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Research

USING OF THE MONOCRYSTALLINE SILICON TO MONITOR THE NUCLEAR-PHYSICAL CHARACTERISTICS OF NEUTRON FIELDS

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ABSTRACT

This article shows dependence between the change of specific electrical resistance and fluence of neutrons. This dependence was put to the basis for measurement of neutron flux which usually need at the experiment time on the research nuclear reactors and accelerators. The possibility of implementation of the method was confirmed by measurements of density of a flux of thermal neutrons by offered and activation methods.

INTRODUCTION

The knowledge about the absolute value of the flux and the fluence of thermal neutrons in experimental channels of reactors are necessary at the solution of many applied and fundamental tasks. Now, self-sufficient and not requiring calibration by means of other methods are activation methods (Bekurtz, 1968; Kramer-Ageev, 1976; Yaryina, 1976) which are realized with the help of activation detectors, for example, of manganese, cobalt, copper, gold. These methods use the links between the induced activity of detectors and density of a flux (or a fluence) of neutrons.

So far, they are considered as reference methods. However, these methods are laborious and require the special equipment. Moreover, at an irradiation of samples they can't always be used as tracking detectors for two reasons. Firstly, because the activity of the detector after irradiation depends not on a fluence during the whole time of irradiation, and only on a fluence for the last time equal to 3-4 half-life periods. Secondly, it isn't always possible to determine a fluence of neutrons at the changing flux of neutrons during irradiation, for example, due to the stops of reactor at long irradiation. To a lesser extent it concerns the cobalt detector which has a long half-life period (5.28 years). However, its discard as a radioactive material is required due to a long half-life time after irradiation.

RESULTS AND DISCUSSION

At the irradiation of silicon with neutrons due to a reaction of radiation capture silicon-31 forms, which with β-decay (a half-life period-2.62 hours) converts into phosphorus-31. This transmutational impurity in the silicon monocrystals of n-type increases the specific electric conductivity (s.e.c.), and in the monocrystals of p-type – reduces. Earlier it was shown (Varlachev *et al.*, 2009) that a change of specific electric conductivity (s.e.c.) in silicon monocrystals after their irradiation and annealing of radiation defects is directly proportional to a fluence of thermal neutrons. This fact was the basis for a method of measurement of a neutron flux in relative units (Varlachev and Solodovnikov, 2009). For the measurement of absolute values of a fluence of thermal neutrons it is offered to irradiate silicon in the cadmium filter and without it as it done in an activation method, using its practices on a method of a cadmium difference (Bekurtz, 1968; Kramer-Ageev, 1976; Yaryina, 1976). In relation to silicon the essence of a method is as follows.

It is possible to present a generated concentration of phosphorus-31 (*C*) during irradiation without cadmium filter in the form of two components: generated by thermal (C_t) and resonance (C_{nt}) neutrons

$$C = C_t + C_{nt} \tag{1}$$

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C is linearly linked with change of s.e.c. (Varlachev and Solodovnikov, 2009).

$$C = (\sigma - \sigma_0) / e\mu_n, \quad (2)$$

where σ_0, σ – s.e.c. of silicon before and after irradiation, e, μ_n – a charge and mobility of electrons respectively. It should be noted that a measurement of σ is carried out after the annealing of radiation defects at a temperature of 800°C, thereby exclude an influence of radiation defects from fast neutrons on the change of s.e.c. Now as an absorber it is accepted to use cadmium-113 due to the large cross section of absorption in thermal area and its fast decrease in the epithermal area. However, the cross section of absorption of cadmium isn't a step function. Therefore, in an activation method of a cadmium difference the concept of boundary energy of absorption of cadmium E_{Cd}, which depends on a thickness and a form of the filter is introduced. It is considered that neutrons with energy is below E_{Cd} are completely absorbed by the filter, and neutrons with energy is higher than this energy – aren't absorbed. The arising mistake (1 – 4%) is compensated by the cadmium amendment F_{Cd}. In such approximation at irradiation of silicon in the cadmium filter

$$C_{nt} = \int_{E_{Cd}}^{\infty} \Sigma(E)\Phi(E)dE = C_{Cd}F_{Cd}, \quad (3)$$

where F_{Cd} - the correction coefficient considering the absorption of the resonance neutrons in the cadmium. The concentration of phosphorus-31 (C_{Cd}) experimentally is determined by the measuring s.e.c. to (σ_0) and after (σ_{Cd}) irradiation:

$$C_{Cd} = (\sigma_{Cd} - \sigma_0) / e\mu_n. \quad (4)$$

V.P. Yaryna and G.B. Tarnovsky (Tarnovskiy *et al.*, 1982) offered an empirical formula for the calculation of E_{Cd} of the cadmium cylindrical filter, placed in an isotropic field:

$$E_{Cd} = 0{,}520 + 0{,}162 \cdot \ln(\xi \cdot d_{Cd}), \quad d_{Cd} = 0{,}5 \div 1{,}5mm \quad (5)$$

$$\xi = 1{,}58 - 0{,}82 \cdot (h/2r) + 0{,}38 \cdot (h/2r)^2, \quad h/2r = 0{,}5 \div 1{,}3 \quad (6)$$

where h and r – height and radius of the cylindrical filter.

For the reactor neutron fields, which are formed in the presence of good moderators (water, graphite, beryllium, etc.), the spectrum of thermal neutrons is approximately described by Maxwell's distribution. In this case, when using the detector, the cross section of the reaction which in thermal area of the spectrum changes according to the law 1/v (v – neutron velocity),

$$C_t = \chi_t \int_0^{E_{Cd}} \Sigma(E)\Phi(E)dE = \chi_t g_t \Sigma_t \Phi_{eff}, \quad (7)$$

where C_t - the generated concentration of phosphorus - 31 by thermal neutrons; Φ_{eff} – an effective fluence of thermal neutrons; Σ_t – the macroscopic cross section of reaction at energy of a neutron, the corresponding to some effective temperature T_{eff}, different from the environment temperature T_0; g_t – Vestkott's factor taking into account the deviation of the dependence of the cross section of thermal neutrons (n, γ) – reaction on the silicon-31 from the law 1/v, χ_t – the coefficient of self-shielding of thermal neutrons (the ratio of the number of neutrons emitted from the silicon to the number of the entered neutrons). According to IAEA Nuclear Data Service the cross section of (n, γ) – reaction on silicon-30 in thermal area strictly follows to the law 1/v, i.e. g_t =1. Because of leak and absorption of neutrons $T_{eff} > T_0$, i.e. not all neutrons reach the thermodynamic balance with environment. In particular (7), at

$$\Sigma_a(kT_0) / \xi\Sigma_s < 0{,}2 \quad (8)$$

where the mean log loss of energy

$$\xi = 1 + [(A-1)^2 / 2A]\ln[(A-1)/(A+1)], \quad (9)$$

Σ_a , Σ_s macroscopic sections of absorption and scattering of the moderator; k – Boltzmann's constant; A – mass number of nuclei of the moderator,

$$T_{эф} = T_0[1 + 0{,}73A\Sigma_a(kT_0)/\Sigma_s \quad (10)$$

For example, for a beryllium moderator $T_{eff} = 1{,}0066T_0$, i.e. approximately on 2 °K.

From the expression (1, 3, 7)

$$\chi_t\Sigma_t\Phi_{eff} = C - F_{Cd}C_{Cd} \quad (11)$$

Then

$$\Phi_{eff} = \frac{C}{\chi_t\Sigma_t}(1 - \frac{F_{Cd}}{R_{Cd}}) \quad (12)$$

And taking into account expression (2) we will obtain an effective fluence of thermal neutrons. Silicon was irradiated with this fluence without cadmium filter,

$$\Phi_{eff} = \frac{(\sigma - \sigma_0)}{e\mu_n\chi_t\Sigma_t}(1 - \frac{F_{Cd}}{R_{Cd}}), \quad (13)$$

where

$$R_{Cd} = C / C_{Cd} = (\sigma - \sigma_0)/(\sigma_{Cd} - \sigma_0) \quad (14)$$

is a cadmium ratio, which is determined by experimental values of s.e.c. From the effective fluence of thermal neutrons it is easy to pass to an average (for time of irradiation τ) value of effective density of a flux of thermal neutrons (φ_{eff}). By definition $\varphi_{eff} = \Phi_{eff} / \tau$. Thus φ_{eff} is the multiplication of volume density of neutrons with energy below boundary energy of cadmium on the velocity of neutrons with energy kT_{eff}.

The values F_{Cd}, χ_t, and E_{Cd} for silicon had been defined by us. Usually F_{Cd} is equal 1,01-1,04 (Nashelskiy, 1989). Therefore with an error up to 2% F_{Cd} can accept F_{Cd} = 1,02.

Self-shielding coefficient of thermal neutrons χ_t (the ratio of number of emitted neutrons from a silicon washer to the number of the entered neutrons) was determined by calculations in an isotropic neutron field. Calculations were executed by the Monte-Carlo method using direct modeling of neutron tracks in natural silicon. The cross-sections were taken from IAEA Nuclear Data Service. The history of a neutron interrupted if either its absorption or an emission from silicon. Radius and thickness of a washer were the varied parameters. 10^7 neutron stories were played for each variant. Results of calculations are shown in Table 1. Also effective optical thicknesses are given, i.e. average values of segments in a silicon plate on a tracks of an entry of a neutron in it.

E_{Cd} of the cadmium cylindrical filter placed in an isotropic neutron field is defined with expressions (6,7). For example, in a standard set of detectors AND-T there is a filter with a diameter of 15 mm, a height of 10 mm and a wall thickness of 1 mm. When using of this filter E_{Cd} = 0,55 eV.

Beside that for definition of thermal neutrons fluence we offered to manufacture the detector in the form of a plate of the monocrystalline semiconductor with ohmic contacts on all surface of each basis of a plate which surfaces have to be parallel. It will allow to establish the one-to-one association of electrical resistance between the bases of a plate and specific electrical resistance in volume of a semiconductor monocrystal.

If the planes of the bases of a plate are parallel, and a lateral area of a plate it is perpendicular to the planes of the bases, according to an Ohm's law specific electrical resistance can be easily defined through electrical resistance between the plate bases:

$$\rho = \frac{SR}{d}, \qquad (15)$$

where ρ – specific electrical resistance, R – electrical resistance between the plate bases, S – the area of the basis of a plate, d – thickness of the plate. Substituting (15) to (13) and taking into account that $\sigma = 1/\rho$ we obtain next

$$\Phi_{eff} = \frac{d(\frac{1}{R} - \frac{1}{R_0})}{Se\mu_n \chi_t g_t \Sigma_t}\left(1 - \frac{F_{Cd}}{R_{Cd}}\right) \qquad (16)$$

Let's note that the bases of a plate can have any configuration: circle, ring, triangle, polygon, etc. For realization of this way of definition of a thermal neutrons fluence it is necessary to define electrical resistance (R) between washer end faces correctly. A potential barrier arises and the related locking layer on contact border of metal and semiconductor. Therefore, these contacts will be straightening. In certain cases this potential barrier is negligible and the current voltage characteristic of such contact represents a straight line. The link between current through such contact and voltage on it is expressed, the linear law – an Ohm's law – regardless of polarity of voltage attached to this contact. Such contact also is ohmic (not straightening). For inclusion of monocrystalline plates in an electric circuit apply ohmic contacts on all plane of each basis of a plate. It is simplest to make it by means of an AlGa pencil or InGa paste (Nashelskiy, 1989).

CONCLUSION

The possibility of implementation of the method was confirmed by measurements of density of a flux of thermal neutrons by offered and activation methods. Measurements were carried out in the channel HEC-4 of Tomsk research nuclear reactor with a power of 6 MW. The specific electric resistance was measured by the 4th probe method before and after irradiation

Table 1. Self-shielding coefficient χ_t and effective optical thicknesses d_{eff} of silicon washer which has radius *r* and thickness *d*.

r, cm	**0,5**			**0,6**			**0,7**		
d, cm	0,4	0,5	0,6	0,4	0,5	0,6	0,4	0,5	0,6
χ_t	0,996	0,995	0,995	0,996	0,995	0,994	0,995	0,995	0,994
d_{eff}, cm	0,583	0,657	0,717	0,634	0,720	0,793	0,677	0,774	0,859
r, cm	0,8			0,9			1,0		
d, cm	0,4	0,5	0,6	0,4	0,5	0,6	0,4	0,5	0,6
χ_t	0,995	0,994	0,994	0,995	0,994	0,993	0,995	0,994	0,993
d_{eff}, cm	0,7145	0,821	0,917	0,747	0,863	0,967	0,777	0,902	1,013
r, cm	1,1			1,2			1,3		
d, cm	0,4	0,5	0,6	0,4	0,5	0,6	0,4	0,5	0,6
χ_t	0,994	0,994	0,993	0,994	0,993	0,993	0,994	0,993	0,992
d_{eff}, cm	0,803	0,936	1,054	0,828	0,966	1,092	0,850	0,994	1,126

and annealing of radiation defects at a temperature of 800°C within 2 hours. The error of measurement of an average on an end face of a washer of specific resistance didn't exceed 3%. Continuous control of a fluence of thermal neutrons was exercised by means of regular chambers of fission of type CIT-4 used in technology of a neutron and transmutation doping of silicon.

During experiment the cadmium relation R_{Cd} (Si) for silicon was defined. For this purpose silicon exemplars, in a cadmium cylindrical case and without it, were symmetrically on an axis of the channel HEC-4 concerning the center of the fissile region of the reactor. The cylindrical case with 10 mm high, a diameter of 15 mm and wall thickness of 1 mm was used. The distance between exemplars was made 15 cm. Irradiation was carried out within 4 clocks at a power of 6 MW. Initial resistance of the exemplar irradiated in Cd the filter - 857 Ω·cm, and without filter – 772 Ω·cm. Terminating resistance – 593,5 Ω·cm and 99,5 Ω·cm respectively. From this $R_{Cd}(Si) = 16{,}9$, $\Phi = 2{,}14 \cdot 10^{17}$ cm^{-2} and $\varphi = 1{,}48 \cdot 10^{13}$ cm^{-2}s^{-1} follows. Then took a similar washer with the ohmic contacts applied on it. In 4 hours initial resistance decreased from R_0=141 Ω to R=39 Ω. R_{Cd}=16.9 at radiation at a power of 6 MW. From this follows $\Phi = 2{,}13 \cdot 10^{17}$ cm^{-2} and $\varphi = 1{,}49 \cdot 10^{13}$ cm^{-2}s^{-1} that corresponds to measurements by a standard method.

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