Irradiation-Resistant Magnetic Field Microsensors

Inessa Bolshakova[1], Volodymyr Yerashok[1], Yuriy Zagachevskyi[1], Olena Makido[1], Serhiy Tymoshyn[1], Roman Stetsko[1], Nazar Kokoten[2], Oleksandr Prykhodko[2], Fedir Shurygin[1]

[1]Magnetic Sensor Laboratory, Lviv Polytechnic National University, UKRAINE, Lviv, Kotlyarevsky street 1, E-mail: inessa@mail.lviv.ua

[2]Department of Semiconductor Electronics, Lviv Polytechnic National University, UKRAINE, Lviv, St. Yura square 1

Abstract – A technology developed for creating radiation-resistant magnetic field sensors based on semiconductor binary compounds of III-V group (InSb, InAs, GaAs) and their solid solutions ($In_XGa_{1-X}As$, $InAs_XIn_{1-X}$) is presented. Studies have confirmed such sensors' operability in neutron fluxes up to high fluences. This has made possible their use in magnetic measuring instrumentation for magnetic field diagnostics in thermonuclear reactors. The instrumentation comprises a 3D probe with Hall sensors and electronics characterized by the function of in-situ self-calibration, which makes available periodic calibration of sensors without their reinstallation, leading to high measurement accuracy. The magnetic measuring instrumentation developed by the team has been applied in European reactors TORE SUPRA (France) and JET (UK), and is aimed at solving tasks at a new charged particle accelerator – collider NICA (Russia).

Key words – semiconductors of III-V group, magnetic field sensors, magnetic measuring instrumentation, high-energy irradiation, radiation resistance, magnetic diagnostics, charged particle accelerators.

I. Introduction

A wide variety of uses magnetic fields have garnered in engineering, scientific studies and medicine brings about the need of creating sensors along with sensor instrumentation operable under the conditions of high-energy irradiation that occurs in nuclear and thermonuclear power engineering, charged particle accelerators (including those of medical purpose) and space research.

The Magnetic Sensor Laboratory of Lviv Polytechnic National University has years' worth of experience in R&D activities targeting the creation of a technology for radiation-resistant magnetic field sensors. The use of such sensors to develop magnetic measuring instrumentation allows solving a topical task of magnetic field control under the conditions of elevated radiation background.

II. Research results

Common materials for Hall sensor production include semiconductor materials Si, GaAs, InSb, InAs. However, Si and GaAs rapidly assume high resistance in radiation environment due to their band structure, and cannot therefore be used in radiation-resistant sensors. Earlier studies have demonstrated that the materials most promising for such sensors are In-containing ones like InSb, InAs and their solid solutions ($In_XGa_{1-X}As$, $InAs_XIn_{1-X}$). The technology for ensuring radiation stability of sensor material parameters has been fine-tuned on the model crystals (so called whiskers) grown at the Laboratory. Whiskers are characterized by perfect, virtually defect-free, structure which makes the effect of irradiation-induced defects tangible [1].

Technological methods of enhancing sensors' radiation stability are based on the methods of chemical doping of sensors' semiconductor materials with a complex of doping impurities (donor, isovalent, rare-earth ones), and on the methods of radiation modification of material parameters [2].

The developed technological approaches have been used in producing sensors on the basis of industrially manufactured thin films and creating sensor-based magnetic measuring instrumentation.

Radiation stability of semiconductor materials and sensors has been tested in neutron fluxes of various nuclear research reactors IBR-2 (Joint Institute for Nuclear Research, Dubna), WWR-M (Petersburg Nuclear Physics Institute, Gatchina) and LVR-15 (Nuclear Research Institute Řež, Czech Republic).

Studies conducted in nuclear reactors have confirmed the sensors' operability in neutron fluxes up to very high fluences $F=3\cdot10^{18}$ $n\cdot cm^{-2}$. Sensors' sensitivity change when irradiated up to fluences $F=10^{15}$ $n\cdot cm^{-2}$ is only 0.04%, at fluences $F=10^{16}$ $n\cdot cm^{-2}$ – 0.08%, at the highest fluences $F=10^{17}$ $n\cdot cm^{-2}$ and $F=10^{18}$ $n\cdot cm^{-2}$ sensitivity drift does not exceed (5-10)%, which is fully amenable to electronic correction [3].

Radiation-resistant sensors have become the basis for the creation of magnetic measuring instrumentation for magnetic field diagnostics in thermonuclear reactors. The instrumentation for magnetic diagnostics comprises a 3D probe with radiation-resistant semiconductor sensors and electronics characterized by the function of in-situ self-calibration. Each 3D probe contains three Hall sensors, three microsolenoids 1÷2 mm in diameter with sensors inside, and a thermodiode. Microsolenoid generates magnetic field of a certain magnitude, and along with the sensor it houses constitutes an integrated magnetometric transducer (Fig. 1).

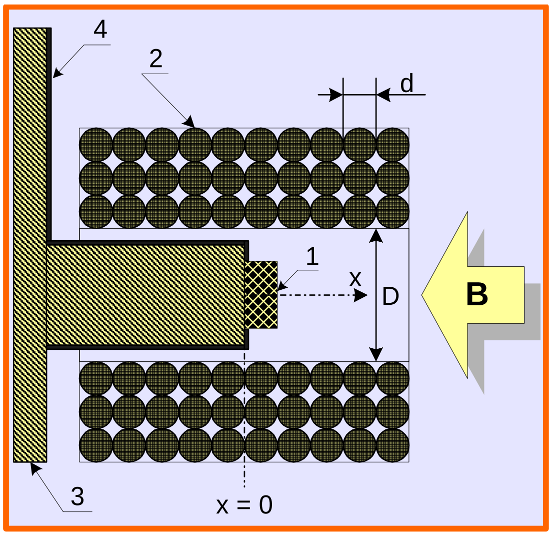

Fig. 1. Integrated magnetometric transducer:
1 – Hall sensor, 2 – microsolenoid's coil, 3 – base, 4 – outputs, D=2mm – microsolenoid's inner diameter, d=0,05 mm – copper wire diameter, B – magnetic flux density

In calibration mode, microsolenoids generate test magnetic field B_{0X}, B_{0Y}, B_{0Z} about 5mT in magnitude (Fig. 2). The test magnetic field generated by microsolenoid's copper coil is not affected by radiation dose, and can therefore be used for periodic calibration of sensors' sensitivity.

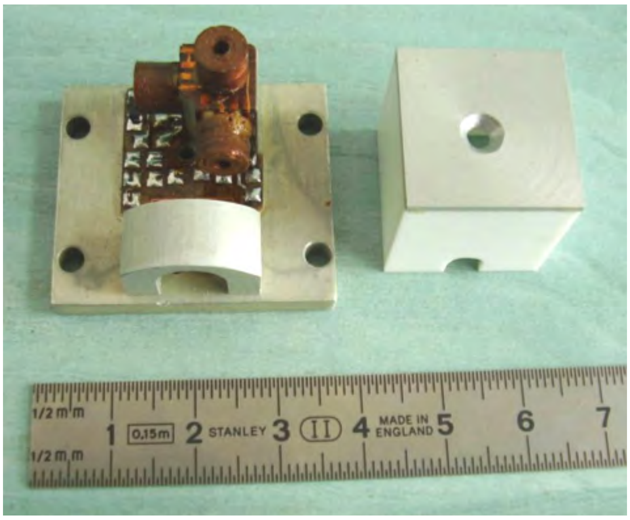

Fig. 2. 3D probe assembly

The developed algorithm of transduction parameter correction allows to avoid the problem of generating strong test magnetic fields; it proves effective in however high measured fields. The algorithm is based on three principles: simultaneous analysis of the transduction parameter by the integral and differential signal components; frequency separation of the differential and integral signal components; progressive method of calculating the values of transduction function and measured magnetic field.

The advantage of the principle that lies in the basis of the instrumentation operation is its availability for periodic calibration without the sensors being reinstalled (in-situ calibration). This factor ensures sensors' sensitivity correction under the conditions of their long-term exposure to penetrating radiation [4].

The magnetic measuring instrumentation developed and produced at the Magnetic Sensor Laboratory has been installed and successfully applied in European reactors TORE SUPRA (France) and JET (UK) [4]. Results yielded by the use of the magnetic measuring instrumentation based on radiation-resistant Hall sensors have demonstrated its operability in reactor's harsh environment and confirmed its promising status for new-generation reactors like ITER.

Lately, the developments pursued by the Laboratory team (involving students and postgraduates) target the creation of high-precision magnetic measuring instrumentation for new charged particle accelerator – collider NICA, which is under construction at an international center in Dubna (Russia).

NICA project is aimed at carrying out in the collider mode an experiment on studying strong interaction between hot and dense quark-gluon matter and search for possible generation of strongly interacting matter's mixed phase, along with applied fundamental research on the beams of light and polarization ions, studies in the field of radiation technologies, medicine and biology.

This research accelerator complex provides for a significant number of superconducting solenoidal, quadrupole and other elements of magnetic system used for controlling charged particle beams. Success of the experiment is directly related to accurate work of the magnetic system, whose requirements to magnetic field homogeneity and stability are very high. Methods and magnetic measuring instrumentation that currently exist do not satisfy all the requirements set to a magnetic system that operates at the complex.

Coming from the set tasks, magnetic measuring instrumentation capable of ensuring the re-quired accuracy of magnetic field control (at least ± 0.1%) and stable operation under radiation load has to be developed and produced for diagnostics, monitoring of magnetic fields at various elements of the complex's magnetic system, including the real-time mode, and creation of data acquisition system.

Conclusion

Technologies and methods for magnetic field measurement developed at the Magnetic Sensor Laboratory using radiation-resistant sensors in magnetic measuring instrumentation have proven to be effective during their operation at European reactors TORE SUPRA (France) and JET (UK). Such instrumentation provides solution to the tasks of measuring the magnetic induction spatial distribution in NICA collider's magnetic systems both at the stage of their development, and during experiments on charged particle beams accompanied with radiation.

References

[1] I.Bolshakova, I.Ďuran, Ya.Kost, N.Kovaljova, K.Kovarik, O.Makido, J.Sentkerestiova, A.Shtabaliuk, F.Shurygin, L.Viererbl. "Effect of neutron irradiation on indium-containing III-V semiconductor micromonocrystals," Key Engineering Materials, vol. 543, pp. 273-276, Mar. 2013.

[2] I.A.Bolshakova, V.M.Boiko, V.N.Brudnyi, I.V.Kamenskaya, N.G.Kolin, E.Yu.Makido, T.A.Moskovets, D.I.Merkurisov. "The effect of neutron irradiation on the properties of n-InSb whisker microcrystals," Semiconductors (Fizika i tekhnika poluprovodnicov), vol. 39, no. 7, pp. 780-785, Jul. 2005.

[3] I.Bolshakova, I.Vasilevskii, L.Viererbl, I.Ďuran, N.Kovalyova, K.Kovarik, Ya.Kost, O.Makido, J.Sentkerestiová, A.Shtabalyuk, F.Shurygin. "Prospects of using In-containing semiconductor materials in magnetic field sensors for thermonuclear reactor magnetic diagnostics," IEEE Transactions on Magnetics, vol. 49, no. 1, pp.50-53, Jan. 2013.

[4] I.Bolshakova, A.Quercia, V.Coccorese, A.Murari, R.Holyaka, I.Ďuran, L.Viererbl, R.Konopleva, V.Yerashok. "Magnetic Measuring Instrumentation with Radiation-Resistant Hall Sensors for Fusion Reactors: Experience of Testing at JET," IEEE Transactions on Nuclear Science, vol. 59, no. 4, part 2, pp.1224-1231, Aug. 2012.