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Neutron irradiation study of silicon photomultipliers from different vendors

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ABSTRACT

We present recent results on the investigation of the KETEK, ZECOTEK, HAMAMATSU and SENSL SiPM properties after irradiation by the 6–35 MeV neutrons. The typical neutron fluence was about 10^{12} n/cm^2. The changing of the internal structure of the irradiated SiPMs was studied by the measuring of the *C–V* and *C–f* characteristics. We have observed the strong influence of the SiPM manufacturing technology on their radiation hardness. The application of the obtained results to the development of the readout electronics is discussed.

1. Introduction

In the recent years there has been interest in the use of so-called silicon photomultipliers (SiPM) in calorimetry for high energy physics. Advantages and disadvantages of these devices are reviewed in [1]. One of the main disadvantages in comparison with the common vacuum photomultiplier is the high sensitivity to radiation damage. Features of influence of various kinds of radiation on SiPM is overviewed in [1–3]. These studies usually consider the parameters directly affecting the quality of the device operation such as dark current, breakdown voltage, gain, quantum efficiency and signal to noise ratio. For several years, we have investigated SiPM to be utilized in the readout of the projectile spectator detector (PSD) calorimeter [4] generated for the compressed baryonic matter (CBM) experiment [5] at the future FAIR facility. The main persistent radiation source for this type of calorimeter are neutrons and our research was focused on the determination of the critical neutron fluence for samples produced by different manufacturers.

2. The research methodology and the physical model applied for the analysis

We assume that the most important are irreversible changes due to neutrons in the material of investigated detectors. Excluding the effects related to a crystalline silicon lattice disorders that are more important when the material is exposed to the charged particles, we come to the hypothesis that the transmutation of the detector material-silicon is the most important from the point of view of the irreversible changes in the structure [6]. For example, the reaction of silicon conversion to phosphorus ultimately leads to the change of the conductivity type [7], and in this case self-annealing phenomena is not possible anymore. It is necessary to change the method of research and data analysis so that we could detect the neutron fluence. For this purpose, we further investigated the detectors in which all the processes of passive self-annealing have practically stopped, i.e. after keeping them at normal room temperature for 2–3 months. Studies were carried out by standard techniques: measurement of *I–V* and *C–V* to determine the change of detector quality. We used the standard model describing the relationship of distribution of the dopant in P–N junction to the measured *C–V* characteristic of the detector. We focused on the change of the depletion region depth on the applied bias voltage. This analysis allows us to evidently detect the structural change occurring as a result of silicon exposure to

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neutrons. Quantitative value of this change can be calculated as the difference between the concentration of the dopant in the given plane of depletion region before and after irradiation. By integration of the resulting value of the concentration differences across the whole depletion region depth, we obtain the total number of impurity centers created in the investigated detector volume. This allows us to determine the value of the effective cross section S_o of creation of new impurity states N_t into depletion region with depth W_{depl} in the detector for the measured neutron flux F:

$$S_o[\text{cm}^2] = \frac{F[\text{n/cm}^2]}{N_t[\text{cm}^{-3}]} \cdot W_{depl}[\text{cm}]. \quad (1)$$

More complicated is the investigation of dynamic parameters of silicon – the processes related to the carriers generation–recombination (G–R) in depletion region. For sufficiently simple analysis of processes in the irradiated detector [8], we propose to use the model of the trap's centers of single type. According to this model, we can analyze the ratio of effective charge carrier life time for the given center and an effective concentration of the traps in the depletion region. This ratio is associated with the easily measured C–f characteristic by:

$$\langle \tau \rangle / \langle N_t \rangle \sim 1/C(f). \quad (2)$$

In the case of independently measured concentration of impurity centers, in accordance with work [9] we can estimate the contribution of G–R noise by:

$$\delta N_t \sim \langle N_t^2 \rangle / N_t \sim 4\tau/(1 + \omega\tau), \quad \text{where } \omega = 2\pi f. \quad (3)$$

Even in the absence of accurate information on the N_t value, we can use the relation (3) for the qualitative assessment of the effect of G–R noise in the chosen frequency band. Since value of G–R noise is

$$\delta N_t \sim N_t \sim \langle \tau \rangle \cdot C(\omega), \quad (4)$$

then for constant τ the dependence of $C(\omega)$ describes the behavior of the G–R noise in the investigated frequency band. Finally, the difference of these characteristics before and after irradiation provides information about the changes of G–R components of the noise as a result of detector irradiation. However, we describe the change in the properties of the detector by the ratio τ/N_t as a more reliable parameter for the measurement and for further interpretation.

3. Experiment, measurements, data processing and analysis

For the detectors irradiation we exploited the neutron source of cyclotron U120 located at the Nuclear Physics Institute of AS CR at Rez and the standard irradiation technique of the samples described in [10]. The standard configuration of the measurement setup has been used for C–V, I–V, and C–f characteristics. The setup includes HIOKI3035 LCR meter and KEITHLEY6510 electrometer. All devices are connected to PC by GPIB bus and controlled by GUI created by NI Lab Windows CVI. To control the fluence in real time we used commercial PIN photodiodes BPW34 [11], which have been calibrated to 1 MeV neutrons and are widely used for radiation monitoring at CERN. We have improved the technique by development of a device with diode temperature control and correction [12]. This allowed us to collect the information on 1 MeV equivalent neutron fluence on-line and avoid the recalculation of the fluence according to the NIEL hypothesis. We utilize neutron beams of quasimonochromatic and “white” continuous spectrum in the energy range from 6 MeV to 35 MeV, for details see [13,14]. The samples were studied immediately after irradiation (with a delay of no more than one hour), and then the measurement was repeated daily during a week and then repeated with the increased interval. The data presented in this paper are obtained for samples in which the process of self-annealing was almost stopped, which means repeatability of measurements with an accuracy of 2–3%. The measurements of characteristics were carried out in a quasi-stationary mode, i.e. each measurement takes few seconds. Therefore, we investigate stationary state of detector and avoid the effects caused by unstable traps with a lifetime within milliseconds. This is particularly important for the study of C–f characteristic, where for the applied analysis model it is important to obtain a statistically averaged value of the capacitance for a given frequency of the test signal.

For data processing and analysis, we developed software in Lab Windows CVI environment carrying out the preliminary analysis of the measurements, and a macro for statistical processing of the data in the Root environment. Each measurement was carried out with the temperature control and a resulting file containing information about the time of measurement and temperature was created. We have previously studied the effect of temperature variation on the data repeatability and selected allowable temperature change interval which does not require additional data correction. Otherwise, the temperature correction was applied. Reconstruction of doping profile and the depletion region depth dependence on the voltage were held by the method of C–V analysis described in [15]. Next step was conduction of additional analysis for calculation of the difference of dependence of depletion region depth on the bias for the irradiated and non-irradiated detector. Then we calculated the concentration differences for the irradiated and non-irradiated detector and plot of the corresponding histogram. The histogram may have symmetry with respect to zero, or it can be asymmetrical. Preliminary analysis showed that the detectors with the symmetrical histogram are more radiation resistant [16], presumably that could be associated with a symmetry of topology and internal structure. For an accurate answer to this question further studies are required. The final step of the analysis was the obtaining of the integral of the absolute change in total impurity concentration in the depletion region and the calculation of the effective cross section of creation of new impurity states for the measured neutron flux. The C–f performance processing was carried out and interpreted as we describe it below.

For comparison of SiPM produced by different manufacturers and different technologies, we proposed the following approach. Because regardless of the technology all the studied detectors are designed to work with light signals, the depletion region depth does not exceed 5 μm to avoid the additional generation of noise in the active volume of the detector. The depth of active avalanche multiplication providing an effective mechanism for avalanche stabilization and restrictions is ~0.1 μm. It identifies the region most important for the detector operation as a region of less than 5 μm under the surface. All the investigated SiPMs had depletion region depth about 2–4 μm at a voltage of 10 V, and this depth is quite stable up to the operating point voltage. Due to this fact, we have chosen the 10 V offset voltage as a reference for studies of changes in the depletion region, and for studies of the C–f characteristics. We represent the difference in dependence of depletion region on biasing voltage. For the analysis of the frequency characteristics we use the relative data, such as the ratio of the maximum difference between the inverse capacitance for the irradiated and non-irradiated detector in chosen frequency range to the difference between the inverse capacitance for irradiated and non-irradiated detector at a predetermined frequency. This allows us to qualify the impact of neutron exposure on change in the τ/N_t ratio, and thus allows us to predict the change of G–R noise component.

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