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Radiation hardness of GaAs:Cr and Si sensors irradiated by 21 MeV electron beam

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Abstract: Silicon detectors generally satisfy the requirements of the modern physics experiments, however, experimental physics develops in the direction of increasing radiation loads, wich leads to increase in the requirements for radiation hardness of detectors. For other applications, such as registration of high energy X-rays, using detectors with high atomic number is important. The interest in using high resistive chromium-compensated GaAs (GaAs:Cr) in high-energy physics and other applied fields is steadily growing. This article presents a comparative study of the radiation resistance of sensors based on GaAs:Cr and Si, irradiated by 21 MeV electrons generated by the LINAC-200 accelerator. The target sensors were irradiated with the dose up to 1.5 MGy. I-V characteristics, resistivity, charge collection efficiency (CCE) and their dependences on the bias voltage and temperature were measured at different absorbed doses.

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

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Contents

1 Investigated GaAs:Cr and Si sensors

Semi-insulating GaAs:Cr sensors made of n-GaAs material using the precision chromium doping technique were produced at Tomsk State University [2, 3]. These sensors have resistivity $\sim 10^9\ \Omega\times$ cm, thickness up to 1 mm and they are suitable for detector construction. The impurity concentration in GaAs:Cr does not exceed 2×10^{17} cm^{-3}. The properties of this material determine the decisive participation of electrons in the charge collection due the low value of $(\mu \times \tau)_p$ product for holes. Thus charge collection efficiency (CCE) is close to 50% for unirradiated sensors at 100% electron collection [4].

As a reference for the radiation hardness study and for the sake of direct comparison with GaAs:Cr, two n-type silicon pad sensors were studied: n-type Si (type 1) made from FZ-Si-n (Wacker), with initial impurity concentration for carbon and oxygen less than 2×10^{16} cm^{-3}, orientation $< 111 >$, $2 < \rho < 4\,\mathrm{k}\Omega\times$ cm (RIMST, Zelenograd, Russia) and n-type Si (type2) made by Hamamatsu Photonics (HPK), orientation $< 100 >$, $1.25 < \rho < 3.25\,\mathrm{k}\Omega\times$ cm as test structures used during silicon strip sensor production for Fermi Gamma-ray Space Telescope [1, 5].

Some of the sensors were originally mounted on PCBs, and for others (kept as bare sensors) plastic holders were made. The sizes and examples of studied sensors are presented in figure 1.

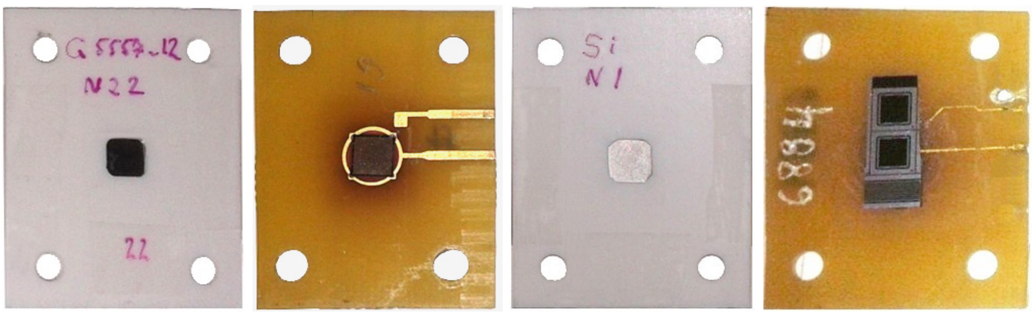

Figure 1. Examples of each studied sensor type. From left to right: (1) GaAs:Cr $5 \times 5 \times 0.3$ mm in plastic holder, (2) GaAs:Cr $4.5 \times 4.5 \times 0.3$ mm on PCB, (3) Si (type1) $5 \times 5 \times 0.25$ mm in plastic holder and (4) Si (type 2) $5 \times 5 \times 0.4$ mm on PCB.

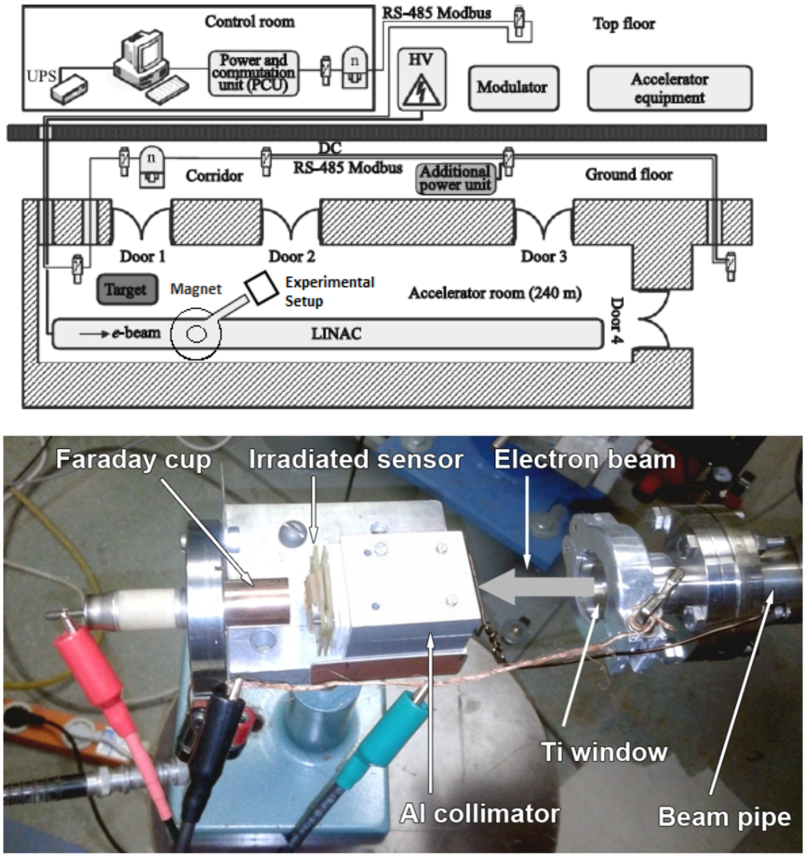

Figure 2. LINAC accelerator (above) with an irradiation setup. The electron beam from the accelerator is shaped by the collimator, passes through the sensor with radiochromic film and finally reaches the copper Faraday cup.

2 Irradiation setup and absorbed dose control

The electron irradiation was performed at the Joint Institute for Nuclear Research (Dubna, Russia) on the LINAC-200 accelerator using a 21 MeV beam channel. The electron beam was bunched with the bunch duration 2 µs, current up to 10 mA and the bunch frequency from 1 to 10 Hz. The irradiation setup is shown in figure 2.

Measured beam charge is converted to absorbed dose using simulation by GEANT 4. Uniformity of beam distribution was controlled by radiochromic film. Sensors were irradiated one by one or in pairs with steps from 50 to 200 kGy, up to absorbed dose of 0.5 MGy or up to 1.5 MGy. After each step, CCE and I-V characteristics were measured.

3 CCE and I-V measurements of irradiated sensors

Electrons from Sr^{90} source are well collimated and triggered by 2 scintillators. These counters allow to get the signal only from electrons passed throw the sensor with energy from 1 to 2.2 MeV and collect spectra close to MIP (minimum ionizing particle). The pedestal was collected separately,

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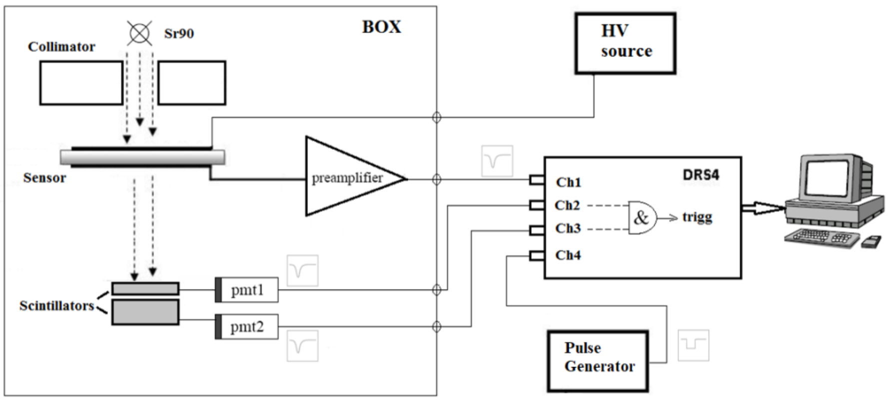

Figure 3. Setup for CCE measurement.

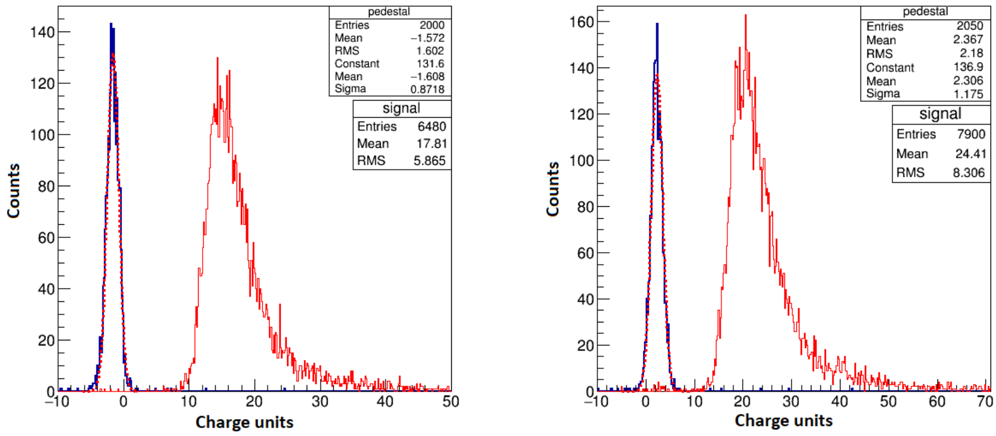

Figure 4. MIP spectra of Si N3(250 µm, left) and GaAs:Cr N5(300 µm, right) sensors. The pedestal distribution is fit by Gaussian (dash). Measured at room temperature.

trigger started from the generator under the same conditions. The width of pedestal determines the resolution of the sensor and amplifier setup.

The setup for measuring the spectra is shown in figure 3. The setup is contained in a shielded and grounded light-tight metal box. The good collimation of the Sr^{90} source and trigger scintillator setup allows to suppress pedestal counts almost completely. As a result, it is possible to measure very low CCE values (about 1%). The sensor is connected to Amptek A250 charge sensitive amplifier. The signal from the amplifier is finally digitized by DRS4 Evaluation Board [6]. The data is read out via USB to a computer for processing. The amplifier integration time is 50 ns and intrinsic noise of the measuring system (FWHM) is about 2.5 ke^- with the trigger activated and about 2 ke^- with self-trigger. A programmable voltage source coupled to the remotely controlled ammeter is used for the measurement of the I-V characteristics. This setup allows to measure sensor parameters both at room temperature and preset low temperature. The spectra of Si and GaAs:Cr sensors before irradiation are presented in figure 4.

We can observe that with an increase in the absorbed dose, the signal peak gradually shifts toward the pedestal and their distributions begin to overlap. At 1.5 MGy the maximum overlap is observed, although the individual signal and pedestal peaks are still distinguishable (figure 5).

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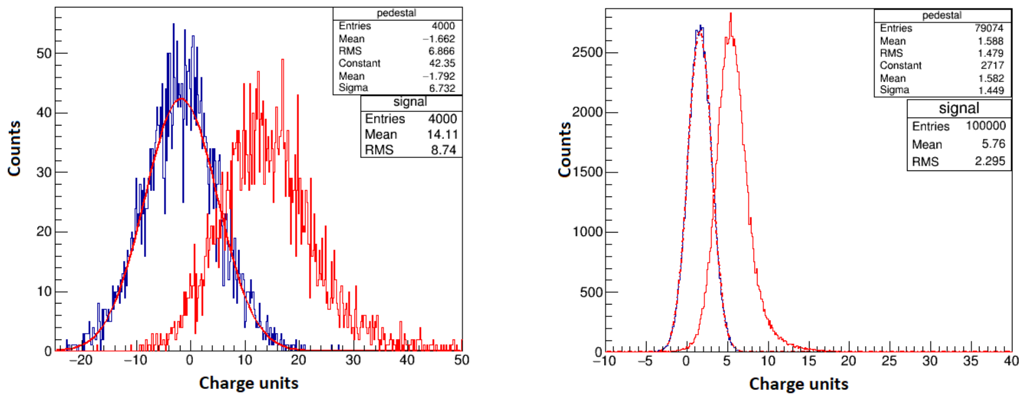

Figure 5. MIP spectra of Si N3 after 1.3 MGy (left) and GaAs:Cr N6 after 1.4 MGy ($U_{\text{bias}} = -500$ V, right). The pedestal distribution is fit by Gaussian (dash). Measured at room temperature.

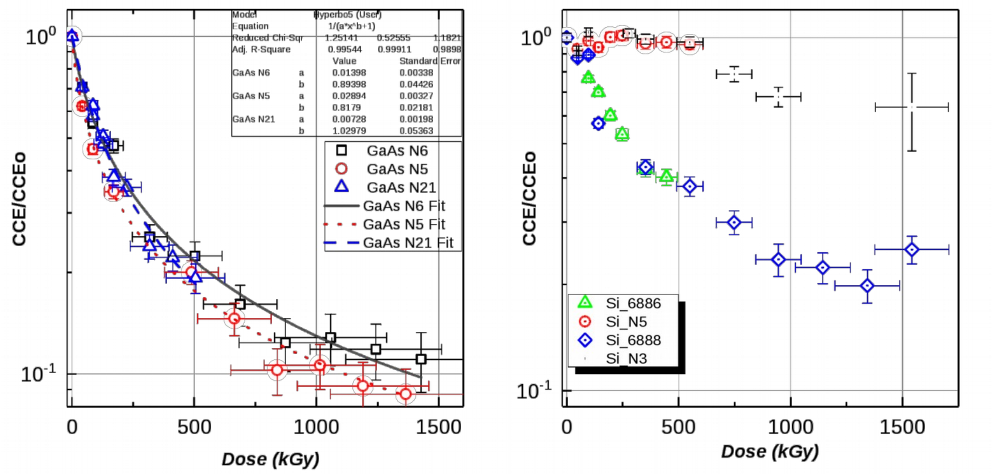

Figure 6. Dependence of CCE on absorbed dose for GaAs:Cr sensors, $U_{\text{bias}} = -200$ V (left) and Si N3, N5 — type1, 6886,6888 — type2, $U_{\text{bias}} = 100$ V (right). Measured at room temperature.

The measurement of pedestal width in a GaAs:Cr shows that it remains almost unchanged during irradiation process. For Si sensors the pedestal considerably broadens due to increase of dark current and the measurement becomes difficult after absorbed doses more than 0.5 MGy.

For both groups of Si sensors the CCE reduction is smaller than for GaAs:Cr detectors. In GaAs:Cr the CCE median falls monotonously and abruptly to the dose of 1 MGy, but then it decreases slowly to the maximum irradiation dose (figure 6).

For silicon sensors, an increase in the leakage current at room temperature reaches almost four orders of magnitude for the maximum absorbed dose of 1.5 MGy. For GaAs:Cr not very strong increase in dark current is observed (figure 7). This explains the significant expansion of the pedestal and, as a consequence, the deterioration of resolution for Si sensors. Cooling of the Si sensor significantly improves the resolution.

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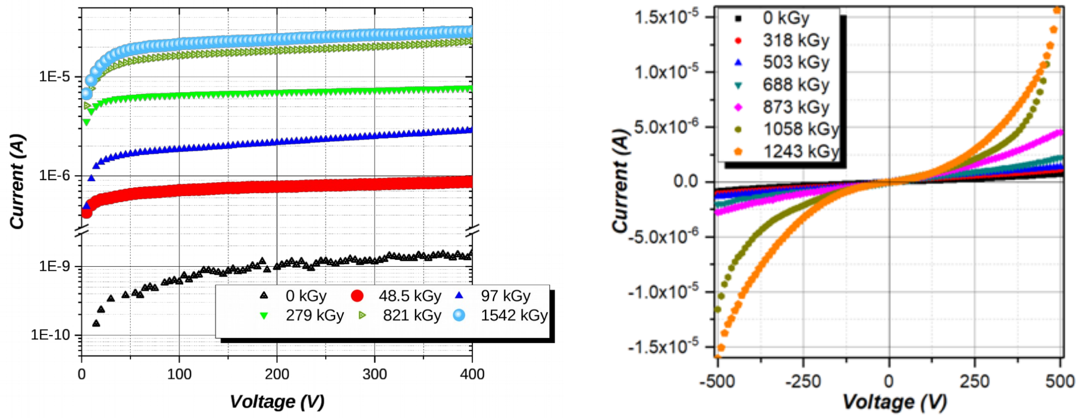

Figure 7. Dose dependence of I-V characteristics for Si N 3 (left) and GaAs:Cr N6 (right). Measured at room temperature.

4 Summary

Irradiation of the high-resistive and barrier GaAs:Cr sensors and the normal and two n-type Si sensors by 21 MeV electron beam of was performed at the LINAC accelerator. Radiation damage in the sensors after dose of 1.5 MGy leads to different effects: in GaAs:Cr sensors signal CCE drops to ~ 10% of initial, when in Si it is above 80%. The dark current grows 3–7 times in GaAs:Cr and 4 orders of magnitude in Si. For Si full depletion voltage is rising with irradiation, more for thick HPK sensors. For GaAs:Cr, the mean free path of electrons decreases with irradiation, which leads to a decrease in CCE; an increase in the bias voltage can slightly compensate for this effect. At room temperature, the signal-to-noise ratio of irradiated GaAs:Cr sensors is higher than that of Si sensors after a dose of 1.5 MGy, and vice versa when cooled to negative temperatures.

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