SOME PROBLEMS OF MODELLING THE RADIATION STABILITY OF MAGNETIC SENSORS

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Basic problems of modeling the radiation stability of magnetic sensors for nuclear reactors are discussed. Basic causes of decreasing the resource of work the magnetic sensors (creation radiation damages and nuclear implantation) are analyzed. Mechanisms and conditions of creation of various types of radiation damages are observed. Basic methods of modeling these processes are used for the indium antimonite and indium arsenide Hall sensors. Comparative analysis the estimated and experimental data are represented too.

Introduction

Problem of increasing reliability of nuclear reactors is connected with problem of controlling its basic parameters [1 – 10]. One of the effective methods of this procedure is Hall magnetic sensors [1]. For example, lifetime of water-water reactors WWR-1000 is 30 years [11]. Controlling detectors of basic types of radiation must be have lifetime no less as lifetime of one charging of reactor. It is low limit of this lifetime. High limit is determined the lifetime of reactor. This lifetime is stipulated the mechanisms of scattering and absorption nuclear radiation (neutron) of InAs and InSb [11].

Basic reactions of neutron decays are next [3 –5]:

$$N \to P^+ + e^- + \bar{\nu}, \quad (\sim 96.5\ \%);$$

$$N \to P^+ + e^- + \bar{\nu} + \gamma, \quad (\sim 0.5\ \%):$$

$$N \to H + \bar{\nu}, \quad (\sim 3.0\ \%).$$

Therefore, we must discuss only first reaction. Electrons of this reaction have energy from 0 to 768 keV [3-5]. These electrons and fast neutrons are basic causes of creation radiation damages. For radiation transmutation of irradiated matter may be used only heat neutrons. It basic processes for radiation changes of InSb and InAs. Therefore, we must model the processes of creation radiation damages in irradiated matter. This problem may be resolved with help of particularly or full annealing of these defects.

The irradiation of our materials at temperature 100°C must be attended of process of thermal annealing the neutron-generated damages. In this case we must know activation energy of these damages. But it isn't full decision of this problem. Problem of annealing neutron-generated damages may be resolved with help CO_2-laser irradiation. These procedure was used for the annealing the ion-implanted damages in Mg^+/InSb and S^+/InAs. Concentration damages were 10^{19} – 10^{20} cm^{-3}. Irradiation may be pulse or stationary. Radiation damages are created metastable or unstable system. Therefore, matter must be irradiated in the regime of saturation of excitation. Main value has integral dose of irradiation. So for Mg^+/InSb these value is 10 J/cm^2 and for S^+/InAs – 12 J/cm^2. For case of neutron irradiation defect accumulation is more slowly process as in the case of ion implantation and this defects are distributed in a volume of irradiated matter. Therefore, we can use two basic regimes of laser-induced restoration of irradiated structures: 1) dynamical – relative low-intensity CO_2-laser irradiation of our sensors in their working regime; 2) periodical – for saturation of defects we must use more intensity irradiation of sensors.

After positive resolution this problem we have two basic causes of decreasing of sensors lifetime: nuclear transmutations and blistering. Both these processes are connected with chemical changes of irradiated matter.

This method may be used for all semiconductor devices, which are used for control nuclear reactors.

Basic results

Now we represented basic results of modeling the processes, which influence on the radiation stability InSb and InAs films. These films use as magnetic sensors for control of nuclear reactors. Parameters of irradiated materials are represented in Table 1 [11].

Table 1. Basic characteristics of irradiated semiconductors

	Sizes, w*l*d, mμ	Electron concentration, cm^{-3}	Impurity
InAs	200*200*.,15	1*10^{18}	Si
InAs	200*200*0.1	1*10^{19}, 3*10^{18}	Si
InAs	320*400*2.6	2,5*10^{18}	Sn
InSb	320*400*2	3*10^{17}	Sn
InSb	320*400*2.3	2.5*10^{18}	Sn

These sensors worked in thermal diapason (20 – 100)^{0}C.

Neutron of irradiation was realized on pulse reactor IBR-2 [2]. Differential effectively of neutron fluxes (DENF) with energy more as 1 MeV may be approximated with help of next formula [2]

$$\Phi(E) = \left(C_1 e^{-0,693E} + C_2 \frac{e^{-\alpha E}}{E} \right) \cdot 10^{12} cm^{-2} \cdot s^{-1} \cdot MeV^{-1}, \quad (1)$$

where $\alpha \approx 1$ and values C_i are represented in Table 2 and it depend only from distance between sample and surface of reactor.

Table 2.

x, m	C_1	C_2
0.3	0.470	0.390
0.5	0.216	0.183
0.7	0.085	0.072

For resonance energies $E < 0{,}1MeV$ DENF may be written as

$$\Phi(E) = C_x e^{-\beta_x}, \quad (2)$$

where $\beta_x = 0{,}88,\ C_x \approx C_2$ [2].

For practical calculations of DENF for energy diapason from 0,5 eV to 14 MeV may be used formula (3)

$$\Phi(E) = \left(C_1 e^{-0{,}693E} + C_2 \frac{e^{-0{,}97E}}{E^{0{,}88}} \right) \cdot 10^{12} cm^{-2} \cdot s^{-1} \cdot MeV^{-1}, \quad (3)$$

where coefficients C_i have values of Table 2 [2]. Dependence DENF from neutron energy is represented on Fig. 1 [2].

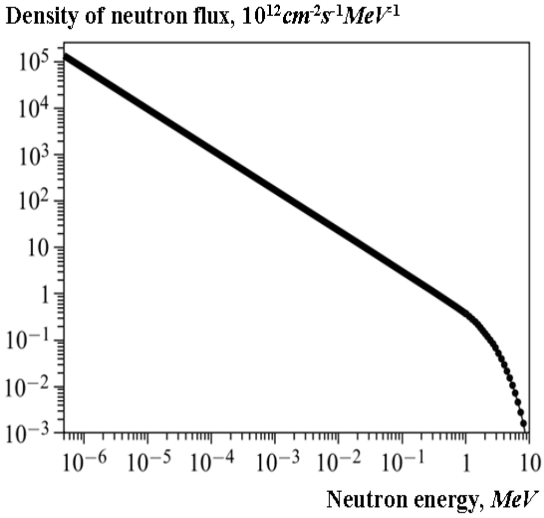

Fig. 1. DENF in channel № 3 for distance from moderating layer is 0.3 m

From physical point of view we must observed processes of nuclear transmutations of basic components of irradiated materials and processes of its blistering. The time of formation these processes must be more lifetime reactor.

The next stage of calculation is next. We must use the cross-section of proper neutron-induced processes and, after this, determine absorptive index with help of next formula [3-7, 9, 11, 12]:

$$\alpha = \sum_{i=1}^{n} N_i \sigma_i, \quad (4)$$

where N_i – concentration of proper centers of neutron scattering, σ_i – cross-section of proper reactions of scattering, n – number of possible channels of scattering. Nature of scattering centers may be various. It may be centers of damage creations, centers of nuclear reaction and other, Formula (4) has integral nature. We must research the various possible channels of neutron scattering, which has general influence on radiation stability of our films.

Corresponding absorptive indexes for basic components of irradiated matter are represented in Table 3.

Next stage of our calculation is determination of numbers absorptive neutrons in irradiated semiconductor layers. We next realized this procedure in next way. Intensity of irradiated neutrons n_i may be determined with help next formula:

$$n_i = (DENF)_i\, E_i\, S\, s^{-1}, \quad (5)$$

where S – irradiated area of our semiconductor.

Table 3.

	In	As	Sb	Si	Sn	Ga
α_{max}, cm^{-1}	0.01	0.6	10	10^{-7}-10^{-6}	$6 \cdot 10^{-7}$-$6 \cdot 10^{-6}$	0.5
α_{min}, cm^{-1}	0.07	0.05	0.06	$2 \cdot 10^{-8}$-$2 \cdot 10^{-7}$	$8 \cdot 10^{-9}$-$8 \cdot 10^{-8}$	0.05

Critical time τ of resource of proper material may be determined with help of next formulas:

$$\Delta N_{imp} = n_i \tau \text{ or } \tau = \frac{\Delta N_{imp}}{n_i}. \quad (6)$$

We must estimate basic two processes, which are interesting with technological point of view.

Let first process is connected with increasing of concentration of doping impurity on one procent [11]. For InSb and InAs this impurity is stannum, which is received after neutron irradiation of indium. Therefore, we must observe the change of indium concentration. Quantity of absorbed neutron in InSb and InAs layers (for indium nuclears) may be determine with help formula [2]:

$$n_i = (DENF)_i\, E_i\, S\, e^{-\alpha_i x} s^{-1}, \quad (7)$$

where x – thickness of proper layer. For structures of Table 1 intensity of transformation neutrons is 10^7 – 10^{10} n/s. ΔN_{imp} is changed from $3 \cdot 10^{15}$ to 10^{17} electrons. We postulated linear dependence concentration of impurity and electrons. Coefficient of this bond let be one. For this case time of reliable work of our devices is changed from $3 \cdot 10^5$ *s* to 10^{10} *s* or from 0,01 to 31,8 years. But this estimation is very rough. We not include real time of irradiation. For pulse reactors this time may be increased in 10 – 100 times.

Second process is connected with radiative destructure of irradiative matter, including blistering [11]. This process is connected with process of hydrogenization of irradiated materials and creation hydrogen clasters, which are transformed to microvoids and blistering. We must estimate critical value of neutron flux, which is necessary for blistering.

For observation the radiation blistering we must have thick samples [11]. Blistering of layers InAs and InSb is impossible practically. In the case of neutron irradiation this phenomenon has bulk nature whereas for case of proton irradiation this process has surface nature. This difference is caused the electrical charge of protons. Therefore, neutrons, which aren't participants of nuclear reactions, absorb in the bulk of irradiated matter and transforms to protons. Blistering may be possible in the bottom layer of our heterostructure – *GaAs*.

Critical doses of proton-radiation-induced surface blistering (swelling) for various materials are various [11]. For aluminium it is $5 \cdot 10^{16}$ cm^{-2}, for vanadium it is from $6.2 \cdot 10^{18}$ cm^{-2} to $3.8 \cdot 10^{19}$ cm^{-2}. This difference is caused various masses of aluminium and vanadium atoms.

In the case of helium irradiation the threshold of blistering is characterized the next condition: number of helium atoms must be 5 – 10 percents from atom of irradiated layer.

This condition may be used for our case and it simplifies and unifies method of calculation. Estimation of threshold creation of blistering may be realized in a way, which is analogous to estimation of first process. But in this case we must estimate blistering in gallium arsenide.

Let thickness of *GaAs* films is 1 mm. Density of atoms N_{ka} may be determined with help next formula

$$N_{ka} = \frac{\rho N_A}{A}, \quad (8)$$

where N_A – Avogadro number, ρ – density of proper matter, *A* – weight of one mole.
For *GaAs* this value is $2.21 \cdot 10^{22}$ cm^{-3}.

For further estimations we can use formulas (6) and (7) too. For this case intensity of neutron flux is 10^{10} – 10^{12} n/s. But for blistering we must have 10^{20} – 10^{21} protons. Therefore, time of creation threshold dose for bulk blistering is equaled 10^{8} – 10^{11} s or 3.2 – 3200 years. It is large time and it show that these sensors may be used for the control of regimes of exploitation of nuclear reactors.

The lifetime of sensors may be increase for the increasing the work temperature and for additional infrared irradiation. These procedures may be used for the regimes of irradiation, which are on one – two order less as for blistering. It may be used for damage concentration 10^{18} – 10^{20} cm^{-3}. Roughly speaking in this case we have clearing of irradiated matter in radiation sense. For more detail modeling we must have structures of defect levels. But for estimation of critical value of intensity of irradiation, which must be used for renewal of irradiated structure, we must have only concentration of radiation defects, absorptive index of laser radiation and can be made approximation that energy of damage activation must be less or equal of photon energy. These characteristics allow to estimate the critical value of intensity the laser irradiation. This method was used for the determination of the regimes of irradiation for laser annealing of ion-implanted layers of Mg^{+}/InSb and S^{+}/InAs.

These methods of estimation of basic two processes of radiation stability of magnetic sensors are very simple and rough. It isn't including the concrete mechanisms of neutron scattering and other channels of neutron scattering and neutron-induced nuclear reactions [13].

We weren't including neutron-proton processes and creation of microvoids and real time of radiation in pulse neutron reactor IBR-2. These estimations were received for the continuous regime of irradiation. For real processes roughly speaking we must include only working time of irradiation.

But in the first approximation this method may be used for previous estimation the requirements to radiation stability of electronic and optoelectronic devices, including magnetic sensors for the case of nuclear transmutations of irradiated matter and blistering processes.

For more precision modeling we must include chain characters of nuclear transmutations of components of irradiated matter and defects evolution.

Conclusion

Basic processes, which are influenced on lifetime InSb and InAs magnetic sensor are analyzed for neutron irradiation in reactor IBR-2. Processes of transmutation of basic elements of irradiated matter are modeled and estimated. Problems of radiation blistering are discussed.

Questions of creation radiation damages and its evolution, including annealing, are analyzed too.

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