Degradation of silicon detectors under long-term irradiation by $^{252}$Cf fission products

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Abstract. The response function of the recoil nuclei in detectors designed for detection of neutrinos or dark matter particles can be determined only through usage of a neutron source with a known energy spectrum. A possible solution for a compact neutron calibration source is a combination of a $^{252}$Cf neutron source and a semiconductor detector that detects fission fragments, and thus records the neutron emission moment. This work is devoted to the degradation study of the operating parameters for silicon semiconductor detectors irradiated by fission fragments of the nuclide of $^{252}$Cf. Two types of Si detectors were under investigations – silicon-lithium Si(Li) p-i-n detectors and silicon surface barrier detectors. As a result of the measurements, the maximum permissible radiation doses for the correct operation of both types of detectors and the relation of the received radiation dose to the spectroscopic characteristics of the detectors were determined.

1. Introduction

Sensitivity of low-background experiments, designed for dark matter and coherent neutrino scattering detection strongly relies on the ability to discriminate the electron and recoil nucleus signals. Such discrimination could be quite effective e.g. for two-phase Time Projection Chambers (TPC) [1, 2], but determination of its efficiency spatial field over the visible energy range remains an important issue that has to be addressed specifically. This could be done with neutron calibration of the detector by a neutron source with either known neutron energy spectrum, either time-of-flight (ToF) neutron energy reconstruction. Direct determination of the neutron energy requires good temporal reference of the neutron emission that could be provided in case of a spontaneous fission source fitted with fission product detection system.

Semiconductor detector is a good option for making such a system since they have decent temporal and energy resolution together with relatively small entrance window that allows reliable detection of fission fragments. The main issue of such detectors is their limited lifetime under the influence of the source radiation that would limit the maximum source activity and/or the source goodness expiration period [3].

In this work we report the preliminary results of the performed investigations of detectors performance degradation under the irradiation by $^{252}$Cf spontaneous fission (SF) source. This
Figure 1. Spectra of the detector in the beginning (blue) and in the end (red) of the measurement. The left plot illustrates the spectrum evolution for the Si(Li) detector sample, the right plot shows the same for surface-barrier sample. One could note the decrease of fission fragment visible energy indicating the increase of entrance window thickness.

source decays into two channels, namely with \( \alpha \)-decay and the SF with branching ratio of 96.908/3.092. Thus the detectors are irradiated with both \( \alpha \)-particles and fission fragments that may produce different damage in the detector. In order to factorize the damage, the influence of \( \alpha \)-irradiation on detectors performance was studied separately [4, 5].

We study the impact of \(^{252}\)Cf radionuclide irradiation on two types of silicon detectors, namely Si(Li) p-i-n detector and p-type silicon surface-barrier detector. The main issue we address is to determine a better technology of a silicon detector for SF calibration source that would allow good separation of \( \alpha \)-particles and SF products after irradiation with a high exposure.

2. The detector samples

Investigated 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 k\( \Omega \times \)cm and carrier lifetime of 1000 \( \mu \)s. After mechanical polishing and etching in HNO\(_3\) : HF solution the front side of the wafer was covered by a thin layer of amorphous silicon which served as a passivation coating. The ohmic contact was made by sputtering 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 the same p-type silicon ingot. A detector with a sensitive region of 20 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 [6].

3. Experimental setup

The detector samples were irradiated by a \(^{252}\)Cf source in a vacuum setup with residual pressure below \( 10^{-3} \) torr operated at room temperature. The source represents a stainless steel substrate
Figure 2. Positions of the lighter (red) and heavier (green) fission fragment visible energy maxima for Si(Li) (left) and surface-barrier (right) detectors. The blue line correspond to the lower border of the fission fragment spectra, derived as $E_{HF} + 3 \times \sigma$. Note, that all these dependencies could be described with linear function.

with an active layer covered by a thin protective coating. It was mounted 1 cm above the detector entrance window, that was collimated in order to exclude side surface effects of incomplete charge collection.

The two samples were operated at 30 V (SB detector) and 400 V (Si(Li) detector) offset voltages. The output signal was read out by a charge-sensitive preamplifier and shaped by CR-3RC (BUI-3K) shaper in order to form the amplitude reference. The signal from the shaper was digitized by 12-bit ADC v161.31, produced by PNPI electronic division in CAMAC crate standard. The data were read out in form of a spectrum, recorded in short 1-hour series that were needed to provide stability control and observe the spectrum evolution. Another 12-bit ADC of CAMAC standard was used for the detector current control. The current was read directly as the voltage drop on the 196 kΩ resistor located inside the vacuum setup and connected in series with the detector. The current was recorded on 5-second basis with the following averaging on 1-hour measurement series.

The setup was operated continuously for 200 hours and 600 hours and a total number of the registered SF (α-particles) amounted to $4.3 \times 10^7$ ($2.2 \times 10^9$) and $4.5 \times 10^8$ ($22.5 \times 10^9$) for SB and Si(Li) detector, respectively. The setup has shown good count rate stability. The spectra evolution is shown in Figure 1.

4. Results and Discussion

The spectra recorded by the detectors in the beginning and at the end of the measurement are presented in Figure 1. The peak at 6.1 MeV corresponds to α-particle registration and another peak at doubled energy of the α-particle is caused by their accidental coincidences. Both were used as reference points for the calibration of the energy scale. Two broad unresolved peaks appearing at higher energies correspond to fission fragments of different energies. Since the radiation source was covered by a protective layer, the indicative energies of fission fragments
Table 1. Degradation of the operational parameters of the investigated detectors. $\Delta E_{FF}/\Delta N_{FF}$ - slope coefficient describing the linear shift of the lower border of fission fragment spectra with the number of absorbed fission fragments $N_{FF}$; $\Delta E_{HF}/\Delta N_{FF}$ - slope coefficient describing the linear shift of heavier fission fragment maximum; $\Delta E_{LF}/\Delta N_{FF}$ - slope coefficient describing the linear shift of lighter fission fragment maximum; $\Delta t$ - increase of the entrance window thickness; $\Delta t/\Delta N_{FF}$ - rate of the window thickness increase; $\Delta I/\Delta N_{FF}$ - rate of the reverse current increase; $N_{FF,\text{max}}$ - maximal permissible exposure by fission fragments.

| Parameter                  | SB detector        | Si(Li) detector   |
|----------------------------|--------------------|-------------------|
| $\Delta E_{FF}/\Delta N_{FF}$ | $5.2 \cdot 10^{-8}$ MeV | $2.3 \cdot 10^{-8}$ MeV |
| $\Delta E_{HF}/\Delta N_{FF}$ | $12 \cdot 10^{-8}$ MeV | $3.9 \cdot 10^{-8}$ MeV |
| $\Delta E_{LF}/\Delta N_{FF}$ | $25 \cdot 10^{-8}$ MeV | $7.8 \cdot 10^{-8}$ MeV |
| $\Delta t$                | $0.8 \ \mu$m       | $1.6 \ \mu$m      |
| $\Delta t/\Delta N_{FF}$  | $19 \cdot 10^{-9}$ $\mu$m | $3.5 \cdot 10^{-9}$ $\mu$m |
| $\Delta I/\Delta N_{FF}$  | $5.4 \cdot 10^{-14}$ $\text{A}$ | $1.8 \cdot 10^{-14}$ $\text{A}$ |
| $N_{FF,\text{max}}$       | $3.7 \cdot 10^8$   | $8 \cdot 10^8$    |

appeared to be somewhat lower than the expected values of 80 MeV and 107 MeV for heavy and light fragment peaks respectively [7]. The ratio of count rates of $\alpha$-particles to fission fragments was found to be around 45:1.

Comparing the spectra measured in the beginning and at the end of the irradiation period, a graduate decrease of fission fragment visible energy for both investigated detectors was revealed. The positions of the two bumps, corresponding to lower and heavier fission fragments were fitted by a Gaussian function with Minuit package within ROOT environment [8] for each 1-hour series. The temporal behavior of these positions shows a dependence that could be described by a linear function in all cases of fission fragment masses and detector samples, see Figure 2. The derived slope coefficients are summarized in Table 1. The same time fitting the $\alpha$-peak does not show a strong temporal dependence in both detectors.

According to the observations we define the moment of the detector becoming “bad” as an overlap of the heavier fission fragment spectrum with the $\alpha$-peak that prevents us from discrimination between them. In order to estimate the expected maximal exposure for each detector at which it comes to this condition, we approximated the heavy fission fragment bump and the $\alpha$-peak with Gaussian functions and considered the beginning of their overlap at 3 standard deviations $\sigma$ from their maxima.

Since the position of $\alpha$-peak remains constant for each measurement, the value that one has to extrapolate in order to determine the maximal permissible exposure by SF is $E_{HF} + 3 \times \sigma$, where $E_{HF}$ is the energy of the heavy fission fragment bump maximum. This value could also be described with a linear function, see Figure 2. Extrapolating this linear dependence, one gets that maximum permissible exposure to be of $8 \times 10^8$ and $3.7 \times 10^8$ for Si(Li) and surface-barrier detector, respectively.

The shift of fission fragments peaks towards the lower energy is obviously related with the increase of the detector entrance window thickness. The thickness of the entrance window was measured at both detectors by a pulse-height variation of the collimated beam of monoenergetic $\alpha$-particles falling on the detector surface normally and at declination of 45 deg [7]. It was found, that entrance window thickness has increased during the irradiation period by 0.8 $\mu$m and by 1.6 $\mu$m in silicon equivalent for SB and Si(Li) detector, respectively. The rate of entrance window increase relative to the number of absorbed fission fragments turned out to be higher for SB detector (see Table 1) being in agreement with lower expected maximal exposure.

The observed increase of the entrance window thickness is obviously related with charge...
carrier trapping by fission fragments induced radiation defects. The absence of the corresponding shift for the \(\alpha\)-peaks in Figure 1 is probably due to the greater depth of electron-hole pairs production. In case of \(\alpha\)-particles the electron-hole pairs are generated mainly at the end of the \(\alpha\)-particles tracks, i.e. at the depths of about 30 \(\mu\)m, whereas for fission fragments the electron-hole pairs generation rate according to the TRIM simulations [9] reaches the maximum in the near-surface region and gradually drops down towards the penetration depth of fission fragments in silicon lattice (which is about 9 - 12 \(\mu\)m). It should be also noted, that no noticeable increase of entrance window thickness was observed on similar detectors irradiated by pure \(\alpha\)-source [4].

Another sign of radiation-induced degradation of the detector parameters was also found to be more pronounced for SB detector. Thus, an increase of the leakage current was found for both detectors which proceeds linearly with the number of absorbed fission fragments and the obtained coefficient for SB detector appeared to be somewhat higher than that for Si(Li) detector, see the values in Table 1. It is interesting to note, that the rates of current increase in case of fission fragments irradiation from \(^{252}\text{Cf}\) source appeared to be approximately 3 orders of magnitude higher than those ones derived for similar detectors irradiated by \(\alpha\)-particles [4, 6].

5. Conclusions

Performed investigations of detectors degradation under prolonged irradiation by \(^{252}\text{Cf}\) radionuclide have shown a considerable increase of the entrance window thickness. This leads to a gradual shift of the fission fragments signal bumps towards the lower energies and limits the maximal exposure the detector could sustain before “degradation”, which is considered to occur when the \(\alpha\)-peak and peak due to heavier fission fragments overlap. Preliminary results indicate that Si(Li) detector can sustain higher exposure of \(8 \times 10^8\) of fission fragments relative to \(3.7 \times 10^8\) for SB detector and may be considered as more radiation hard.

Further investigations on a larger set of samples providing more reliable statistics are needed in order to find the most radiation hard Si detector best suitable for production of a neutron calibration source.

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