

Instrumentation for Hall sensor testing in ITER-like radiation conditions

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Limitation in the application of existing industrial Hall sensors designed for the measurement of magnetic fields in radiation environment is linked to the instability of their characteristics under irradiation. The development of radiation-hard Hall sensors requires large number of experiments to be carried out for investigating the impact of neutron irradiation with energy of 1 to 20 MeV on the properties of semiconductor materials of sensor active elements [1-4].

There are two methods for investigating the effect of neutron irradiation upon semiconductor materials: conventional method based on comparing the results of material parameter measurements made before and after irradiation (hereafter: off-line measurements), and study of the material parameters change during irradiation (hereafter: on-line measurements).

The method of off-line measurements is hampered by a number of drawbacks. Mainly it is a considerable delay between the end of irradiation and subsequent parameter measurement due to the decay of induced radioactivity down to background level, imposed by safety regulations for human manipulation with activated samples. The time for irradiated samples radioactivity to fall back down to background level depends upon the accumulated radiation fluence and may vary from several days up to several years. Additionally, because of the above mentioned delay it is impossible to monitor the relaxation processes of generated defects in the course of irradiation or shortly afterwards. On the other hand, off-line measurements allow simultaneous irradiation of a large number of sensors placed in special containers.

The method of on-line measurements avoids these drawbacks, but it is complex, significantly more expensive, and it requires the development of unique measuring equipment.

Off-line testing

The tests of semiconductor materials for active elements of Hall sensors by applying off-line measurement were carried out at IBR-2 (Dubna, Russia) and WWR-M (Gatchina, Russia) nuclear reactors. Irradiation of sensors with the full spectrum of reactor neutrons was carried out up to fluences of $\Phi = (10^{14} \div 10^{16}) \text{ n}\cdot\text{cm}^{-2}$ with a neutron fluence rate of $\sim 10^{10} \text{ n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ and irradiation temperature of 17°C and 60°C, respectively. In the course of the experiments, the samples of InSb and InAs semiconductor materials and their based solid solutions, doped up to different levels of free charge carrier concentration, were tested. The sensitivity change in the samples with optimal dopant composition in sensitive elements' material was 0.04 %, 0.05% and 0.8% under irradiation up to fluences of $\Phi = 10^{14} \text{ n}\cdot\text{cm}^{-2}$, $\Phi = 10^{15} \text{ n}\cdot\text{cm}^{-2}$, and $\Phi = 10^{16} \text{ n}\cdot\text{cm}^{-2}$, respectively [1-4].

However, for the samples irradiated up to a neutron fluence of $5\cdot 10^{15} \text{ n}\cdot\text{cm}^{-2}$, it was possible to carry out the measurements after irradiation and analyze the results of the experiment only after a period of several months needed for the induced radioactivity of the samples to fall back down to background level. For the samples irradiated up to a fluence of $1\cdot 10^{16} \text{ n}\cdot\text{cm}^{-2}$ – the analysis could be done after one year. Carrying out such experiments under higher fluences ($10^{17} \div 10^{18}$) $\text{ n}\cdot\text{cm}^{-2}$ increases the waiting time to several years. Such delays not only cause working inconveniences, but also make impossible a timely evaluation of the experiment results. Therefore, the research on the influence of neutron irradiation upon Hall sensor parameters at high fluences up to $10^{19} \text{ n}\cdot\text{cm}^{-2}$ is only possible using on-line method, for which dedicated multifunctional and high-precision instrumentation has been created.

Methods and instrumentation for carrying out on-line measurements

Methods developed for carrying out on-line measurements allow the measurement of the sensor parameters in real-time mode during the process of irradiation. Such experiments are extremely complex, because they require the development of a measuring system, one part of which comprises the samples being tested and is located in a nuclear reactor channel. The other part – measuring instrumentation – is located at considerable distance away, in the area allowing personnel access. Since such experiments are typically continuous: from several weeks up to several months, the reliability of the instrumentation, exposed to neutron irradiation and high temperatures, and of each of its chains has vital importance. Such

experiments aiming to test Hall sensors require placing a magnetic field source in reactor channel. For this purpose, we used a small-size electromagnet (solenoid). To place tiny Hall sensors in a field of such magnet, a special measurement head was designed and manufactured. Its constructive elements were made of special ceramics MACOR (Germany). MACOR ceramics allows quality mechanical processing and it offers high radiation and temperature hardness. Electromagnet and the cables located in the neutron irradiated area were made of anodized aluminum wire. A block diagram of the unit used for carrying out such measurements is presented in Fig.1.

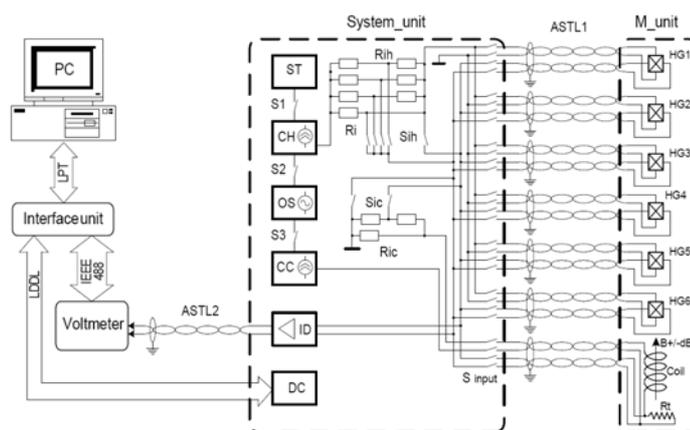


Figure 1. Block diagram of the measuring unit: (HG1-HG6) – tested samples, ST – voltage stabilizer, CH and CC – current sources, OS – reference voltage generator, ID – input amplifier, DC – command decoder, ASTL 1, ASTL 2 – signal transmission lines.

The tested sensors are supplied with direct currents of several mA, and the electromagnet – with pulses of alternating-sign current with frequency of 200 Hz. For Hall signal transmission over a considerable distance from the reactor (tens of meters), a method has been suggested to ensure amplification of these signals and their noise-immunity from numerous pickups from surrounding equipment. This method of signal synchronous detection with further analog-to-digital conversion with the help of 24-bit micro-converter ensures a measurement accuracy of $\pm 0.1\%$ with a signal level of 0.5mV and signal transmission line length of 20 m. Measuring circuit allows monitoring of sensor sensitivity, offset voltage, temperature with high temporal resolution in the course of long-term irradiation.

On-line measurement results

The developed instrumentation has been successfully implemented for studying the Hall sensor parameters in the process of irradiation up to high fluences ($10^{18} \div 10^{19}$) $\text{n}\cdot\text{cm}^{-2}$, typical for ITER reactor. The experiments were carried out in vertical channels of IBR-2 and WWR-M nuclear reactors under a neutron flux rate of $3 \cdot 10^{12}$ $\text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$, which is two orders of

magnitude higher than during off-line testing. The performed experiments allowed registration of the dynamics of the process of Hall sensor parameters change during their irradiation with the spectrum of reactor neutrons. In these experiments, sensors with various initial material parameters and with different radiation pretreatment were investigated. The results of the performed research are presented in Fig.2 and Fig.3.

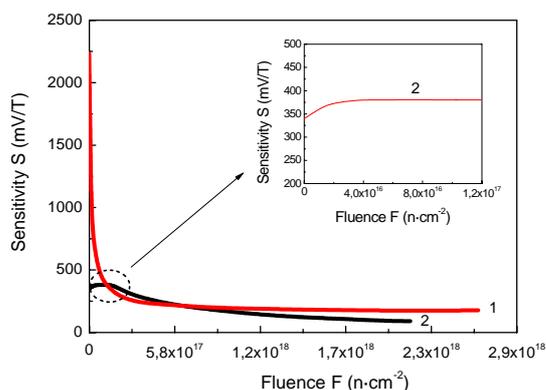


Figure 2. InSb-based Hall sensors testing in IBR-2 reactor: 1 – $n_0 = 2 \cdot 10^{16} \text{ cm}^{-3}$; 2 – $n_0 = 2 \cdot 10^{17} \text{ cm}^{-3}$ (n_0 – initial charge carrier concentration)

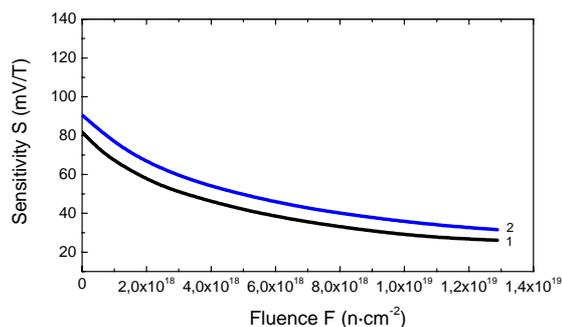


Figure 3. InAs-based Hall sensors testing in WWR-M reactor: 1 – $n_0 = 3 \cdot 10^{18} \text{ cm}^{-3}$; 2 – $n_0 = 2 \cdot 10^{18} \text{ cm}^{-3}$ (n_0 – initial charge carrier concentration)

All the tested Hall sensors were remaining operable during the whole experiment up to neutron fluences of $> 10^{19} \text{ n} \cdot \text{cm}^{-2}$. The developed multifunctional and high-precision instrumentation has successfully withstood the test during 1200 hours of continuous operation. The results of the performed experiments allow the selection of sensors for operating at their positions in the ITER reactor.

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