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ON POSSIBILITY OF APPLICATION OF INSB-BASED HIGH-TEMPERATURE HALL SENSORS FOR ITER MAGNETIC DIAGNOSTICS

ABSTRACT *We report on irradiation experiments of InSb-based Hall samples at two types of neutron spectrums. One with thermal neutrons (natural neutron spectrum of fission reactor) and second with fast neutrons (filtered spectrum). Fluences in both cases reached almost 10^{18} cm^{-2} and that led to significant decreasing of electron mobility of samples. In case of thermal neutrons, transmutation process led to increasing of electron concentration of about 2.3×1018 cm^{-3}. For samples irradiated with fast neutrons, twofold effect was observed: increase in electron concentration for samples with low carrier density and decrease in electron concentration for samples with high carrier density. All results raise important issue, that in case of ITER ex-vessel steady state sensors, research at different spectrum of neutrons are necessary.*

Keywords: *high temperatures, neutron irradiation, Hall sensor, ITER, magnetic diagnostics*

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1. INTRODUCTION

Among the many possibilities of producing energy in the future, thermonuclear power station is one of the most promising options. Building of thermonuclear power station, especially based on device called tokamak, is associated with overcoming many difficulties, previously unheard in any other projects. The next step in this way is building of tokamak ITER (International Thermonuclear Experimental Reactor) being the most complicated and complex device in human history. Conditions that will come to be met will be much more severe, compared to all other previous tokamaks. Major challenge facing designers of control and measurement systems, which will be responsible for proper operation of the device. One of the most important parameter to control, if not the most one, is magnetic field in tokamak. Magnetic diagnostic systems include measurements of fields, fluxes, plasma current and diamagnetic flux made inside and outside the vacuum vessel [1]. In case of ex-vessel magnetic field sensors, Hall element is one of the most promising candidates for steady state sensor [2]. However, it must be resistant to high doses of neutron radiation (fluence $F > 10^{18}$ cm^{-2}) and must operate at temperatures as high as 220°C, or even higher (up to 300°C). In Ref. [3] we demonstrated High Temperature Hall Sensors (HTHSs), based on epitaxial heterostructure of InSb/GaAs highly donor doped with tin, designed to operate over a wide range of temperature: from 4.2 K to 573 K (300°C). It shows that our sensors meet the thermal requirements imposed by the ITER project and puts them in the first place of HTHSs in the world.

From the viewpoint of resistance to neutron radiation, indium antimonide (InSb) has already been widely studied, starting from about 1960. The first advanced research on radiation resistant Hall sensors performed Bolshakova [4], but her samples did not meet temperature and neutron radiation requirements imposed by the ITER project [5]. In 2010 we published a paper [6], where we described study on neutron irradiation of highly donor doped InSb-based Hall sensors on experimental fission reactor LVR-15 in Czech Republic. Spectrum of neutrons was natural of that reactor (not filtered) and fluence reached 1.12×10^{17} cm^{-2}. We demonstrated that our sensors survived irradiation process and showed that a part of defects introduced by high energy neutrons can be easily removed by annealing at high temperatures. However, transmutation process occurring through thermal neutrons prevented the return of parameters to the state before irradiation. In present paper we will describe research on irradiation of samples with not only high carrier density, but also with low carrier density, for better highlighting the changes introduced by neutron irradiation process. Except that, samples divided into two groups, were irradiated by neutrons with different neutron energy spectrum – natural of experimental fission reactor MARIA in Swierk (Poland) and filtered neutron energy spectrum (fast neutrons). It allowed to compare results of these irradiations and to assess the suitability of production of Neutron Resistant Hall Sensors (NRHSs) for different kind of neutron radiation.

2. EXPERIMENT

For research purpose, 18 samples based on non-intentionally and intentionally doped with selenium, tellurium and tin, InSb thin films were prepared. About a half of the samples was evaporated on GaAs substrate and the rest on sital (ceramics). Technology of production of InSb thin films was described in detail in Ref. [7]. Bridge-shaped Hall structure was obtained by vacuum evaporation through proper mask. That shape guarantee high accuracy of measurement of samples resistances, ignoring the impact of the contact resistances. Thickness of films ranged from 1 µm to 4.5 µm. Gold or copper electrodes were obtained through vacuum evaporation. Gold covered copper wires were attached to the electrodes with high temperature conductive graphite paste. Surface of InSb was protected against influence of external environment by evaporating 0.1 nm thick SiO_2 layer. Figure 1 shows photos of two samples: the first with GaAs substrate and the second with sital substrate.

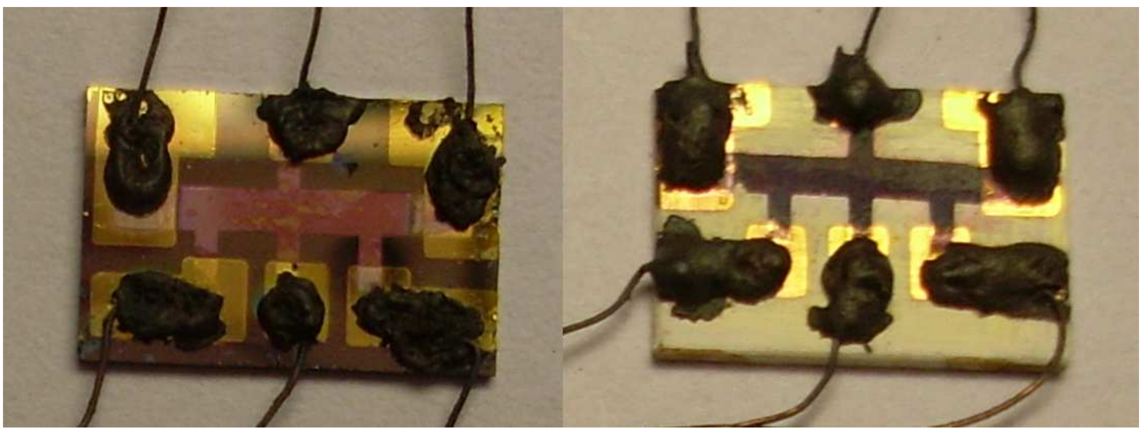

Fig. 1. Two samples, one with GaAs substrate (left) and one with sital substrate (right)

Before irradiation, parameters of samples were thermally stabilized at high temperatures, as it is described in the paper [3]. For irradiation purpose, samples were divided into two groups, one designated for irradiation with neutrons with natural energy spectrum of MARIA reactor, and second with fast neutrons (filtered spectrum). For the first group fluence reached $F = 9.7\times10^{17}$ cm^{-2} at average fluence rate $\varphi = 2\times10^{14}$ cm^{-2}s^{-1}. In case of second group fluence was $F_{fast} = 6.8\times10^{17}$ cm^{-2} and fluence rate was $\varphi = 2\times10^{12}$ cm^{-2}s^{-1}. Figure 2 shows graph of dependence $\varphi(E_n)$ for both neutron energy spectrum.

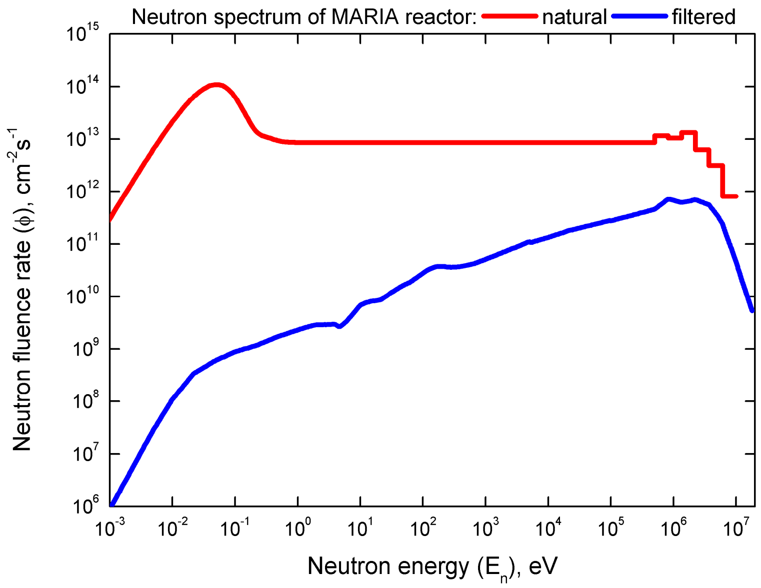

Fig. 2. Two spectrums of neutron energies, natural of MARIA reactor and filtered

3. RESULTS OF MEASUREMENTS

Results of measurements will be presented in two parts, first we will describe samples irradiated with thermal neutrons (mostly, not filtered spectrum), and then samples irradiated with fast neutrons. All measurements were done using an apparatus for Hall effect studies. Samples were measured at room temperature at the current of 10 mA, and magnetic induction value of 400 mT.

3.1. Samples irradiated with thermal neutrons

Table 1 shows the results of measurements of 4 representative samples, before and after the irradiation.

TABLE 1
Results of irradiation samples with thermal neutrons

Sample	d μm	Substrate/ Dopant	Irrad.	R Ω	$\Delta R/R_0$ %	μ $cm^2/(Vs)$	$\Delta\mu/\mu_0$ %	n cm^{-3}	Δn 10^{18} cm^{-3}
751/7	2.0	Sital <->	before	86.7	-92	20300	-69	7.2×10^{16}	+2.8
			after	6.9		6200		2.9×10^{18}	
1137/9	1.0	GaAs <->	before	22.8	-14	10800	-59	1.0×10^{18}	+2.0
			after	19.6		4400		3.0×10^{18}	
1178/6	1.0	GaAs <Sn>	before	23.8	-5	10000	-61	1.1×10^{18}	+1.8
			after	22.5		3900		2.9×10^{18}	
1171/3	1.0	GaAs <Sn>	before	22.3	-21	9000	-52	1.3×10^{18}	+2.1
			after	17.6		4300		3.4×10^{18}	

It is clear that strong influence on samples parameters had thermal neutrons, because of transmutation process. In that case, production of Sn atoms from In (and to a much lesser extent Te atoms from Sb) occurred. This contributed to increase of electron concentration in the films by amount from 1.8×10^{18} cm^{-3} to 2.8×10^{18} cm^{-3}, with average amount for all samples of 2.3×10^{18} cm^{-3}. It shows that amount of produced donors is approximately the same to all samples, regardless of the initial electron concentration, type of dopant and type of substrate. Behavior of electron mobility also does not depend on these factors, and average decreasing of that parameter was 59%.

3.2. Samples irradiated with fast neutrons

Table 2 shows results of measurements of 5 representative samples, before and after irradiation process.

TABLE 2
Results of irradiation samples with fast neutrons

Sample	d μm	Substrate/ Dopant	Irrad.	R Ω	$\Delta R/R_0$ %	μ $cm^2/(Vs)$	$\Delta\mu/\mu_0$ %	n cm^{-3}	Δn 10^{18} cm^{-3}
751/10	2.0	Sital <->	before	123	+72	10400	-90	9.8×10^{16}	+0.49
			after	211		1000		5.9×10^{17}	
1150/1	1.0	GaAs <->	before	237	+681	15900	-97	6.7×10^{16}	+0.24
			after	1850		400		3.1×10^{17}	
477/6	2.0	Sital <Te>	before	31.2	+724	15500	-89	3.7×10^{17}	-0.08
			after	257		1700		2.9×10^{17}	
1192/7	1.0	GaAs <Sn>	before	15.6	+1477	10000	-82	1.6×10^{18}	-1.04
			after	246		1800		5.6×10^{17}	
1122/9	1.1	GaAs <Sn>	before	16.5	+1767	5100	-75	2.9×10^{18}	-2.34
			after	308		1300		5.6×10^{17}	

Table 2 shows that decrease in the electron mobility was significant and for all samples it was on average 83%. It is independent on type of substrate and type of dopant. The behavior of electron concentration cannot generally be considered for all samples, because changes of that parameter depend strongly on its initial value. For non-intentionally doped samples electron concentration increased and the amount of the generated donors, both of the defect and the transmutation nature were higher than the concentration of the generated acceptor nature defects. In case of highly donor doped samples, we observe a decrease in the electron concentration. This behavior is not understood at present However, we can assume, that for a certain value of electron concentration, the balance of all those processes will be equal to zero. That means that it is possible to produce sensors, which can survive high doses of high energy neutron irradiation without significant changes in the sensitivity of the sensors.

As we can see, fast neutrons affect different on InSb thin films than thermal neutrons. According to our research on the impact of neutron irradiation on semiconductors, transmutations can be negligible in case of the irradiation of highly donor doped films with fast neutrons. It is known that the role of those neutrons is to disturb the structure of the crystal lattice. In a single act of collision of fast neutron and crystal atom, it is possible to heat 1000 ÷ 10000 atoms to temperature of about 10^4 K, and then rapidly to cool down during the time of 10^{-11} s. Atoms are permanently precipitated from lattice points and acceptor (mostly) and donor defects are created in that process.

4. SUMMARY AND CONCLUSIONS

In the experimental fission reactor MARIA in Swierk (Poland), 18 Hall structures based on InSb thin films, were irradiated with neutrons. Samples were non-intentionally and intentionally doped with selenium, tellurium and tin, on GaAs or sital substrate. 7 samples were irradiated with thermal neutrons (natural neutron energy spectrum of MARIA reactor) to the fluence of 9.7×10^{17} cm^{-2}, and the rest were irradiated with fast neutrons (filtered neutron energy spectrum of MARIA) to the fluence of 6.8×10^{17} cm^{-2}. Neutrons of different energy spectrum show totally different influence on thin films of InSb. In case of group of 7 samples, we observe increasing of electron concentration in films by an average value of 2.3×10^{18} cm^{-3} and decreasing of electron mobility by average value of 59%. It was independent on type of used substrate and type of dopant. Increasing of electron concentrations was generally caused by transmutation process, where In atoms changes into Sn atoms (about 97% of the whole transmutation process) and Sb atoms changes into Te atoms. Sn and Te atoms act as donors in InSb.

For samples irradiated with fast neutrons, changes in parameters of samples are caused by three processes: production of donor defects, production of acceptor defects and transmutations. In case of the low electron concentration samples (about 10^{16} cm^{-3}) we observe increasing of electron concentration, caused by dominance of transmutation process and production of donor defects over production of acceptor defects. For samples with high electron concentration (about 10^{18} cm^{-3}), behavior of that parameter is quite different – electron concentration decreased after the irradiation process.

All samples showed significant decrease in the electron mobility after irradiation with fast neutrons, with average value of 83%. This is caused by the disturbance of the crystal structure by high energy neutrons. That process does not depend on type of substrate and type of dopant and it is hard to prevent it.

Acknowledgments

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O MOŻLIWOŚCI ZASTOSOWANIA WYSOKOTEMPERATUROWYCH CZUJNIKÓW HALLA OPARTYCH O InSb W DIAGNOSTYCE MAGNETYCZNEJ TOKAMAKA ITER

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STRESZCZENIE *W artykule przedstawione zostały wyniki badań nad napromieniowaniem neutronami struktur halotronowych bazujących na antymonku indu (InSb). Część próbek została napromieniowana w strumieniu neutronów termicznych (widmo naturalne neutronów reaktora MARIA w Świerku), a pozostałe próbki w strumieniu neutronów prędkich (widmo filtrowane neutronów reaktora). W obu przypadkach dozy neutronów były zbliżone do poziomu* 10^{18} *cm*$^{-2}$*, doprowadzając do znacznego spadku ruchliwości elektronów w cienkich warstwach InSb. W przypadku napromieniowania neutronami termicznymi zaobserwowano wzrost koncentracji elektronów o wartość ok.* $2{,}3\times10^{18}$ *cm*$^{-3}$*, głównie za sprawą transmutacji In -> Sn. Dla próbek napromieniowanych neutronami prędkimi wystąpiły dwa przeciwne efekty: wzrost koncentracji elektronów dla próbek o niskiej początkowej koncentracji elektronów, oraz spadek koncentracji dla próbek o wysokiej początkowej koncentracji elektronów. Wyniki badań wskazują, że w przypadku zastosowania czujników Halla w tokamaku ITER niezbędne jest przeprowadzenie badań w strumieniach neutronów o różnym widmie energetycznym.*

Słowa kluczowe: *wysokie temperatury, napromieniowanie neutronami, czujnik Halla, ITER, diagnostyka magnetyczna*