magnetic measure, precise measurement devices (Keithley 2000) and special methods of the signal processing, providing effective noise-immunity of all the measurement channels.

Measurement bench was manufactured on the base of HMS-7504 facility by Lake Shore Cryotronics, Inc., USA, which provides the automation and commutation of 10-channel measurement together with the specially developed software.

Fast neutron irradiation was performed at IBR-2 facility at the Joint Institute of Nuclear Research up to the fluences 10^{15} n·cm^{-2} and 10^{16} n·cm^{-2}, the average energy of neutrons was equal to 1.35 MeV and the flux density was equal to $5 \cdot 10^{13}$ cm^{-2}·s^{-1}.

RESULTS

Radiation resistance of InSb microcrystals doped by impurity complexes depends on impurity complex composition as well as on doping level.

Fig. 1 and 2 show the lines of the relative change in the carrier concentration depending on the values of the initial concentrations in the microcrystals. The data are shown for three mentioned above compositions of impurity complexes after irradiation of microcrystals with the fast neutrons up to the fluences 10^{15} n·cm^{-2} and 10^{16} n·cm^{-2}.

According to Fig.1, the minimal change in the concentration $\Delta n/n = 3.2$ % is observed in InSb<Sn:Cr> with the initial concentration of $1 \cdot 10^{17}$ cm^{-3}. For InSb<Sn:Al> with the same initial concentration this amount is twice as large and equals to 6.1 %. However, beginning from the initial concentration of $3 \cdot 10^{17}$ cm^{-3} the inverse thing – much better radiation resistance is observed. In particular, for InSb<Sn:Al> with the initial concentration of $1 \cdot 10^{18}$ см$^{-3}$ the concentration change does not exceed 0.3 %. And for InSb<Sn:Cr> this change is equal to 0.4 %.

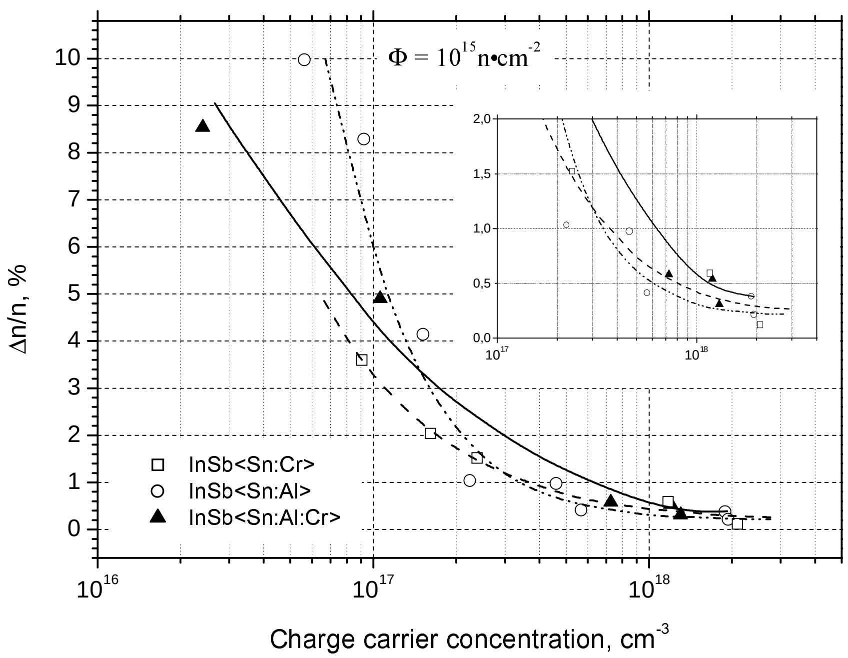

Fig. 1. Relative change in the charge carrier concentration Δn/n depending on the values of initial concentrations of InSb microcrystals after their irradiation with the fluence up to 10^{15} n·cm^{-2}

Introduction of the additional impurity Cr into the impurity complex of InSb<Sn:Al> leads to ambiguous effect. Namely, in the range of $5\cdot10^{16} \div 1.5\cdot10^{17}$ cm^{-3} the radiation-stimulated change of the concentration for InSb<Sn:Al:Cr> is 1.5 - 2% less than for InSb<Sn:Al>. However, the opposite effect is observed for concentrations above $1.5\cdot10^{17}$ cm^{-3}.

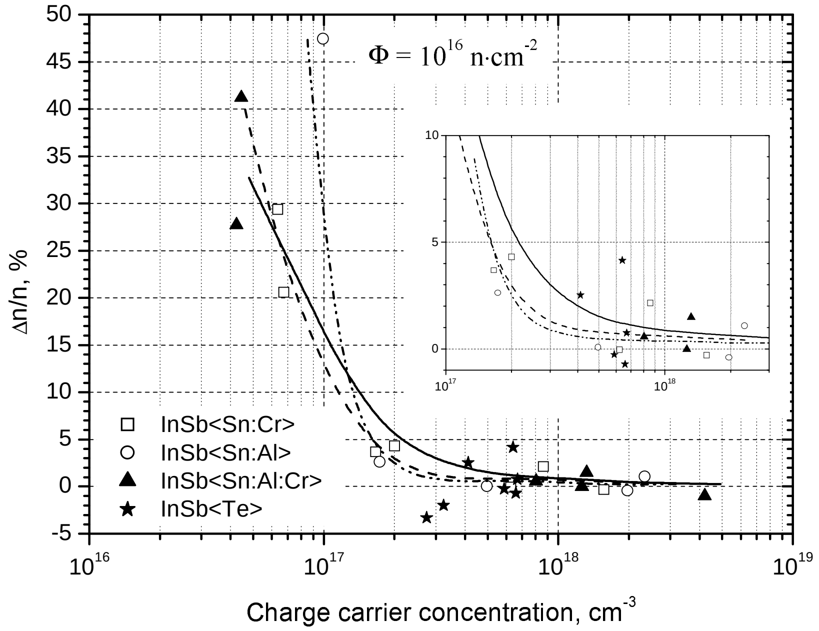

Fig. 2. Relative change in the charge carrier concentration Δn/n depending on the values of initial concentrations of InSb microcrystals after their irradiation with the fluence up to 10^{16} n·cm^{-2}

The same tendency remains under fast neutron fluence up to 10^{16} cm^{-2} (Fig.2) in consequence of competing processes of the lattice vacancy displacement by atoms of main and doping impurities as well as the amphoteric nature of Sn impurity. Probably, introduction of the impurity Al into the impurity complex somehow limits the introduction of Sn atoms into Sb sublattice.

Fig.3 demonstrates the lines of the relative change in the carrier mobility for the various initial concentrations under the irradiation with fluence up to 10^{16} n·cm^{-2}. The minimal change in the carrier mobility is observed for InSb<Sn:Al:Cr> in the most part of the investigated range of concentrations. This may serve as a confirmation of the existing hypothesis about the aluminium gettering of the oxygen background impurity, which has negative influence on the radiation resistance of III-V crystals.

Investigation results of the relative change in carrier concentration and mobility in InSb microcrystals doped by Te are shown at the Fig.1 and 2. as separate points marked by asterisks. Evidently, InSb<Te> microcrystals have much worse radiation resistance then InSb<Sn:Al:Cr> microcrystals.

As one can see from Fig.1 and 2, the relative change in the charge carrier concentration for all investigated impurity complexes in InSb microcrystals tends to the minimum values when the initial concentrations in the material is about $(2\div3)\cdot10^{18}$ cm^{-3}. At the same time, such tendency remains for all the fluences.

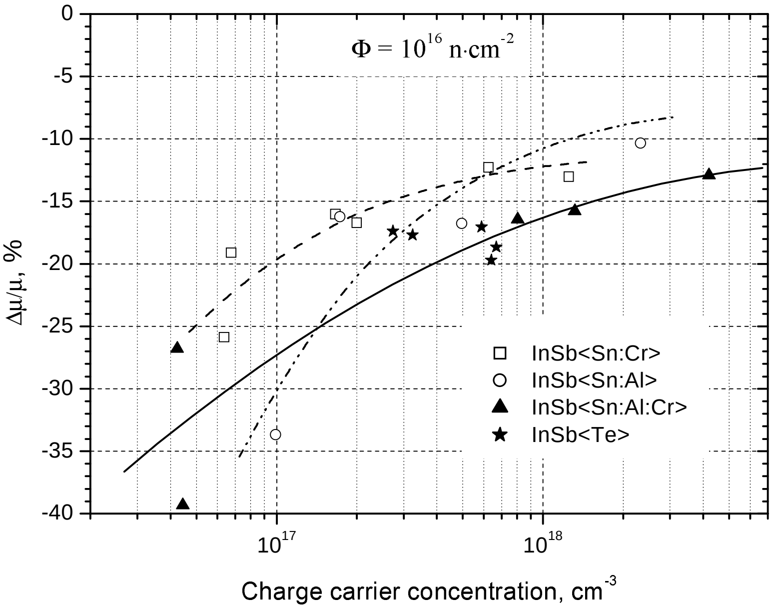

Fig. 3. Relative change in charge carrier mobility of complex doped InSb microcrystals after the fast neutron irradiation with the fluence up to 10^{16} n·cm^{-2}

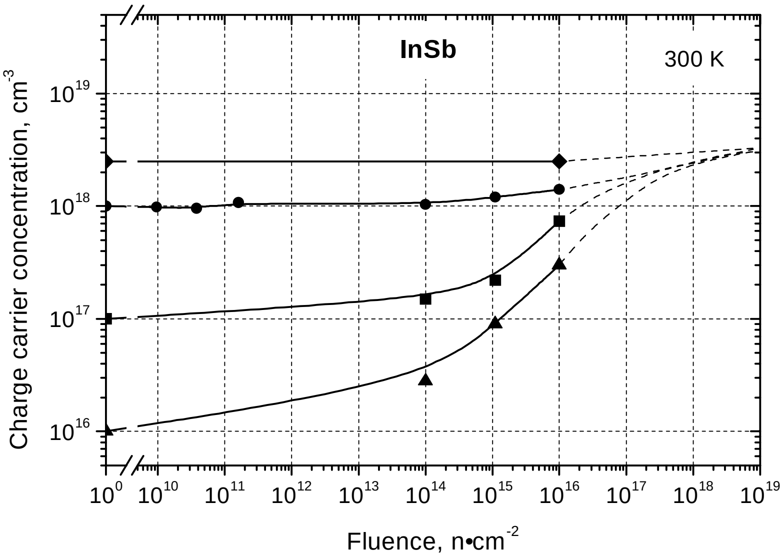

Fig. 4. Dependence of the charge carrier concentration in InSb microcrystals from the fast neutron fluence. Solid lines - experimental results, dashed lines – extrapolation

From the lines of the concentration dependence from the fast neutron fluence (Fig.4), the optimal value of the concentration for doped InSb microcrystals was determined by means of extrapolation and it is equal to $2.5 \cdot 10^{18}$ cm^{-3}. It agrees well with the data of N.Kolin [1] for InAs - another semiconductor material of this group.

CONCLUSIONS

It was experimentally demonstrated that InSb microcrystals with the optimum carrier concentration of $2.5 \cdot 10^{18}$ cm^{-3} may be obtained by means of the complex doping with the use of Sn, Al, Cr impurities. These crystals with such concentration have sufficient stability even under the high fast neutrons fluences. The change in the charge carrier concentration is about 0.1 % under the fast neutron fluence up to 10^{15} n·cm^{-2} and 0.4 % under the fluence up to 10^{16} n·cm^{-2}. The charge carrier concentration is the main parameter of microcrystals, which is responsible for the parameters of the sensors manufactured on their base. When irradiated up to the fluence 10^{14} n·cm^{-2} InSb microcrystals have high radiation resistance: the change in their carriers concentration does not exceed 0.01 %.

Obtained microcrystals are sensitive elements of Hall effect based magnetic field sensors. An intelligent magnetic measuring system for magnetic field monitoring with the high accuracy in radiation conditions of LHC-type charged particle accelerators was developed on the base of such microsensors with the dimensions (0.06×0.03×0.01) mm^3. Due to its minimal dimensions, weight and power consumption as well as radiation resistance, such microsensors are already applied in magnetic systems of orientation and stabilization of the spacecraft.

REFERENCES

[1] Bolshakova I. Improvement of radiation resistance of magnetic field microsensors // Sensors & Actuators: A. Physical. – 1999. - V.76. - P.152-155.
[2] Bolshakova I., Moskovets T., Krukovsky S., Zayachuk D. Radiation resistant microcrystals and thin films of III-V semiconductors // Materials Science & Engineering. – 2000. – B 69-70. - P. 441-443.
[3] Bolshakova I., Koptsev P., Melnyk I., Moskovets M., Krukovsky S., Zayachuk D. Control of parameters of III-V compound microcrystals and epitaxial layers by means of complex doping // Crystal Research and Technology. - 2001. V. 36. - № 8-10. – P. 989-997.
[4] Zaitov F., Isayev F., Polyakov A., Kuzmin A. Influence of penetrating radiation on the properties of indium antimonide and indium arsenide. – Baku, 1984. – 205 p.

[1]V.T. Adamiv, [1]Ya.V. Burak, [1]I.Yu. Martynyuk-Lototska, [1]M.E. Kostyrko, [1,2]R.O. Vlokh, [1]G.M. Romanyuk, [3]W. Shranz

[1]Institute of the Physical Optics, 23 Dragomanov Str., 79005, Lviv, Ukraine
[2] Lviv Polytechnic National University, 12 Bandera Str., 79013, Lviv, Ukraine
[3]Institut fur Experimental Physic, Universitat Wien, Strudlhofgasse 4, A-1090 Wien, Austria

OPTICAL, ELASTICAL AND PIEZOOPTICAL PROPERTIES OF THE β-BAB_2O_4 AND $LI_2B_4O_7$ BORATE CRYSTALS

Keywords: borate crystal, optical and piezooptical properties

The optical, elastic and piezooptical properties of the borate crystals have been investigated. The dispersions of the indexes refraction of the $Li_2B_4O_7$ crystals have been determinated in wavelength range 350 - 650 nm. The results of the measurement velocity of the longitudinal and transverse ultrasonic waves on borate crystals are presented. Using ultrasonic velocity measurements the components of the elastic matrix C_{mn} of these crystals have been determined. Using the determined values of the elastooptical tensor components the acoustooptical quality M_2 of β-BaB_2O_4 crystals has been calculated.

INTRODUCTION

The borate crystals: β-BaB_2O_4 (BBO, point group of symmetry 3m) are known as efficient material for the optical applications [1,2] and $Li_2B_4O_7$ (point group of symmetry 4mm) are used in the acoustoelectronics techniques [3]. But the elastic and piezooptical properties of these crystals