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Ways of improving radiation resistance of magnetic sensors for charged particle accelerators

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The paper presents the results of investigation into radiation resistance of semiconductor Hall sensors and cases of their application in magnetic measuring systems of varying complexity.

В работе представлены результаты исследований радиационной стойкости полупроводниковых холловских сенсоров и примеры их использования в магнитоизмерительных системах разного уровня сложности.

Способи підвищення радіаційної стійкості магнітних сенсорів для прискорювачів заряджених частинок. *І.А.Большакова, І.С.Василевський, Н.І.Каргін, О.Ю.Макідо, Ф.М.Шуригін, Р.М.Стецько, М.Н.Стріханов.*

В роботі представлено результати дослідження радіаційної стійкості напівпровідникових холлівських сенсорів і приклади їх використання у магнітовимірювальних системах різного рівня складності.

1. Introduction

Today there are a number of areas of science and technology for which magnetic field measurement and control is an essential task. These areas include: new generation fusion reactors, research reactors, space instrumentation, accelerator facilities, including medical-purpose ones. Typically, the task of measuring magnetic fields for these industrial areas is associated with the need for measuring inhomogeneous magnetic fields in a wide range of magnetic induction values and the determination of magnetic field spatial distribution. The solution to this problem involves the necessity to carry out measurements under the conditions of destabilizing factors, particularly, under radiation loads.

Magnetic measuring devices for such tasks should be based on sensors with high sensitivity in a wide range of magnetic fields and capability of measuring heterogeneous and dynamic magnetic fields; the sensors should also display sufficient parameter stability under the conditions of substantial radiation fields. Hall sensors based on semiconductor materials satisfy the above mentioned requirements; however, stabilization of their parameters under the radiation loads requires special approaches, including a choice of materials and their initial parameters, as well as specific technological solutions.

2. Experimental

To ensure high sensitivity of Hall sensors in a wide range of magnetic fields it is necessary to use materials with high mobility of free charge carriers. Si and Ge are widely used for such sensors, as well as III–V semiconductor materials: GaAs, InSb, InAs and their solid solutions with *n*-type conductivity.

It is known that due to features of their band structure Si, Ge, GaAs quickly become highly resistive when exposed to radiation, which makes them unsuitable for production of the sensors intended for the high radiation load conditions [1]. This is primarily associated with the fact that irradiation with high-energy particles triggers effective formation of acceptor-type defects in these materials. Concentration of the defects increases simultaneously with the irradiation dose, which results in the compensation of the material and change in the type of conductivity.

Indium-containing materials hold interest in terms of radiation resistance of the sensors; apart from formation of acceptor-type defects, they are also characterized by formation of donor impurities resulting from transmutation of indium atoms into tin when exposed to thermal neutrons, which progresses with high efficiency [2, 3]. The result of irradiation of such materials is that processes of acceptor-type and donor-type defect formation can compensate each other. Among indium-containing materials InSb, InAs and solid solutions InSb–InAs and InAs–GaAs are the most suitable for the Hall sensors, as these are materials of *n*-type conductivity, which possess the high free charge carrier mobility.

To study the radiation resistance of the electrical and physical parameters of these materials, a substantial number of samples were studied under varied radiation conditions in order to determine mechanisms of the radiation defect formation. The most suitable subjects for these studies are filamentary microcrystals which grow under the conditions of free gas-phase crystallization and are characterized by a low level of intrinsic structural defects in comparison with thin-film heterostructures and bulk crystals.

It is known that neutron irradiation of indium-containing semiconductor materials initiates transmutation of indium atoms into tin atoms. For these materials tin is a donor impurity, thereby increasing the concentration of free charge carriers [2].

Transmutation proceeds according to the following reactions:

$$^{113}\mathrm{In}(n,\gamma),\ \ ^{114}\mathrm{In} \rightarrow {}^{114}\mathrm{Sn}, \qquad (1)$$

$$^{115}\mathrm{In}(n,\gamma),\ ^{116}\mathrm{In} \rightarrow {}^{116}\mathrm{Sn}. \qquad (2)$$

The efficiency of these reactions is very high with more than 90 % of produced tin being electroactive. Therefore, formation of the donor defects in the process of exposure of these materials to radiation, and its speed depends on the magnitude of the thermal neutron flux. At the same time, the rate of formation of the acceptor-type radiation defects for these materials depends not only on the magnitude of fast neutron flux and the band structure of the material, but also on the initial doping level. Thus the choice of the material's initial parameters, namely, the initial charge carrier concentration for a specific range of exposure can bring about the effect of compensation of these two mechanisms and stabilization of free charge carrier concentration in the process of irradiation even up to high fluences.

Experimental determination of the optimal initial parameters that would ensure the material's radiation resistance required investigation into the effect of irradiation on samples of the materials with different levels of doping in a wide range of concentrations.

A wide range of charge carrier concentrations can be achieved in two ways. Firstly, by chemical doping of the material in the process of thin film and crystal growth, and secondly, by nuclear doping while irradiating the material with thermal neutron flux on account of the progress of transmutation reactions.

Selection of tin as a dopant in the process of chemical doping was based on the fact that conversion of indium into tin is the main transmutation reaction during neutron irradiation.

3. Results and discussion

To investigate the radiation resistance of electrical and physical parameters of semiconductor materials of InSb, InAs, and their solid solutions InSb–InAs, InAs–GaAs a number of samples with different initial doping levels ranging from $2 \cdot 10^{16}$ cm^{-3} to $1 \cdot 10^{19}$ cm^{-3} was used.

Investigations of the effect of neutron irradiation on the parameters of InSb and InAs microcrystals and their solid solutions InSb–InAs, InAs–GaAs were carried out in the following nuclear reactors: IBR-2 at the Joint Institute for Nuclear Research

(Dubna, Russia) and LVR-15 (Rez, Czech Republic) to the fluence of $F = 1{\cdot}10^{16}$ n·cm^{-2} at flux rate of $\varphi = 10^{10}$ n·cm^{-2}·s^{-1}. The studies were carried out under irradiation with a full flux of the reactor neutrons.

Evaluation of radiation resistance of the samples under study was carried out by determining the relative change in charge carrier concentration (n) in the irradiated semiconductors, as the stability of this particular parameter determines first of all the stability of sensitivity (S) of the magnetic field sensors in radiation environment.

Measurement of the samples was carried out before and after irradiation preserving all measurement conditions on a precision bench TI-3 on the basis of the HMS 7504 stand (USA), which makes it possible to determine the relative change in the concentration of material's free charge carriers ($\Delta n/n$) with margin of error less than 0.01 %.

As seen from the obtained concentration dependences (Fig. 1), the value of radiation resistance of InSb, InAs semiconductor materials and their solid solutions depends on the initial doping level of the material. Simultaneously with the increase of free charge carriers concentration, the rate of change of concentration decreases and tends to zero on condition of a certain value of the initial doping level (for InSb — at (4–6)$\cdot10^{17}$ cm^{-3}, for $\mathrm{InAs_{0.84}Sb_{0.16}}$ — at (1–2)$\cdot10^{18}$ cm^{-3}, for InAs — at (2–3)$\cdot10^{18}$ cm^{-3}). This is explained by the fact that at higher levels of doping the efficiency of formation of the acceptor-type radiation defects increases for the both materials.

Fig. 1 shows that at a low initial doping level the rate of concentration change during irradiation is significantly higher for indium arsenide than for InSb. This is due to the fact that an interaction of InAs with the fast neutrons in the material triggers a generation of the radiation defects of both donor and acceptor type. The effectiveness of the donor-type defect formation predominates up to the charge carrier concentration of $1\cdot10^{18}$ cm^{-3} [4, 5]. When this value is reached, the efficiency of formation of the donor-type and acceptor-type defects comes to a balance, and the effect of secondary nuclear doping becomes less noticeable, which ensures the effect of the material's parameter stabilization.

For InSb, unlike InAs, the efficiency of formation of the acceptor-type radiation defects prevails for all values of the initial doping level. Furthermore, the rate of the acceptor defect formation increases simultaneously with the charge carrier concentration. The effect of the material's parameter stabilization is achieved by leveling up the rates of formation of donor defects due to nuclear doping and of acceptor defects produced under the influence of the fast neutrons.

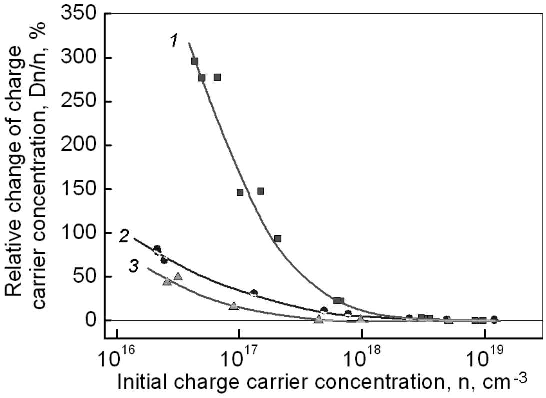

Fig. 1. Concentration dependences of relative change in charge carrier concentration after exposure to reactor neutrons to the fluence $F = 1\cdot10^{16}$ n·cm^{-2}: *1* — InAs microcrystals; *2* — $\mathrm{InAs_{0.84}Sb_{0.16}}$ microcrystals; *3* — InSb microcrystals.

Sensors for magnetic measuring devices and systems for particle accelerators should be selected considering the following factors: a ratio of the fast and thermal neutrons, nature of the sensor's material and the initial doping level of the material. The samples produced by group technologies, namely, film structures, should be used as sensing elements of commercial devices and measuring systems. Defect level of thin-film sensors is initially higher than that of microcrystals, which required additional research to determine the optimal parameters of the sensor material.

Contemporary technologies for obtaining indium arsenide film structures involve the use of transitional buffer layers between the substrate and the active layer. Buffer layers are typically solid solutions of InAs–GaAs and InAs–AlAs. The use of buffer layers in planar technology for producing indium arsenide films is conditioned by the difference between the lattice parameters of the substrate and the active layer. This technology makes it possible to obtain low-defect active layers with the free charge carrier mobility that is sufficient for the Hall sensors. However, indium-containing buffer layers with low free charge carrier concentration when irradiated with a neutron flux

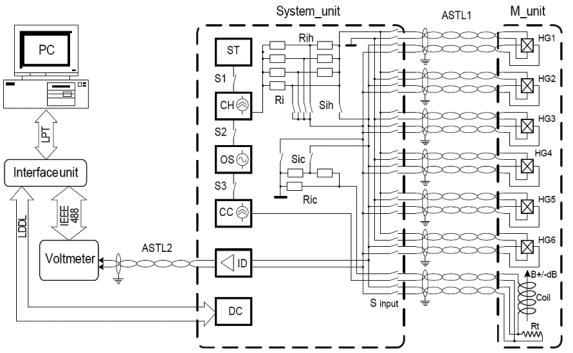

Fig. 2. Diagram of measuring equipment: (HG1–HG6) — specimens under study, ST — voltage regulator, CH and CC — current sources, OS — reference voltage generator, ID — input amplifier, DC — command decoder, ASTL 1, ASTL 2 — signal transmission lines.

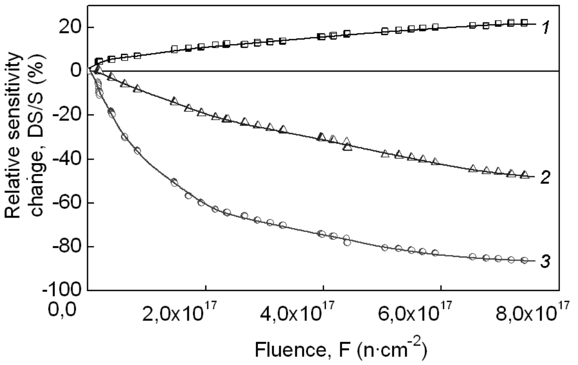

Fig. 3. Relative sensitivity change of InSb-based thin-film sensors with varied initial charge carrier concentrations under the influence of neutron irradiation: *1* — $n_0 = 2\cdot10^{18}$ cm^{-3}; *2* — $n_0 = 2\cdot10^{17}$ cm−3; *3* — $n_0 = 2\cdot10^{16}$ cm^{-3}.

undergo a substantial increase in the conductivity due to formation of the donor defects resulting from the nuclear doping. This effect leads to a considerable permanent uncontrolled drift of the sensor signal under the influence of irradiation [6]. Film sensors based on InAs, which are promising in terms of their radiation resistance, can only be obtained using film structures without indium-containing buffer layers.

The technology for growing InSb/i–GaAs heterostructures makes it possible to obtain layers with the mobility sufficient for the Hall sensors without use of buffer layers. Such structures, as will be shown below, can be effectively applied for the sensors in magnetic measuring devices and systems intended for operation under conditions of charged particle accelerators.

In the process of long-term operation in particle accelerators the magnetic field sensors can receive a high radiation dose up to fluences of 10^{18} n·cm^{-2}. To assess the radiation resistance of the magnetic field sensors in such circumstances, studies of film-based InSb Hall sensors were conducted with the different initial charge carriers concentrations of $n_1 = 2\cdot10^{16}$ cm^{-3}; $n_2 = 2\cdot10^{17}$ cm^{-3}; $n_3 = 2\cdot10^{18}$ cm^{-3} up to neutron fluence $F = 8\cdot10^{17}$ cm^{-2}.

Investigation into the effect of irradiation on the sensor parameters to such high fluence by measuring their parameters before and after exposure (off-line method) is not possible due to a very long period (up to several years) while the induced radioactivity of the samples decays to background levels and it becomes possible to bring them outside the territory of the reactor [2]. For these experiments an on-line method for studying the Hall sensors was developed which makes it possible to measure the sensor signals directly in the process of exposure. To implement this method multifunctional high-precision instrumentation was developed and manufactured, a part of which — rigging with specimens under study — is placed within the channel of the nuclear reactor, and the other — the measuring equipment — at a considerable distance, in the safe personnel area. The block diagram of the facility for carrying out these measurements is shown in Fig. 2.

The sensors were tested in the process of exposure to a full spectrum of reactor neutrons in the WWR-M reactor of Petersburg Nuclear Physics Institute at the intensity of the reactor neutron flux of $2.5\cdot10^{11}$ n·cm^{-2}·s^{-1} to the fluence $F = 7.4\cdot10^{17}$ n·cm^{-2}, the irradiation temperature was 110°C. The necessary 1:1 balance between the fast and thermal neutrons was achieved using cadmium screen.

The results of conducted research are shown in Fig. 3.

As can be seen from the obtained results, a variation of the sensors' sensitivity under neutron irradiation depends on the initial concentration of free charge carriers in the material. The specimens with a lower initial concentration of free charge carriers in the material ($n \le 2\cdot10^{17}$ cm^{-3}), curves *2* and *3* in Fig. 3, display a significant reduction in the sensitivity due to the predominance of the donor defect formation mechanism as a result of nuclear doping of the material. Reduction of the sensor's sensitivity is associated with an increase in the concentration of free charge carriers in the sensor's material. Since the highly doped specimen ($n = 2\cdot10^{18}$ cm^{-3}), curve *1*, displays a minor change in the charge carrier concentration under the influence of nuclear doping, change of the sensor's parameters is conditioned predominantly by formation of the acceptor-type radiation defects. As a result of exposure the given sample displayed a decrease in concentration of free charge carriers and a corresponding increase of the sensor's sensitivity.

However, at the fluence of $2\cdot10^{17}$ cm^{-2} parameter changes of the irradiated material do not exceed 10 %, at the highest fluences of $8\cdot10^{17}$ cm^{-2} — 20 %. This signal drift can be compensated using dedicated electronics. In recent experiments the materials were obtained with parameter changes at high fluences being less than 5 %.

We can assume that maximum radiation resistance will be displayed by sensors based on materials in which the rate of formation of the donor levels as a result of nuclear doping is commensurate with the rate of formation of the acceptor levels under the influence of the fast neutrons. This can be achieved by ensuring a certain optimal level of doping for the material of sensor's sensing element, which in the case of thin-film InSb heterostructure amounts to $n = (4–6)\cdot10^{17}$ cm^{-3}.

4. Practical application and prospects

Magnetic Sensor Laboratory designed and produced the magnetic measuring instrumentation on the basis of the obtained radiation resistant Hall sensors for different accelerator complexes such as: TORE SUPRA (France), JET (UK), NICA (Russia). These devices are one-and three-axis systems for magnetic field monitoring, as well as the systems for mapping complex inhomogeneous magnetic fields. To ensure the high measurement accuracy and long term stability these systems make use of the principles and functions of self-diagnosis and sensor signal correction, which make it possible to compensate the slight drifts of the sensor signal under irradiation.

At present several sets of magnetic measuring equipment, which includes 3D probe, electronics unit and software, are successfully used to measure the ex-vessel magnetic fields in the octants 5 and 8 of the JET reactor, in ports 5DLICP and 8DLICP [7].

In 2011 the Laboratory produced the magnetic measuring instrumentation for measuring three magnetic field components with an accuracy of 0.1 % in the superconducting solenoid, which is one of the elements in the magnetic system of the NICA accelerator complex. The works on development and production of the magnetic measuring equipment are in progress for magnetic elements of NICA accelerator complex such as: dipole magnets for beam transport channels extracted from the Nuclotron; magnetic elements of Booster; superconducting solenoid of electronic cooling system; MPD detector; analyzing magnet SP-41 for the BM@N experiment.

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