

# Influence of $\alpha$ -particles irradiation on the properties and performance of silicon semiconductor detectors

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**Abstract.** Deterioration of the operation parameters of p-type Si surface-barrier detector and Si(Li) p-i-n detector upon irradiation by alpha-particles was investigated. The detectors were irradiated at room temperature up to a total number of the registered  $\alpha$ -particles  $N_\alpha$  equal to  $6 \times 10^9$ . Prolonged irradiation has resulted in a deterioration of the detectors energy resolution ability and it was found that the increase of  $\alpha$ -peaks broadening can be described by a linear function of  $N_\alpha$  with a slope  $\Delta\sigma/\Delta N_\alpha \sim (1.4-1.8) \times 10^{-9}$  keV/ $\alpha$  for both detectors. Resolution deterioration was associated with the increase of the detectors leakage current, which proceeds linearly with the number of absorbed  $\alpha$ -particles with the slope  $\Delta I/\Delta N_\alpha \sim (7-17) \times 10^{-17}$  A/ $\alpha$ . The increase of the detectors reverse current was related with appearance of radiation-induced defect level at 0.56 eV above the valence band.

## 1. Introduction

Nowadays there is an increasing demand for the compact calibration neutron sources suitable for various research and industrial applications caused by the necessity to calibrate neutron measuring devices [1-2]. A possible solution could be a combination of  $^{252}\text{Cf}$  radionuclide source which undergoes  $\alpha$ -decay and spontaneous fission with a branching ratio of 97:3, whereas each spontaneous fission event liberates also a number of fast neutrons, with a semiconductor detector that detects the fission fragments and thus provides a time reference of the neutron production. Silicon semiconductor detectors are capable of detecting fission fragments and  $\alpha$ -particles due to their thin entrance window and high energy resolution. Constraints on the usage of semiconductor detectors are imposed by their finite radiation resistance. Incoming radiation does not only generate the electron-hole pairs in the detector's sensitive volume producing thus an information signal, but also creates the atomic displacement damage in the crystal lattice [3-4]. Accumulation of the radiation-induced defects reduces the non-equilibrium carrier lifetime, increases significantly the detector leakage current and therefore degrades the main operational parameter of the detectors – the energy resolution. Most effectively this process proceeds in case of irradiation by alpha particles, accelerated ions or fission fragments which are capable of transferring a significant fraction of their energy to the atoms of the detector lattice [5].

This paper is devoted to the investigations of operational parameters degradation of a silicon-lithium Si(Li) p-i-n detector and p-type silicon surface-barrier detector under irradiation with  $\alpha$ -particles, which inevitably accompany spontaneous nuclear fission. Performed investigations are focused on the establishment of the correlation between the radiation density and operational signs of the detector degradation (deterioration of the energy resolution, increase of the reverse current of the detector, etc.). The achievements in the understanding of the relation between the irradiation density, degradation of the detector parameters and the created defect types and density would be essential for production of the effective radiation resistant silicon detectors as well as for the optimization of the construction of possible calibration neutron sources.

## 2. Experimental details

A surface-barrier (SB) detector was fabricated from p-type boron-doped silicon wafer of (111) orientation. The diameter of the wafer was 10 mm, it had resistivity of  $2.5 \text{ k}\Omega\text{-cm}$  and a carrier lifetime of  $1000 \mu\text{s}$ . After mechanical polishing and etching in  $\text{HNO}_3 : \text{HF}$  solution the wafer was oxidized in concentrated boiled  $\text{HNO}_3$  solution in order to produce thin tunnel transparent oxide layer which serves as a passivation coating (so-called NAOS method [6]). Ohmic contact was made by evaporation of Pd layer on the whole rear side of the wafer, whereas the rectifying one – by evaporation of Al dot with diameter of 7 mm in the center of the wafer's front side. The investigated Si(Li) detector was produced from similar p-type silicon ingot. A detector with a sensitive region of 18.5 mm in diameter and 4 mm thick was produced using standard technology that has been developed and tested by PNPI. The characteristics of such detectors were described in [7-8].

Spectrometric channel for  $\alpha$ -particles registration consisted of a charge-sensitive preamplifier connected with BUI-3K shaping amplifier with a shaping time of 1-2  $\mu\text{s}$  and a 4096-channel 12-bit CAMAC analog-to-digital converter with 2 keV/chan resolution. Additionally, 200 Hz pulse signal was fed to the preamplifier to generate the “reference peak” enabling accurate separation of the intrinsic detector resolution from the noise contribution of the detector-amplifier system. The total variance of the pulse amplitude distribution in the response of a spectrometric detector system to  $\alpha$ -particles irradiation can be written as the sum of two components [9]

$$\sigma^2 = \sigma_{el}^2 + \sigma_{det}^2 \quad (1)$$

where  $\sigma_{det}^2$  – is the variance due to statistical processes of charge generation in the detector (which accounts the contribution of the Fano factor, losses in the detector dead layer as well as the spread of  $\alpha$ -particles energies from the radiation source) and  $\sigma_{el}^2$  – is the variance due to electronic noise of the system, which would define the full width at half-maximum (FWHM) of the reference peak. In case of a normal distribution, the energy resolution characterized by FWHM of a spectral line will be  $2.355\sigma$ .

The detectors were irradiated by a reference spectrometric ternary source containing  $^{233}\text{U}$ ,  $^{239}\text{Pu}$  and  $^{238}\text{Pu}$  isotopes emitting  $\alpha$ -particles at 4824 keV, 5156 keV and 5499 keV respectively, with almost equal activities. The source represents a stainless steel substrate covered with a thin layer of the active material and the spread of  $\alpha$ -particles energies from the source doesn't exceed 20 keV. As for irradiation and  $\alpha$ -spectrum measurement investigated detector was mounted in a vacuum chamber operating at room temperature and the irradiation was performed through a collimator providing counting rate of about 2400 cps of  $\alpha$ -particles. Reverse bias voltage applied to SB detector was set to 10 V what was proved to be enough to register the  $\alpha$ -particles (space charge region depth corresponding to 10 V was around 50  $\mu\text{m}$  in our detector, while the penetration depth of  $\alpha$ -particles in Si is about 30  $\mu\text{m}$ ) whereas the reverse current remained small. Operating bias at Si(Li) detector during the irradiation period was set at 400 V. The detectors were exposed to  $\alpha$ -irradiation up to a total number of the registered  $\alpha$ -particles  $N_\alpha$  of  $6 \times 10^9$ , which corresponds to a fluence  $\Phi$  of approximately  $2 \times 10^{10} \text{ cm}^{-2}$  for SB and  $5 \times 10^9 \text{ cm}^{-2}$  for Si(Li) detector respectively. Acquisition of the detector reverse current and the number of absorbed  $\alpha$ -particles was performed continuously during the whole

irradiation period. The FWHM of the recorded  $\alpha$ -peaks was determined by performing a Gaussian fit of the peak high-energy shoulder, as a low-energy shoulder is often distorted by a presence of a low-energy tail.

### 3. Experimental results

#### 3.1. Surface-barrier detector

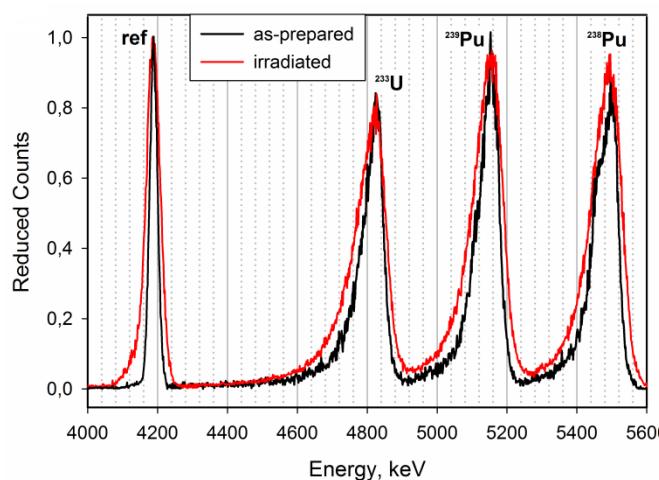
The  $\alpha$ -particles spectra measured by as-prepared SB detector and by SB detector after prolonged irradiation are shown in Figure 1, where along with three peaks of the  $\alpha$ -particles of different energies the reference peak due to the pulse signal is clearly visible. No noticeable shift of the energy position of the  $\alpha$ -peaks was revealed during the process of irradiation.

The FWHM of 5499 keV  $\alpha$ -peak on the as-prepared detector was measured to be about 70 keV, whereas FWHM of the reference peak – 25 keV. After irradiation the energy resolution of the detector has degraded – FWHM of 5499 keV peak has increased up to 100 keV and as for the reference peak – up to 48 keV. The degradation of resolution is especially obvious when comparing the shape of 5499 keV peak recorded by as-prepared detector and by irradiated one: the doublet structure of 5499 keV line (which consists of two lines with energies of 5456 keV and 5499 keV with their branching ratio of 29:71) is clearly seen on the spectrum measured by as-prepared detector but becomes unresolved on the spectrum measured by the detector after irradiation.

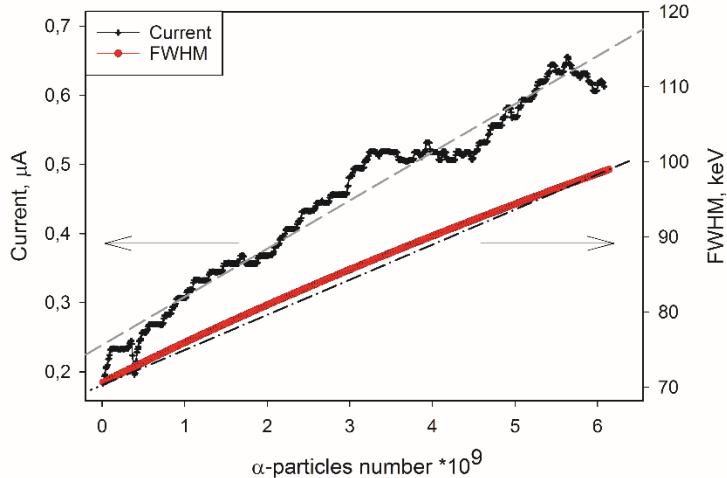
However, the intrinsic variance of the detector  $\sigma_{det}^2$  calculated by Equation 1 remained quite similar before and after irradiation at about 27-28 keV. Thus it could be concluded, that deterioration of the energy resolution of the irradiated detector is caused by increase of  $\sigma_{el}^2$  term in Equation 1. The latter includes the contributions of detector leakage current  $\sigma_I^2$ , detector capacitance  $\sigma_C^2$  and the feedback resistance  $\sigma_R^2$  [9]

$$\sigma_{det}^2 = \sigma_I^2 + \sigma_C^2 + \sigma_R^2 \quad (2)$$

Since the feedback resistance as well as the capacitance of the detector at the reverse bias of 10 V remained unchanged during the irradiation, the degradation of the detector performance is definitely due to increase of  $\sigma_I^2$  term as the detector reverse current at applied reverse bias of 10 V has increased from 0.2  $\mu$ A up to 0.65  $\mu$ A during the irradiation, see Figure 2. Measured current vs. the number of registered  $\alpha$ -particles dependence can be satisfactorily approximated by the straight line with the slope of  $\Delta I / \Delta N_\alpha \sim 7 \times 10^{-17}$  A/ $\alpha$  (sin-like oscillation of the current visible in Figure 2 are caused by minor temperature instability during the irradiation period).



**Figure 1.** The  $\alpha$ -particle spectrum in the range of 4600–5600 keV and the “reference” peak at 4200 keV measured by as-prepared and by irradiated SB detector.



**Figure 2.** Increase of the SB detector reverse current at applied bias 10 V and the calculated growth of the  $\alpha$ -peak FWHM with the number of absorbed  $\alpha$ -particles. Thin dashed line shows the best linear fit to the current dependence, whereas dash-dotted one – to that of FWHM.

The dependence of  $\sigma_I^2$  term in a circuit with a charge-sensitive preamplifier on the reverse current  $I$  is determined by the charge fluctuations associated with the current and by the shaping time  $\tau$  of the amplifier and could be expressed as [9,10]

$$\sigma_I = k_I \sqrt{\tau I} \quad (3)$$

The proportionality coefficient  $k_I$  is defined by a specific shaping filter. For SB detector the increase of FWHM from 70 keV to 100 keV can be described by the reverse current growth from 0.2  $\mu$ A to 0.65  $\mu$ A where the proportionality coefficient  $k_I$  is equal to  $3.3 \times 10^7$  keV/(A\*s) $^{1/2}$  for the shaping time of 2  $\mu$ s, as it is shown by the calculated dependence of peak FWHM on  $N_\alpha$  number in Figure 2. Obtained  $k_I$  value is rather typical for the used preamplifier type [10]. According to Equations 1-3 the linear increase of the reverse current should result in square root increase of the peaks FWHM, however for the considered range of the registered  $\alpha$ -particles number the FWHM dependence could be satisfactorily approximated by a simple linear dependence with the slope  $\Delta\sigma/\Delta N_\alpha = 1.9 \times 10^{-9}$  keV/ $\alpha$ , see Figure 2.

### 3.2. Si(Li) p-i-n detector

For the irradiated Si(Li) detector similar signs of operating parameters degradation were observed. The resolution of the Si(Li) detector has degraded from 130 keV up to about 150 keV of 5499 keV  $\alpha$ -peak FWHM without noticeable change of the peak position. Higher reverse current on the as-prepared Si(Li) detector of 7  $\mu$ A at the operating reverse bias of 400 V results in a worse resolution in comparison with SB detector.

Unfortunately, due to high temperature instability during the period of Si(Li) detector irradiation, the dependence of the reverse current on the number of the registered  $\alpha$ -particles appeared to be modulated with high temperature-induced current variations (it can be shown, that temperature increase by only 2°C from 20°C to 22°C causes the current growth by 17% [11]), so the reliable  $\Delta I/\Delta N_\alpha$  slope value couldn't be determined. Nevertheless, it could be stated that current has increased by approximately 1  $\mu$ A as a result of  $\alpha$ -particles irradiation. The linear increase of the reverse current with the number of absorbed  $\alpha$ -particles observed for SB detector agrees with the theoretical predictions and earlier experimental results [4,11-12], thus implying the linear growth of the reverse

current with  $N_\alpha$  number of  $\alpha$ -particles for Si(Li) detector as well we may roughly estimate the current growth coefficient to be  $\Delta I/\Delta N_\alpha \sim 17 \times 10^{-17} \text{ A}/\alpha$ .

The increase of the  $\alpha$ -peaks FWHM is satisfactorily described by Equations 1-3 with shaping time of 1  $\mu\text{s}$  and the variation of the peak broadening with the total number of absorbed  $\alpha$ -particles could be described then by a coefficient  $\Delta\sigma / \Delta N_\alpha = 1.4 \times 10^{-9} \text{ keV} / \alpha$ . It could be thus concluded, that the values of  $\Delta I/\Delta N_\alpha$  and  $\Delta\sigma / \Delta N_\alpha$  coefficients derived for Si(Li) detector are in a fairly good agreement with similar values obtained for SB detector (accounting the uncertainty in the determination of the leakage current growth).

#### 4. Discussion

As a result of a prolonged room temperature irradiation of a p-type Si surface-barrier and Si(Li) p-i-n detectors the degradation of the detector energy resolution and the increase of the detectors reverse current were revealed. The degradation of the energy resolution of the semiconductor detectors during irradiation may be related with two main factors. These are the increase of the detector reverse current and the increase in thickness of the surface insensitive layer of the detector [13].

Surface insensitive layer (or dead layer) corresponds to a layer with none or incomplete charge collection of generated electron-hole pairs and could be related either with undepleted p-region in case of Si(Li) p-i-n detector or with the layer of extremely high recombination activity which may arise in both detector types as a result of the irradiation. In passing through this dead layer a certain amount of charge produced by the incident radiation is lost from the resulting detector signal what manifests itself as a downward shift in the position of peaks in the amplitude spectrum. In the investigated detectors the downward shift of  $\alpha$ -peaks position was not observed, implying thus a negligible increase of the insensitive layer thickness.

Therefore, the observed increase of  $\alpha$ -peaks FWHM should be related with irradiation-induced increase of the reverse current, which influences the detector resolution via  $\sigma_I^2$  term (Equation 3). The obtained linear dependence of the peak variance upon the number of absorbed  $\alpha$ -particles allows simple prediction of the peak FWHM expected at higher fluences – for example, the  $\alpha$ -peak FWHM for  $N_\alpha = 10^{10}$  is expected to be around 115 keV for SB and 170 keV for Si(Li) detectors investigated in this work. Such peak broadening will not prevent the reliable distinction between the  $\alpha$ -peaks of different energies in Figure 1 as well as between the peaks due to  $\alpha$ -particles and fission fragments when using such detector as a part of a calibration neutron source.

It is well-known that the impurity composition (oxygen, carbon, etc) of the initial silicon wafer strongly influences the specific types as well as the concentrations of the radiation defects formed in the irradiated silicon wafers from the primary vacancy-interstitial pairs. Since both investigated detectors were made from the same silicon ingot, we may expect the formation of similar radiation defects in both of them and therefore similar coefficients describing the detector degradation. DLTS measurements performed on irradiated SB detector (details will be published elsewhere) have revealed a presence of near-mid gap level with the activation energy of 0.56 eV, which according to a Shockley-Read-Hall theory would give the main contribution to the increase of the generation leakage current. Therefore, the presence of the same defects could be expected for Si(Li) detector as well. Additional investigations are needed to clarify the possible impact of lithium impurity on the process of radiation defects formation in Si(Li) detector.

The increase of the detector reverse current and hence the increase of  $\alpha$ -peak FWHM could be diminished by cooling the detector. Recently the slope values of  $\Delta I/\Delta N_\alpha \sim 1.4 \times 10^{-17} \text{ A}/\alpha$  and  $\Delta\sigma/\Delta N_\alpha \sim 8.4 \times 10^{-10} \text{ keV}/\alpha$ , respectively, were obtained during prolonged irradiation of Si(Li) p-i-n detector by the same  $\alpha$ -source at liquid nitrogen temperature [14]. Comparing with the slope coefficient obtained in this work it follows that fourfold decrease of the current growth coefficient  $\Delta I/\Delta N_\alpha$  that results in twofold decrease of the peak FWHM broadening coefficient  $\Delta\sigma/\Delta N_\alpha$  in accordance with Equation 3. Besides, during previous measurements performed at liquid nitrogen temperature a linear shift of the

peak position described by a coefficient  $(-4.8 \pm 0.6) \times 10^{-9}$  keV/  $\alpha$  was observed. Obviously, worse detector resolution (i.e. broader  $\alpha$ -peaks) at room temperature due to much higher reverse current as compared with that at liquid nitrogen temperature made this shift (which should be less than about 10 channels) hardly observable.

## 5. Conclusions

The surface-barrier p-type Si and Si(Li) p-i-n detectors were subjected to prolonged room temperature irradiation by  $\alpha$ -particles produced by decay of  $^{233}\text{U}$ ,  $^{238}\text{Pu}$  and  $^{239}\text{Pu}$  nuclei up to a total number of absorbed  $\alpha$ -particles of about  $6 \times 10^9$ . After such treatment, the degradation of the detector energy resolution was revealed and related with the increase of the detector reverse current which increases linearly with  $N_\alpha$  number with the slope of  $\Delta I/\Delta N_\alpha \sim (7-17) \times 10^{-17}$  A/ $\alpha$ . Accounting for such current growth the changes in the energy resolution could be satisfactorily described by linear dependence of the peak broadening on  $N_\alpha$  number with the slope of  $\Delta\sigma/\Delta N_\alpha = (1.4-1.9) \times 10^{-9}$  keV/ $\alpha$  for the particular spectrometric setup. The leakage current increase in the irradiated detector was related with the appearance of the radiation-induced defect level at  $E_V + 0.56$  eV. Nevertheless, such degradation of the detector energy resolution would not prevent a reliable separation of the signals from  $\alpha$ -particles emitted by the ternary  $\alpha$ -source and in case of similar detector application for fission fragments detection – the separation of the  $\alpha$ -particles signal from the signal of the fission fragments up to  $N_\alpha$  number of  $10^{10}$  at least.

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