# Analysis of radiation effects on some properties of GaAs: Cr and Si sensors exposed to a 22 MeV electron beam

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## Abstract

Nowadays, the experiments related to High Energy Physics and others fields demand the use of detectors with greater radiation resistance, and the novel material GaAs:Cr has demonstrated excellent radiation hardness compared with other semiconductors. On the basis of evidence obtained in the JINR experiment with the use of 22 MeV electrons beam generated by the LINAC-800 accelerator, an analysis of electron radiation effects on GaAs:Cr and Si detectors is presented. The measured I-V characteristics showed a dark current increase with dose, and an asymmetry between the two branches of behaviors for all detectors. Analyzing the MIP spectra and CCE dose dependence measurements a deterioration process of detectors collection capacity with dose increase was found, although behaviors are somewhat different according to the detector type. The detailed explanation of these effects from the microscopic point of view appears in the text, and are generally linked to the generation of atomic displacement, vacancies and other radiation defects, modifying the energy levels structure of the target material. These changes affect the lifetime and concentration of the charge carriers, and other characteristics of the target material.

***Key words:*** *chromium; gallium arsenides; physical radiation effects; traps; high energy physics; radiation detectors.*

# Análisis de los efectos de la radiación en algunas propiedades de sensores de GaAs:Cr y Si expuestos a un haz de electrones de 22 MeV.

## Resumen

Actualmente, los experimentos relacionados con la física de altas energías y otros campos, demandan el uso de detectores con mayor resistencia a las radiaciones y el novedoso material GaAs:Cr ha demostrado poseer una excelente fortaleza comparado con otros semiconductores. En base a las evidencias obtenidas en el experimento del IUIN con el uso de un haz de electrones de 22 MeV generado por el acelerador LINAC-800, se presenta un análisis de los efectos de la radiación en detectores de Si y GaAs:Cr. Las características I-V medidas mostraron un incremento de la corriente de fuga con la dosis y una asimetría entre las dos ramas de estos comportamientos para todos los detectores. Analizando las mediciones de los espectros MIP y la dependencia de la CCE con la dosis, fue encontrado un proceso de deterioro de la capacidad de detección de los detectores con el aumento de la dosis, sin embargo, los comportamientos son diferentes de acuerdo al tipo de detector. La explicación detallada de estos efectos desde el punto de vista microscópico aparece en el texto, los cuales están relacionados generalmente con la generación de desplazamientos atómicos, vacancias y otros defectos producto de la radiación, modificando la estructura de los niveles energéticos en el material sensor. Estos cambios afectan el tiempo de vida y la concentración de los portadores de carga, así como otras características del material..

***Palabras clave:*** *cromo; arseniuros de galio; efectos físicos de las radiaciones; trampas; física de altas energías; detectores de radiaciones.*

## Introduction

It is a fact that experiments developed in the field of modern physics demand the use of detectors with greater radiation resistance. For purposes like high energy X-ray detection or the use of detectors as active targets, silicon semiconductor detectors are not sufficient. Therefore, composite semiconductor materials, as cadmium telluride (CdTe), iodide mercury ($HgI_2$), thallium bromide (TlBr) and gallium arsenide (GaAs), are used for more efficient detectors manufacture.

Of these materials, great interest has aroused GaAs because of its advantageous properties over the classic silicon [1, 2]. For example, for the same applied electric field GaAs would be able to exhibit an 8 times larger current in an n-type material, so one can apply a smaller voltage to achieve the same amount of current, this is due to its major band gap. These detectors can be operated at much higher frequencies than silicon equivalents and generate less noise, allowing them to work at higher power levels as a result of their higher breakdown voltages. Moreover, high detection efficiency per unit thickness is achieved with GaAs due to its high effective atomic number. Consequently, GaAs can be used for radiation detection in harsh environments without the need for cooling and shielding, and with good energy resolution [3].

The parameters of the detectors based on semi-insulating gallium arsenide compensated with chromium (GaAs:Cr) are radically different; the resistivity of this material is two orders of magnitude higher than that of undoped GaAs, and for GaAs:Cr, the I–V characteristics are nearly linear, in contrast to the devices based on undoped GaAs [4]. Chromium compensated gallium arsenide represents a useful material due its use as the substrate for integrated circuits and also in high-energy physics for the production of nuclear radiation detectors, specifically, for measuring high-intensity proton beams [5]. Chromium is a well-known deep acceptor in GaAs [6, 7, 8] that compensates residual shallow donors to render the material semi-insulating, being the chromium compensation of bulk material an excellent method of reducing the concentration of EL2+ centres [9]. For these reasons the GaAs:Cr has become a promising material for the development of radiation detectors, and therefore in the target of many investigations aimed to evaluate its resistance to the radiation damage for different experimental conditions.

In correspondence with this, the main objective of this work is the analysis of the results obtained in an irradiation experiment of GaAs:Cr and Si detectors with different doses in a 22 MeV electron beam, and try to give a possible explanation from the microscopic point of view to the phenomena that are observed.

## Materials and methods

In the 22 MeV electron beam irradiation experiment carried out in the DLPN were studied two types of semi-insulating GaAs:Cr detectors developed from n-GaAs material using the precision chromium doping technique [10]: barrier transition $\pi$-$\nu$ type and high resistive type. All these sensors are made in Tomsk State University from the p-$\pi$-$\nu$-n type GaAs:Cr with electron carrier concentration from $8x10^{16}$ to $3x10^{17}$ $cm^{-3}$.

As references for the radiation hardness study and for comparison with GaAs:Cr, two types of silicon sensors were studied: normal n-type Si and radiation hard n-type Si from Santa Cruz University, California (USCS).The main sensors characteristics are listed in table 1.

**Table 1.** Sensors characteristics.

| No. | Type | Size [$mm^3$] | Sensitive area [$mm^2$] |
|---|---|---|---|
| 1 | Barrier GaAs:Cr | 5x5x0.3 | 5x5 |
| 2 | High resistive GaAs:Cr | 5x5x0.3 | 4.5x4.5 |
| 3 | Normal n–type Si | 5x5x0.3 | 4x4 |
| 4 | Radiation hard n–type Si from USCS | 10x5x0.4 | 4x4 |

The electron irradiation was performed at the LINAC-800 accelerator using the 22 MeV beam channel. The electron beam was bunched, having a bunch current up to 10 mA and a frequency in the interval from 1 to 10 Hz. The pulse duration was 2 μs.

The electron beam exits the pipe to the air through a titanium window, and at 60 mm from the output was placed a 10 cm length aluminum collimator which cuts the beam shaping it to a 5x5 $mm^2$ square, the same dimensions of the studied sensors. The collimated electron beam hits the target sensor, crosses it and a sensitive film, finally reaching the Faraday cup. The measurement of the charge in Faraday cup allows to estimate the electron flux and to calculate the absorbed dose. The measured by this method integral electron flux varied in the range 0.5 - 5 x $10^{14}$ $e^{-}$/hour, which corresponds to the absorbed dose from 50 to 500 kGy/h. The placed behind the sensor radiation sensitive film allows additionally to measure the absorbed radiation in the sensor dose, and to control the uniformity of electron flux.

Charge collection efficiency was measured by using a $^{90}Sr$ ß-source. After each dose step the CCE for at least 2 bias voltages and the I-V dependences were measured.

In the general schema of the experimental setup designed in order to measure the GaAs:Cr and Si sensors CCE, the collimated electrons from a $^{90}Sr$ $\beta$-source pass across a biased sensor producing the active material ionization. The generated charges are collected and the resulting signal is amplified and digitized. In order to only consider the signal generated by the MIP, the electrons that cross the detector are triggered by two scintillation counters operating in coincidence and having two different thicknesses. This arrangement allows to select and measure signals only from electrons passed throw the sensor with energy from 1 to 2.2 MeV, which is close to MIP electrons.

## Discussion

### I-V measurements

The figures 1 and 2 present the I-V characteristics of 2 types GaAs:Cr sensors and 2 types Si sensors before and after irradiation at several doses.

Figure 1 shows that the dark current increases in 3 times for high resistive GaAs:Cr and approximately in 7 times for barrier GaAs:Cr detectors, when the absorbed dose reaches 1.55 and 1.15 MGy respectively. This fact results in a decrease in resistivity with increasing irradiation dose, most markedly in the barrier type detector.

Some authors, such as [11, 12], argue that this behavior is fundamentally due to the introduction of displacement damages in the material as consequences of irradiation, so that new defects are created in the lattice. Such defects can act as recombination-generation centers that are able to modify the surrounding electric field, leading to the formation of energetic states located deep in the band gap. The formation of these new states leads to an easier electrons transition from the valence band to the conduction band, and therefore to the leakage current increase in the detector. In parallel, the defects generated by the radiation close to the middle of the energy gap are efficient electron-hole pair generation centers and thus are also responsible for the leakage current increment.

In the paper [13] the authors describe the energy levels structure generated when GaAs is irradiated with electrons and gamma rays, indicating the appearance of the shallow E1, E2 and E3 electron traps, located in the center of gap E4 and E5, and the hole traps H1 and H2 near the valence band. It is explained here that several studies of defect production by electron irradiation in n-type material provide several arguments that the traps observed correspond to primary defects, i.e. vacancies and interstitials in the As sublattice: $V_{As}$ and $As_i$. Finally, complex defects are also formed by electron irradiation at 300 K when the flux is high enough to induce the migration of the primary defects through a carrier recombination-enhanced mechanism. Some As atoms, escape from recombination with $V_{As}$ and migrate until they are captured by impurities. Antisites are also formed, probably by the replacement of donor impurities on Ga sites by $As_i$. As it can be seen, all this defects could be related by different ways to the behavior of the trap EL2 previously explained at the beginning of this work, and that decisively influences the GaAs conduction properties.

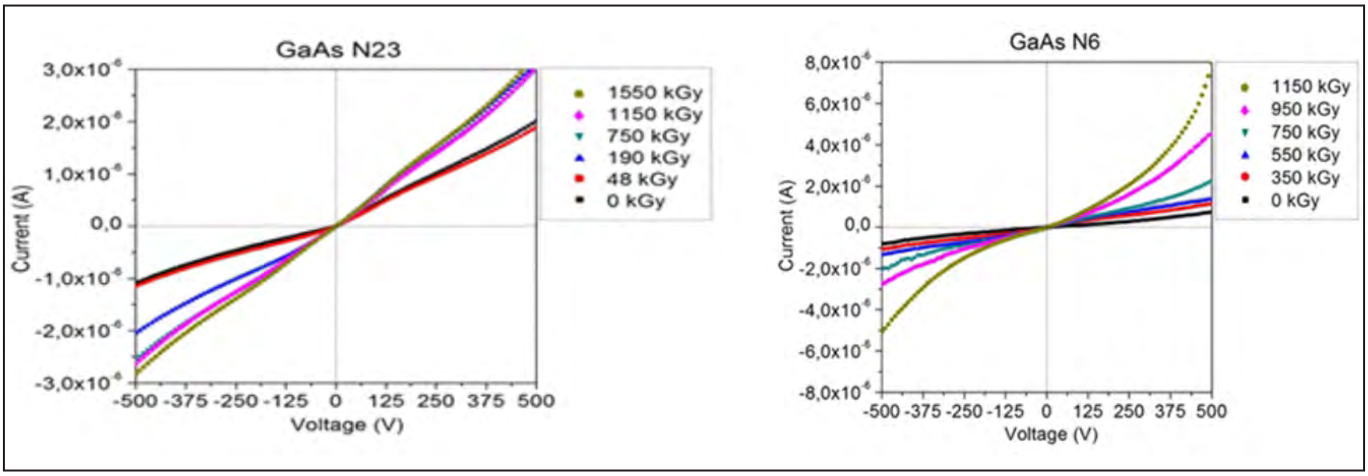

**Figure 1.** I-V characteristics before and after irradiation with different doses for high resistive (left) and barrier(right)GaAs:Cr sensors.

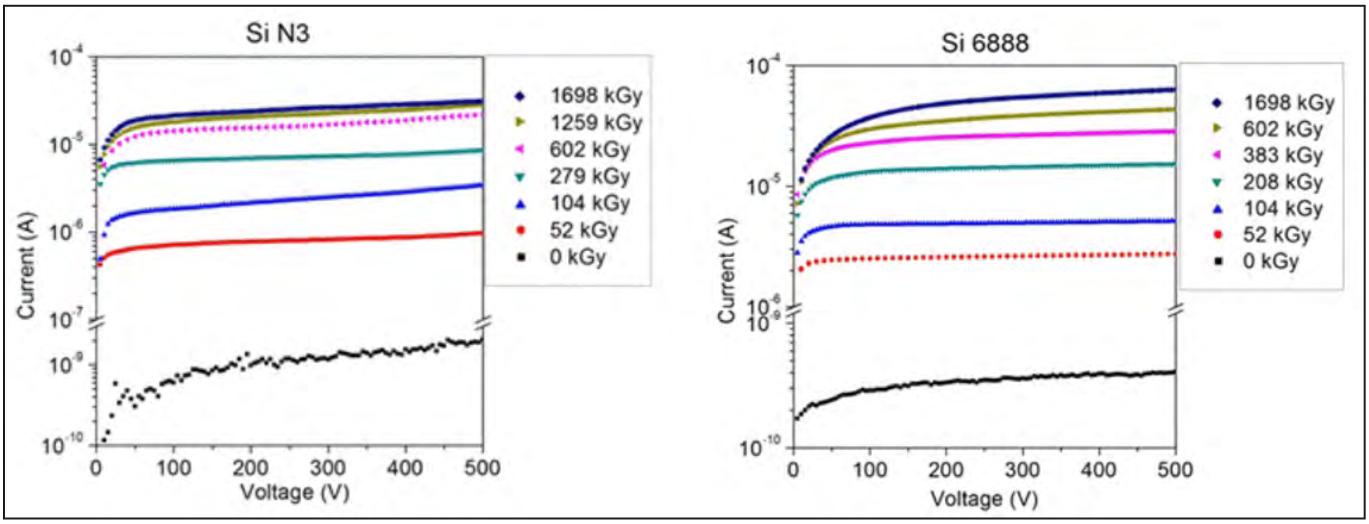

**Figure 2.** I-V characteristics before and after electron irradiation with different doses for normal n-type(left) and USCS radiation hard n-type(right) Si sensors.

Finally, the presence of a slight asymmetry between the two branches of the I-V characteristic, more accentuated for barrier detector at higher doses, is shown in figure 1. This asymmetry is related to the asymmetric potential distribution within the device, which was engineered by using appropriate growth conditions, but evidently it changes with the induced radiation damage.

For two silicon sensors, an increase in the leakage current by almost 4 orders of magnitude for the maximum applied dose is observed in figure 2. The first fact that stands out when comparing this detector with the GaAs detectors is that the effect of the radiation on the Si is, as expected, stronger. The difference between the increase of the leakage current for the normal detector and the one corresponding to the high resistive detector is minimal.

About the effect of the electron irradiation on the structure and properties of Si there is a great amount of information, since it has been well studied, and therefore, we will not go into the topic. Literature examples that can be consulted are [14, 15, 16].

### CCE Measurements

The MIP spectra for barrier GaAs:Cr sensor after the irradiation doses of 550 and 1550 kGy are presented in figure 3. Spectra were collected at room temperature 21°C. Observe that with dose increasing takes place the progressive displacement of the signal peak towards the lower energy channels, and the process of the signal and the pedestal overlapping takes place. At the dose of 1550 kGy the maximum overlap is observed, although the peaks of signal and pedestal are still distinguishable.

The shift of the signal up to its overlap with the pedestal is due to the depression of the sensor charge collection capacity with the irradiation dose. The main phenomenon that supports this behavior is the shortening of the charge carrier lifetime as consequence of the irradiation dose. With the irradiation, increases the traps concentration, decreases the mobility of free carriers and their lifetime, which leads to the decrease of the drift length.

The measurements of pedestal width in a GaAs:Cr show that it remains practically unchanged in all irradiation process, while for Si, due to increasing of the dark current, the pedestal considerably broadens and the measurement becomes difficult for doses higher 493 kGy.

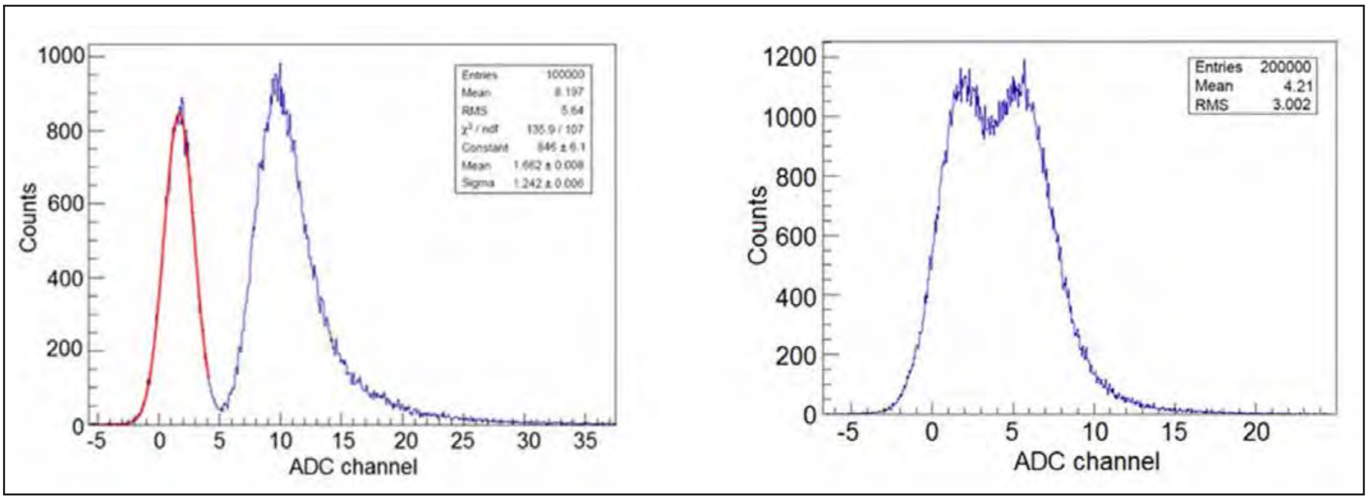

**Figure 3.** MIP spectra for barrier GaAs:Cr sensor after irradiation dose 550 kGy (left) and 1550 kGy (right). The pedestal is visible on the left. Measurement temperature 21°C.

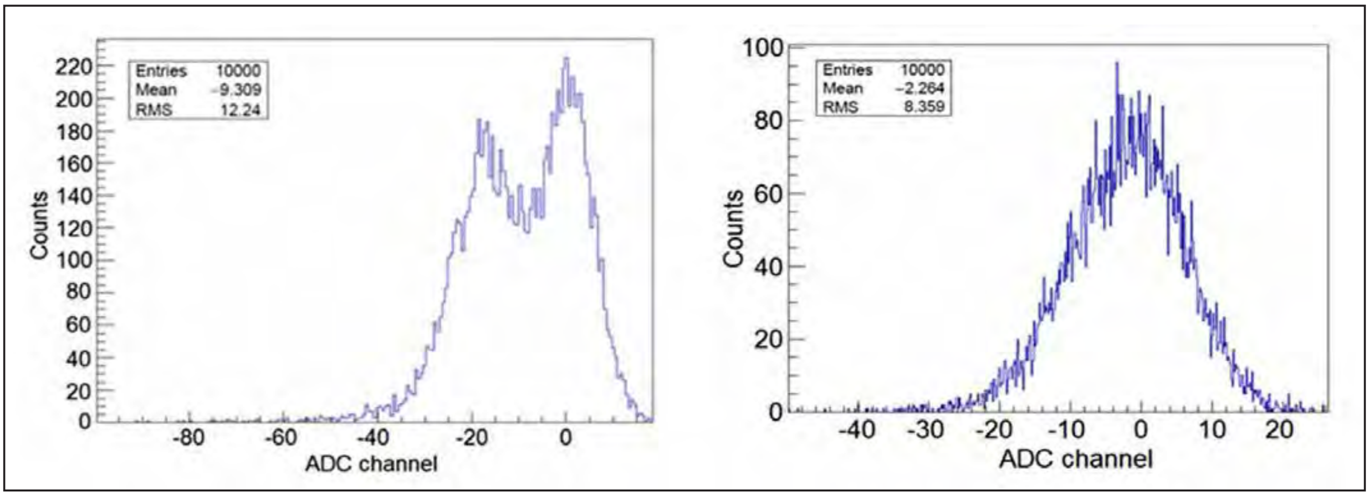

**Figure 4.** MIP spectra for Si sensor after irradiation dose 493 kGy (right) and 1260 kGy (left). The pedestal is visible on the right. Measurement temperature 21°C.

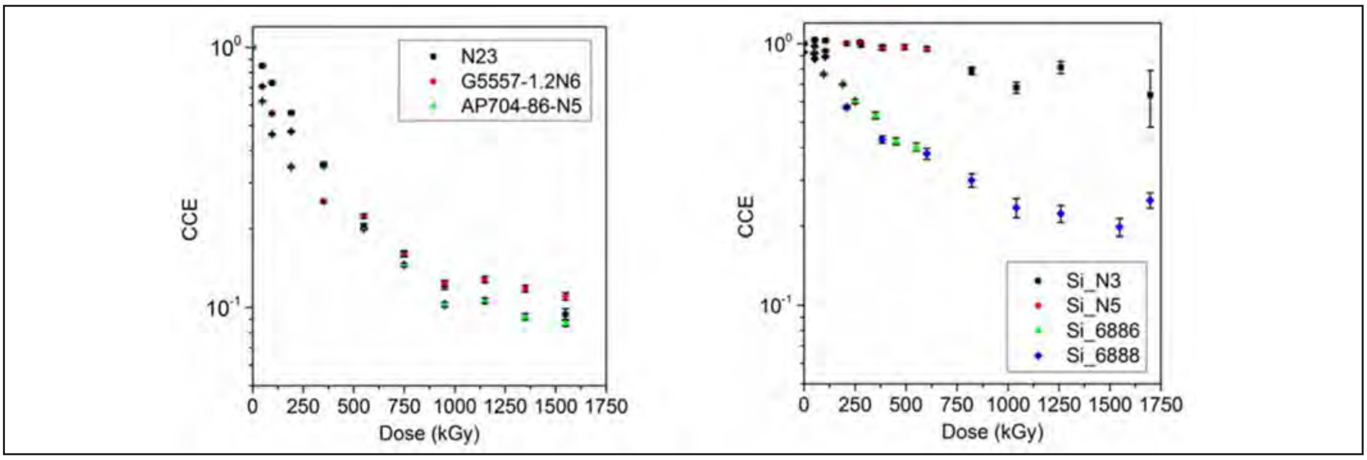

**Figure 5.** CCE as function of irradiation dose for GaAs:Cr (left) and Si (right).

Figure 5 shows the experimental CCE behavior with the irradiation dose normalized to the CCE before irradiation, for some selected GaAs:Cr an Si sensors.

In GaAs:Cr the CCE falls monotonously and abruptly until to dose 1000 kGy, but then it decreases slowly up to the maximum irradiation dose. It was observed for all the studied samples, the barrier ones and the high resistivity ones.

For silicon sensors, we can differentiate two groups of samples according to their CCE vs. dose behavior. One group is the normal n-type sensors, for which the CCE remains practically unchanged up to doses of 1.7 MGy. The second group corresponds to the USCS “radiation hard” samples, for which it is observed a slight decrease in the charge collection with the dose in practically the whole dose interval, only attenuated for doses superiors to 1500 kGy. For both groups of Si sensors the collecting properties reduction is slightly lower than for GaAs:Cr detectors.

High-energy electron irradiation causes the permanent effect that considerable lattice damage in the form of vacancies, interstitials and complexes are produced and the defects can behave as charge traps. Such radiation-induced charge trapping has been studied by [17].

As known, the most important defect in GaAs is the EL2 complex, which is responsible for the poor charge transport properties of this material, as well as instability in the detector electric field. Therefore, the presence of EL2 centers defines the electric field distribution within the sensor and limits the sensitive volume for radiation detection. Its large electron trapping cross-section limits the electron lifetime to values on the order of $10^{-9}$ s, reducing the drift length of electrons and leading to poor CCE [9].

This fact allows us to assume that CCE deterioration with the dose increase up to 1550kGy in the studied GaAs:Cr detectors responds to the creation of new EL2 traps in the bulk material as result of the 22 MeV electron irradiation. Also, it is possible that the radiation may activate a number of previously compensated EL2 traps. This limits the average free path of carriers, leading to a deficit in charge detection.

Certainly, the whole analysis of the results above presented leads to the conclusion that with the irradiation the resistivity of the material decreases (the number of free carriers increases), while the charge collection is depressed (the lifetime of the carriers falls); and the balance between these two phenomena is that allows to observe the manifested effects.

## Conclusions

The study of I-V characteristic showed that the dark current increased in 3-7 times for GaAs:Cr detectors with the maximum doses. This is due to the introduction of displacement damages in the material, corresponding to primary and complex defects, leading to the formation of energetic states in the band gap and an easier electrons transition from the valence band to the conduction band, generating current in the depletion region. The presence of a slight asymmetry between the two branches of the I-V characteristic related to the asymmetric potential distribution within the device was observed. For Si sensors, the increase in the leakage current by almost 4 orders of magnitude confirms that in Si, the radiation effects are, as expected, stronger than in GaAs detectors.

The MIP spectra showed that pedestal width in GaAs:Cr remains practically unchanged in all irradiation process, while for Si, as the dark current increases, the pedestal considerably broadens and the measurement becomes difficult for doses higher 493 kGy. The overlapping between the signal and pedestal is the result of the depression of the sensor charge collection capacity with irradiation, produces the increase of traps concentration and the decrease of free carriers mobility and their lifetime, leading to a drop in drift length. The CCE measurements allowed to assume that CCE deterioration with the dose increase in the GaAs:Cr detectors responds to the creation of new EL2 traps in the bulk material as a result of electron irradiation. Also, it is possible that radiation may activate a number of previously compensated EL2 traps. This limits the average free path of carriers, leading to a deficit in charge detection. For Si sensors the collecting properties reduction was slightly lower than for GaAs:Cr ones.

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