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Radiation hardness study of semi-insulating GaAs detectors against 5 MeV electrons

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Abstract: A radiation hardness study of Semi-Insulating (SI) GaAs detectors against 5 MeV electrons is described in this paper. The influence of two parameters, the accumulative absorbed dose (from 1 to 200 kGy) and the applied dose rate (20, 40 or 80 kGy/h), on detector spectrometric properties were studied. The accumulative dose has influenced all evaluated spectrometric properties and also negatively affected the detector CCE (Charge Collection Efficiency). We have observed its systematic reduction from an initial 79% before irradiation down to about 51% at maximum dose of 200 kGy. Relative energy resolution was also influenced by electron irradiation. Its degradation was obvious in the range of doses from 24 up to a maximum dose of 200 kGy, where an increase from 19% up to 31% at 200 V reverse voltage was noticed. On the other hand, a global increase of detection efficiency with accumulative absorbed dose was observed for all samples. Concerning the actual detector degradation we can assume that the tested SI GaAs detectors will be able to operate up to a dose of 300 kGy at least, when irradiated by 5 MeV electrons.

The second investigated parameter of irradiation, the dose rate of chosen ranges, did not greatly alter the spectrometric properties of studied detectors.

Keywords: Radiation damage to detector materials (solid state); Radiation-hard detectors; Solid state detectors

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Contents

1 Introduction

Recent progress in the field of high energy physics and in space applications involves use in a radiation harsh environment where high-energy electrons play an important role. Radiation belts of planets contain electrons with energies of a few MeV and fluxes up to 10^{10} cm^{-2}day^{-1}sr^{-1} [1, 2]. The electron-positron collider foreseen as the ILC [3] will involve exposure to electron-positron pairs from bremsstrahlung of a dose of about 1 MGy per year.

There are only a few studies dealing with radiation resistance of GaAs detectors to high-energy electrons [4–8]. Afanaciev et al. irradiated the Cr-doped GaAs sensors by 10 and 8.5 MeV electron beam and a dose rate of 20 to 400 kGy/h to a total dose of 1.5 MGy and observed the charge collection efficiency (CCE) degradation with the absorbed dose in [4].

We have also studied the radiation hardness of GaAs detectors irradiated with high-energy electrons in previous research [5–8]. In our experiments we have irradiated three groups of four Schottky barrier semi-insulating (SI) GaAs detectors with 5 MeV electrons up to a dose of 120 kGy using a different dose rate for each group. We have compared the influence of electron irradiation on spectrometric properties of GaAs detectors to the effect of other types of radiation, the fast neutrons and gamma-rays from ^{60}Co in [5]. In paper [6] we aimed at electrical properties of tested detectors influenced by electron irradiation. The resistivity and the electron Hall concentration of GaAs substrate slightly decreased with increasing cumulative dose in whole range of doses from 1 up to 104 kGy. On the other hand, the numerical value of the Hall coefficient was increasing linearly with rising applied dose. The electron Hall mobility was increasing too, up to cumulative dose of 24 kGy, followed by a decrease to 7000 cm^2/Vs at 104 kGy. The breakdown voltage initially increased (in the dose range from 1 to 10 kGy) followed by decrease to 75–80 % of its initial value, depending on the dose rate used during irradiation. Similar behaviour was observed also with the reverse current flowing through the detector structures. In papers [7] and [8] the spectrometric properties of GaAs detectors were analysed. First tests up to a dose of 24 kGy [7] have revealed slight improvement of energy resolution at low doses (1 kGy) and decrease of CCE with increasing dose. Continuation in irradiation process (up to a dose of 120 kGy) led to degradation of detector CCE and energy resolution. However, we have observed a global increase of detection efficiency [8]. In this paper, we have proceeded with our last two studies [7, 8] reaching the accumulative dose of 200 kGy at the same dose rates during irradiation used in previous experiments: (20, 40 and 80 kGy/h). We continued the precise characterization of detectors from the point of view of their spectrometric properties: the charge collection efficiency, the relative energy resolution and the detection efficiency. We wished to understand an interesting phenomenon where the number of counts in photo-peak registered by detector when measuring gamma-rays increases with cumulative dose induced by high energy electrons.

2 Experimental part

2.1 Detector characterisation

Examined detectors were the same samples as those investigated and described in our previous papers [7] and [8]. The Schottky barrier detectors were made of a bulk VGF (Vertical Gradient Freeze) SI GaAs grade double-side polished to a thickness of 230 μm. Three groups of detectors, each containing four detectors, were prepared on separated square shaped wafer parts (1×1 cm^2) from the middle of 3” GaAs wafer and labelled 4A, 5A and 6A. Chosen wafer segments exhibited similar electrical properties (the resistivity and the electron Hall mobility) [6]. The Schottky electrode of the detector, a 135 nm thick Ti/Pt/Au (10/35/90 nm) metallization of circular shape with 1 mm diameter, was evaporated onto the top side of the wafer using photolithographic masking. A whole area Ni/AuGe/Au (30/50/90 nm) quasi-ohmic metal electrode was formed on the back side of the substrate. Each wafer segment (4A, 5A, 6A) with four detectors was glued onto a separate PCB (Printed Circuit Board) support with detectors wire bonded.

2.2 Irradiation by electrons

SI GaAs detectors were irradiated from the detector Schottky contact side by a pulsed scanning beam (3.5 μs pulse duration) of 5 MeV electrons at room temperature using a linear accelerator UELR 5-1S. Detectors fixed on the PCB holder were placed on a 1 cm thick Al board during the irradiation. The distance between the Al board surface and the foil of the accelerator exit window was 95 cm. Three repetition rates of the beam were used in the experiment, 10 Hz for the segment labelled 4A, reaching the dose rate of 20 kGy/h during irradiation, 20 Hz for the segment 5A obtaining the dose rate of 40 kGy/h and finally 40 Hz repetition rate leading to the dose rate of 80 kGy/h. By modifying the beam repetition rate from 10 through 20 up to 40 Hz the average beam current was changing from 8 to 16 and 32 μA, respectively.

The detectors were irradiated in fifteen steps to a total dose of 200 kGy (figure 1). Each segment of detectors (4A, 5A, 6A) was irradiated separately, with a different dose rate, but to identical partial doses as other groups adjusting the irradiation period. The doses were measured using B3 radiochromic films, evaluated by Spectrophotometer GENESYS20 and verified with RISO polystyrene calorimeters. The doses showed in the graphs and those mentioned in the text are the doses measured on the detector surface. However, the dose induced by electrons in GaAs material

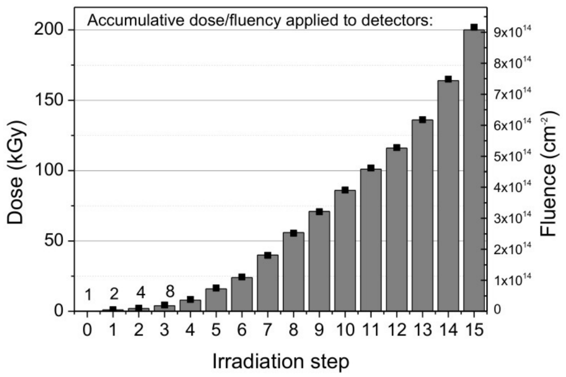


Figure 1. The accumulative dose and fluence (calculated from dose with help of CASINO 2.5.1) applied to detector surface at each step of electron irradiation.

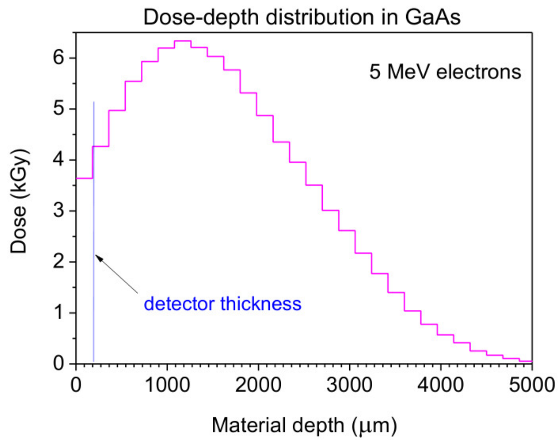


Figure 2. The dose depth distribution of 5 MeV electrons in GaAs material according to simulation in ModePEB [9].

changes with material depth as is shown in figure 2. As the thickness of GaAs detector material was only 230 µm, the dose was increasing from the surface to the bottom of detector material by about 23% according to simulation (figure 2) [9], which is in agreement with the experimental dose measurement giving the average difference in measured bottom-top doses of 19%.

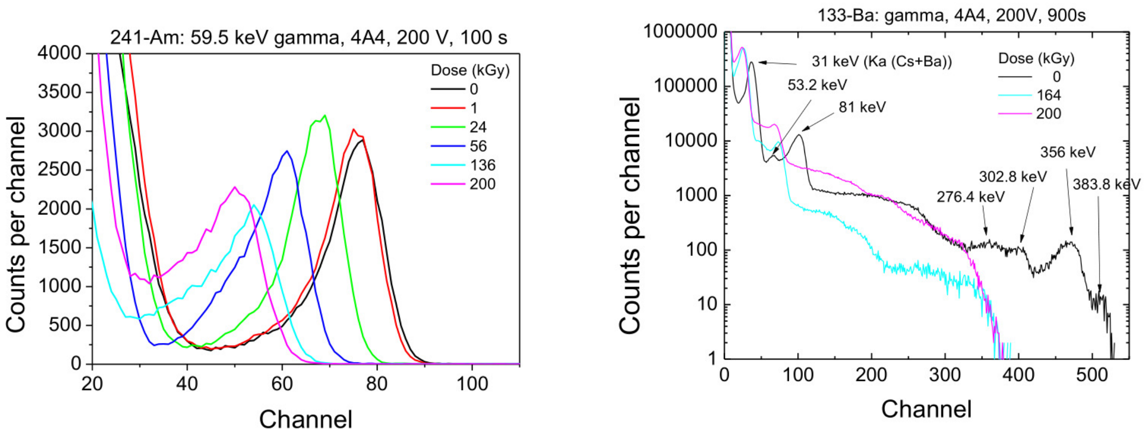
3 Results and discussion

To evaluate the quality of tested SI GaAs detectors after their radiation degradation by 5 MeV electrons, the gamma spectra measurements were performed. The spectrometric properties of investigated SI GaAs detectors were evaluated from measured pulse-height gamma spectra of ^{241}Am and ^{133}Ba at detector reverse voltages from 50 V up to breakdown voltage. The distance between the detector and the gamma source was about 8 mm. The investigated detectors were connected to a spectrometric chain based on InSpector2000 readout electronics.

Figure 3 shows examples of chosen gamma spectra measured by the detector from group 4A at reverse voltage of 200 V before irradiation and after particular doses up to 200 kGy for both sources used ^{241}Am and ^{133}Ba. One can observe that as the dose increases the photo-peaks shift to lower channels, which indicates worsening of detector CCE. The degradation of the peak to valley ratio with rising dose can also be seen. However, precise evaluation of the spectrometric properties as a function of applied dose is displayed in figures 5–7. Figure 4 shows good linearity of calibration curves obtained from peak positions in spectra in figure 3. Also the effect of chosen irradiation doses (164 and 200 kGy) on energy calibration curve is visible. As the dose increases the channel position decreases which again indicates worsening of detector CCE.

3.1 Charge collection efficiency

The CCE was determined from measured pulse-height spectra as was described in paper [8]. The influence of cumulative electron dose on the detector CCE depending on the dose rate applied during irradiation is shown in figure 5a. The CCE values were obtained as an arithmetic average of



a) b)

Figure 3. Gamma spectra measured by detector #4A4 at reverse voltage of 200 V before irradiation and after chosen doses up to 200 kGy using the ^{241}Am (a) and ^{133}Ba (b) gamma sources.

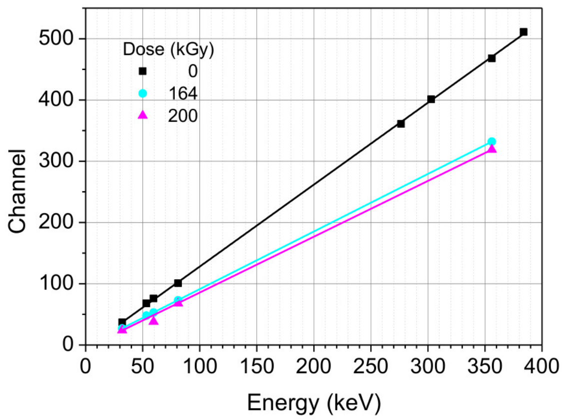


Figure 4. Energetic calibration curves obtained from peak positions in spectra shown in figure 3 are compared for doses 164 and 200 kGy and before irradiation.

CCE of four detectors on one detector segment irradiated by the same dose rate. The initial CCE of about 73–74% at 200 V reverse voltage before irradiation was almost linearly decreasing with cumulative dose down to 49.4–52% at 200 kGy. On the other hand, the effect of used dose rates on CCE decrease is not evident from the results obtained in this study.

The decreasing trend of CCE with applied dose was also observed with Si based detectors in [10], but with higher energies of electrons (900 MeV). The radiation hardness studies of GaAs detectors against high energy electrons are very rare. In [4], degradation of CCE of Cr-doped GaAs sensors with the dose was observed. CCE degradation was more pronounced at lower doses and it was much slower after dose higher than 500 kGy. A similar trend can be observed also with our results (figure 5a), where CCE decreases more steeply at lower doses applied. The sensors described in study [4] were kept under bias voltage during irradiation in contrast to our experiment.

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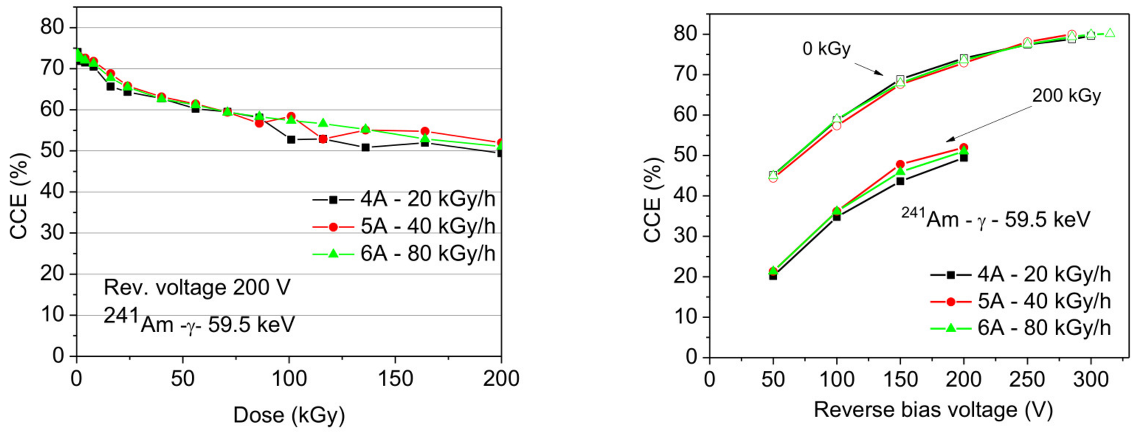

a) b)

Figure 5. Average CCE of each group of detectors irradiated by electrons with different dose rates: a) as a function of applied dose at reverse bias voltage of 200 V, b) as a function of reverse bias voltage before irradiation and after maximum applied cumulative dose of 200 kGy.

Figure 5b) shows the CCE as a function of applied reverse voltage for two extremes: before irradiation and after irradiation with maximum dose of 200 kGy. CCE increases with the applied voltage, as the intensity of the electric collecting field in the detector volume grows. Before irradiation, one can observe the increase of CCE from 45% (at 50 V) up to 81% (at 315 V). After irradiation, CCE dropped to 20% (at 50 V) and grew only to 51% at maximum applied reverse voltage of 200 V. Radiation induced defects in GaAs material the most probably deteriorated the charge collection in it due to shortening of charge carriers lifetime.

3.2 Relative energy resolution

Relative energy resolution labelled FWHM (%) (Full Width at Half Maximum) of investigated detectors is displayed in figure 6a as a function of applied dose in logarithmic scale. Each curve represents the average FWHM of four detectors from one group irradiated by the same dose rate. One can observe an initial slight improvement of FWHM, after first irradiation to a dose of 1 kGy, in all three groups of detectors by about 1 up to 5%, which might be caused by temporary compensation of radiation induced defects with natural defects in SI GaAs. This decrease of FWHM is followed by a its slight increase in the dose range from 2 to 24 kGy and further steeper increase up to a maximum applied dose of 200 kGy However, the trend of FWHM is independent of the dose rate used during irradiation.

Figure 6b shows FWHM as a function of applied reverse bias voltage for un-irradiated detectors and for those irradiated by the maximum applied dose of 200 kGy. Before irradiation, all tested detectors exhibited improvement of FWHM with increasing reverse voltage with the best value of 17% at highest applied reverse voltage. After irradiation we can also find the best FWHM for the highest applied reverse voltage, however, the maximum voltage is lower than before irradiation (200 V) and the values of FWHM are significantly higher (minimally 31%).

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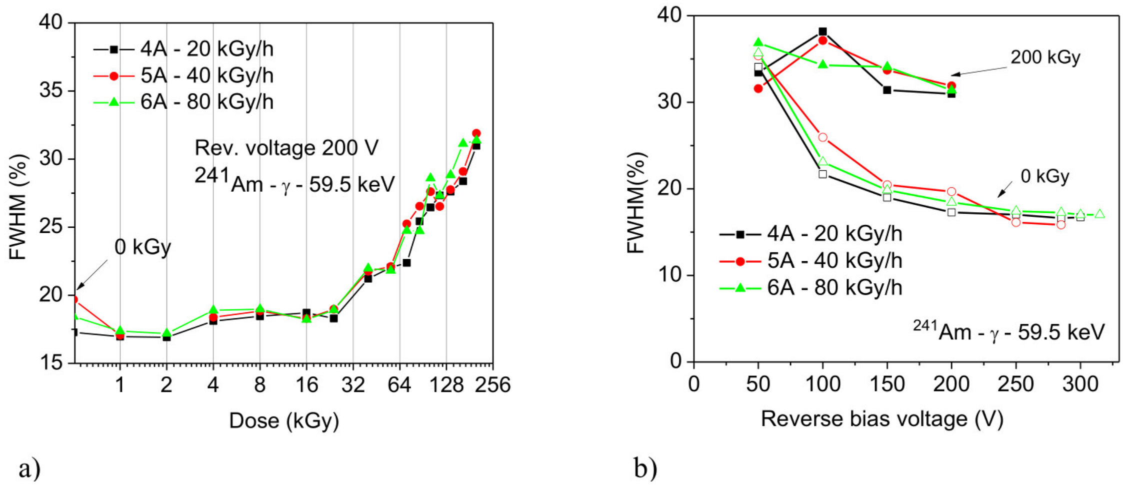
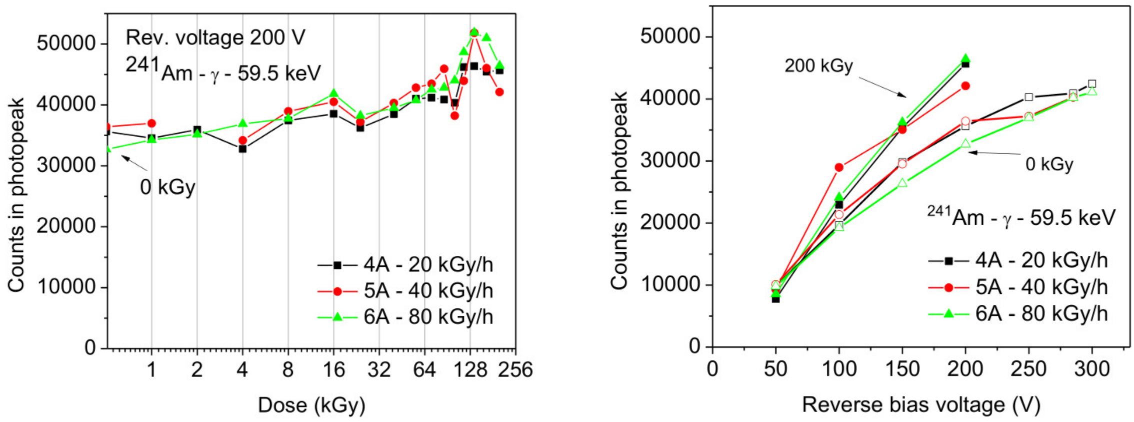


Figure 6. Average FWHM of each group of detectors irradiated by electrons with different dose rates a) as a function of applied dose at reverse bias voltage of 200 V, b) as a function of reverse bias voltage before irradiation and after maximum applied cumulative dose of 200 kGy.

3.3 Detection efficiency

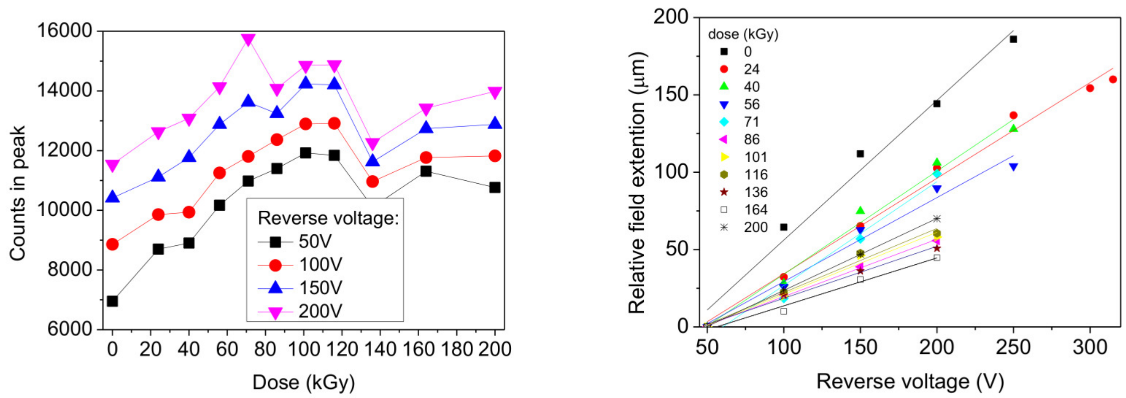
Detection efficiency is proportional to the number of counts in photo-peak which is displayed as a function of the applied dose in figure 7a. The curves represent the arithmetic average of the photo-peak areas of detectors from one group, irradiated with the same dose rate. A global trend of increasing detection efficiency can be observed with increasing applied dose. Local deviations from the trend could be caused by inaccuracy in gamma source positioning over the detector during spectra measurement. Observed global trend is more evident in figure 7b, where two extremes of experimental results are depicted as a function of reverse voltage. Here, it is obvious that the detection efficiency increases more steeply with reverse voltage after applied dose of 200 kGy compared to results before irradiation.

Detection efficiency of gamma rays increases with reverse voltage due to enlargement of detector active volume. In SI GaAs detectors the active detector volume penetrates to the depth of the substrate [11] and also to the sides, behind the detector contact edges [12, 13], linearly with increasing applied voltage, thus increasing the probability of photon detection. However, this does not explain higher detection efficiency after damaging irradiation. But, the radiation induced defects in GaAs material could enhance the lateral spreading of the detector active area to sides, behind the detector contact edges. This theory can be verified if instead of gamma ray spectra the alpha spectra are evaluated. The 5.5 MeV alpha particles from ^{241}Am have the projected range in GaAs of 18.4 µm, which is less than detector active volume depth (38 µm) at reverse voltage of 20 V. It means that the peak detection efficiency will change only if the active area of detector spreads independent of the active volume depth. Figure 8a shows the integral of counts in peak of alpha spectra as a function of applied cumulative dose for different reverse voltages applied (50 to 200 V). One can observe not only an increase of integral counts with reverse voltage applied but also their increase with cumulative dose up to about 80 kGy at constant voltage. The increase of the detection efficiency of gamma rays is, in fact, caused by enlargement of the active detector area (by lateral



a) b)

Figure 7. Average of registered counts in photo-peak for each group of detectors irradiated by electrons with different dose rates a) as a function of applied dose at reverse bias voltage of 200 V, b) as a function of reverse bias voltage before irradiation and after maximum applied cumulative dose of 200 kGy.



a) b)

Figure 8. a) Counts registered in peak of ^{241}Am alpha spectra as a function of cumulative dose for various reverse bias voltages and b) the active detector area relative extension calculated from number of registered counts as a function of reverse voltage for various degradation doses of electrons.

field spreading behind physical contact size) caused by radiation induced degradation. The relative field extension behind the contact edges in μm was evaluated from integral number of counts in peak related to the counts registered at reverse voltage of 50 V at particular dose. In figure 8b it is depicted as a function of reverse voltage. The linear increase of field extension with reverse voltage can be observed. From point of view of applied dose one can observe that the active area enlargement with reverse voltage is more moderate for higher doses.

4 Conclusion

We have evaluated the influence of 5 MeV electron irradiation on the spectrometric properties of SI GaAs detectors. Two irradiation parameters were modified: the applied dose in the range of 1 to 200 kGy and the dose rate used during irradiation reaching the values of 20, 40 and 80 kGy/h, respectively. We did not observe any significant effect of used dose rates on studied spectrometric properties. On the other hand, the cumulative dose influenced all three parameters. We observed worsening of detector CCE, a slight initial improvement of energy resolution followed by its increase and global improvement of detection efficiency with the applied dose. We suppose that the radiation induced defects increased the inhomogeneity of the SI GaAs material, which could led to the electric collecting field spreading to the sides behind the contact edges. Consequently, the increase of detection efficiency, but worsening of the energy resolution and CCE with the applied dose were observed. However, the investigated detectors are still functional after exposition to 5 MeV electrons of 9×10^{14} cm^{-2} fluence inducing the dose of 200 kGy. They reach the CCE of about 51%, the FWHM of 31% and in photo-peak there is about 28% more counts detected (at 200 V) than before irradiation. We plan to proceed with our experiments to find the operational limits of SI GaAs detectors in the field of 5 MeV electrons. We can assume that the investigated detectors will be able to operate up to a dose of 300 kGy or higher as estimated from the results of this study.

Acknowledgments

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