Investigation of the radiation hardness of GaAs:Cr semiconductor detectors irradiated with fast neutrons at the reactor IBR-2

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Abstract. Investigation of the semiconductor detectors properties under neutron irradiation is very important for their practical application. High-resistivity gallium arsenide detectors (GaAs:Cr) were irradiated with various fast neutron fluences in range from $3.9 \times 10^{11}$ cm$^{-2}$ to $3.7 \times 10^{16}$ cm$^{-2}$ at the IBR-2 reactor, FLNP, JINR. The neutron fluence was measured by placing silicon planar detectors at the measured points and measuring the 1 MeV (Si) equivalent fast neutron fluence. The charge collection efficiency and the current-voltage characteristics of irradiated detectors were measured, and their degradation after neutron irradiation was compared with the results obtained by irradiation with 21 MeV electrons.

1. Introduction
Gallium arsenide (GaAs) has attracted a lot of interest in the recent years because of its suitability for applications in sensors of ionizing radiation for high-energy physics experiments, medical imaging or space applications. This was mainly due to its electrical characteristics (large band-gap, high resistivity, good stopping power and high carrier mobility). This material offers high charge carriers mobility, good signal-to-noise ratio and a good detection efficiency for minimum ionizing particles (MIP) [1, 2, 3]. The possibility of using GaAs:Cr sensors at future high-energy colliders such as ILC (International Linear Collider) and CLIC (Compact Linear Collider) is being investigated. Its advantages are relatively low cost advanced production technology and its radiation hardness.

Few studies of radiation hardness of GaAs:Cr detectors in comparison with Si detector were done [2, 3]. Studying the properties of these materials under high neutron fluence is needed to obtain more information on their behavior under high neutron fluence. In this paper, we report studies of charge collection efficiency and I-V of GaAs:Cr sensors under neutron irradiation and try to convert neutron fluence to electron fluence. As is well known, it is possible to convert neutron fluence to electron fluence as a function of radiation damage using non-ionizing energy losses (NIEL). This is especially clear for Si and pure GaAs. For pure GaAs this coefficient is about 5.5, but in our case we have chromium compensated GaAs:Cr, so this coefficient probably will be slightly different.

2. Experimental
In this work, we studied six GaAs:Cr sensors made of n-type GaAs material using the precision chromium doping technique. The property of this material relies mainly on electrons participating in the charge collection due the low value of mobility lifetime product for holes ($\mu \times \tau_p$). Thus CCE is close to 50% for unirradiated sensors at 100% electron collection [3]. These sensors were produced at...
Tomsk State University. As a monitoring device for neutron fluence calculations we used silicon n-type pad made from FZ-Si-n (Wacker), orientation <111>, 2 < ρ < 4 kΩ×cm (RIMST, Zelenograd, Russia) [4].

The method for measuring the fast neutron fluence (1 MeV equivalent in silicon) is based on the linear dependence of the reverse bulk detector current increment on the neutron fluence. The reverse bulk current increment induced by the irradiation of a silicon detector has linear dependence from the neutron fluence [4].

Thus, having measured the current increment after irradiation and knowing the detector parameters (area and thickness) for silicon, one may calculate the fast neutron fluence.

The concept of this method is scaling the NIEL normalized to the equivalent damage in silicon caused by 1 MeV neutron. This provides an opportunity to compare radiation damage produced by different particles such as neutrons, electrons, γ-quanta etc. The fluence of a given radiation type is related to the 1 MeV neutron fluence equivalent in silicon damage can be calculated as follows:

\[ \Phi_{eq}(1 \text{ MeV/Si}) = k \times \Phi \]  

where \( k \) is the hardness coefficient for the given radiation. This coefficient is larger (lower) than unity for radiation that is harder (less hard) than 1 MeV neutrons [4].

An alternative method that was used in order to estimate the neutron fluence was the measurement by neutron activation analysis using a nickel satellite (NAA) [5].

The neutron fluence was calculated for 6 measured points by two methods (1 MeV equivalent by Si monitor and NAA) and is presented in the table 1.

### Table 1: Irradiation of six sets of samples with fast neutrons on the channel No. 3 IBR-2 reactor. Flux density measured by the NAA method (En> 1 MeV) and by using of Si monitors (1 MeV equivalent).

| Sample № | n-flux (n×cm²×s⁻¹) | n-fluence by NAA method, (n×cm²) | n-fluence by Si monitor, (n×cm²) |
|-----------|-----------------|-------------------------------|-------------------------------|
| №1_Nov’16 | 6.3×10⁵         | 5.5×10¹¹                      | 3.91×10¹¹                      |
| №2_Nov’16 | 2.3×10⁶         | 2.1×10¹²                      | 1.83×10¹²                      |
| №3_Nov’16 | 5.2×10⁷         | 4.5×10¹³                      | 7.76×10¹³                      |
| №4_Nov’16 | 5×10⁶           | 4.7×10¹²                      | 7.22×10¹²                      |
| №5_Nov’16 | 1.1×10¹⁰        | 1.1×10¹⁶                     | 1.32×10¹⁵                      |
| №6_Nov’16 | -               | -                             | 3.72×10¹⁶                      |

3. Results and discussion

3.1. I-V measurements

Figure 1 presents the I-V characteristics for five Si sensors and figure 2 presents the I-V characteristics for two GaAs:Cr sensors, both of which were taken before irradiation and after irradiation by different neutron fluences. As can be seen from the figure 2 (a) at neutron fluence 3.9×10¹¹ n/cm² the dark current increased slightly, but figure 2 (b) with fluence 1.3×10¹⁵ n/cm² we can see the dark current increased more than one order of magnitude.
3.2. Charge collection efficiency measurements

Figure 3 shows the MIP spectra of GaAs:Cr sensors before irradiation at room temperature. The pedestal is described by a Gaussian distribution and its width is determined by the readout system resolution. It can be seen for detectors of both types that the pedestal and the MIP signal are well separated. The readout system was calibrated by charge injection and the resulting calibration value was calculated to be 1.05 ke\(^{-}\) per ADC channel.

The experimental dependence of CCE on absorbed dose for GaAs:Cr sensors under irradiation can be approximated by the next formula:

\[
CCE = \frac{1}{a \times D^{b+1}}
\]  (2)

where \(D\) is the dose, \(a\) and \(b\) are normalization factors, the \(b\) factor is related to CCE [2].
Figure 3. MIP spectra for GaAs:Cr irradiated by neutron with fluence up to $3.7 \times 10^{16}$ n/cm$^2$ at the temperature 20°C, $U_{\text{bias}}$ ~200V.

Figure 4 shows the comparison of CCE between electron and neutron irradiation at different fluences.

![Graph](a)

![Graph](b)

**Figure 4.** Dependence of CCE on fluence for GaAs:Cr sensors irradiated by neutrons (a) and GaAs N5 under 21 MeV electron irradiation (b) at the temperature 20°C, $U_{\text{bias}}$ ~200V.

The neutron fluence was measured by the method 1 MeV neutrons equivalent in silicon damage. Both dependences of CCE on the neutron fluence and the electron fluence were fitted by the formula 2.
Figure: 5. Comparison of CCE dependences for GaAs:Cr sensors irradiated with 21 MeV electrons and fast neutrons. For samples irradiated with neutrons the flux is reduced to the equivalent electrons flux by formula 1 using the hardness coefficient $k=3.5$.

Figure 5 presents GaAs:Cr N23 and N5 sensors irradiated by 20.8 MeV electrons with different fluences at the accelerator LINAC-200 [2] and six GaAs:Cr sensors (№ 1, 7, 13, 14, 16, 17) irradiated by neutrons with different fluences. As can be seen from the figure 5 there is agreement between neutron and electron irradiation using the hardness coefficient $k=3.5$ to convert the neutron fluence to electron fluence.

4. Conclusion
Irradiation of 6 sets of silicon and GaAs:Cr sensors with neutrons was carried out at the reactor IBR-2, FLNP, JINR and results were compared with irradiation by 21 MeV electrons. As it mentioned before, CCE is dependent on radiation damage. After irradiation with a fluence of $8 \times 10^{13}$ n/cm$^2$, the charge collection dropped by about a third. After fluence of $\sim 10^{15}$, about 2% of the initial CCE remained, this means that the sensor has almost completely lost its detecting properties.

It was shown that CCE drop under neutron irradiation can be described by formula 2. Comparing the behaviour of CCE in GaAs:Cr sensors after irradiation by fast neutrons and 21 MeV electrons, the hardness coefficient was calculated. This empirically calculated coefficient $k = 3.5$ can be used for GaAs:Cr sensors to convert between 1 MeV neutron and 21 MeV electron fluences.

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