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

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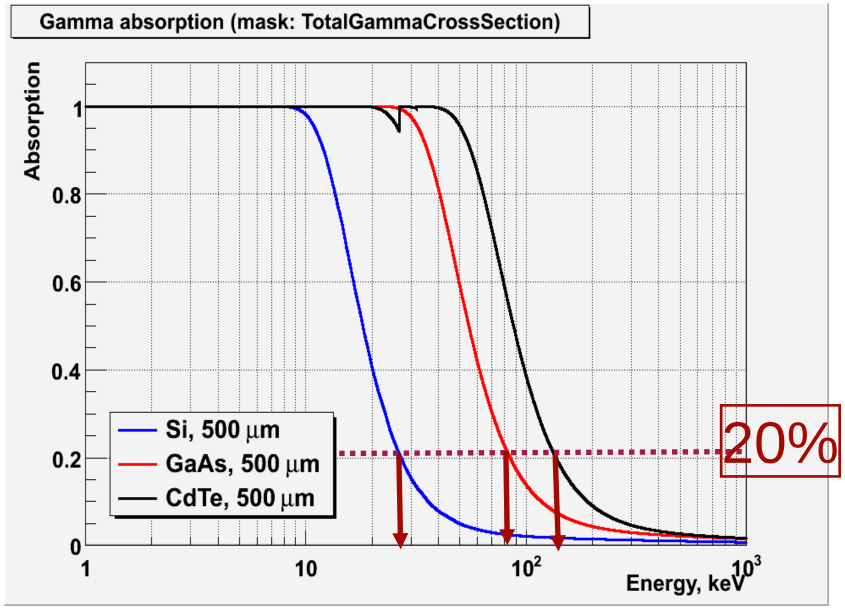
GaAs:Cr as a material for a new generation of detectors

- GaAs is a well-known semiconductor, second widespread after silicon
- Limited use in particle detection because of low resistivity, low CCE and high intrinsic noise
- New modification of GaAs, compensated by Cr (GaAs:Cr), has been invented in Tomsk State University in 2000-2005
  - suitable for detector construction
  - radiation hard
  - Z(GaAs)~ 32 vs Z(Si)=14 → higher photon detection efficie

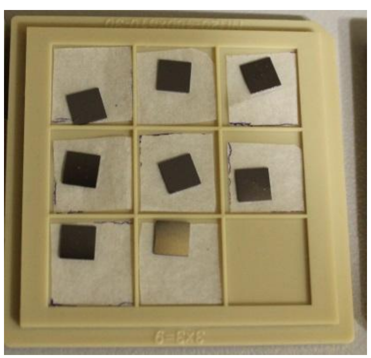


Material	main charge carriers	electron drift length	bulk resistivity	active sensor thickness	intrinsic noise
LEC SI-GaAs	holes	0.3-0.5 mm	$<2{*}10^8$ Ω*cm	<300 μm	high
GaAs:Cr	electrons	0.7 – 2 mm	$\sim 10^9$ Ω*cm	up to 1 mm	low

GaAs:Cr and Si sensors

N	Type	Producer	Holder	Size, x y z, mm^3	Sensitive area, mm^2	Donor concentration, cm^{-3}	CCE, %
1	GaAs:Cr (1)	TSU (Tomsk, Russia)	Plastic	5x5x0.3	5x5	~ 10^{17}	~50
2	Si $(p^{+}nn^{+})$ n-type	RIMST (Zelenograd, Russia)	Plastic	5x5x0.25	13	$(0.8\text{-}1.6)\times10^{11}$	100

GaAs:Cr (№1,7,13,14,16,17)

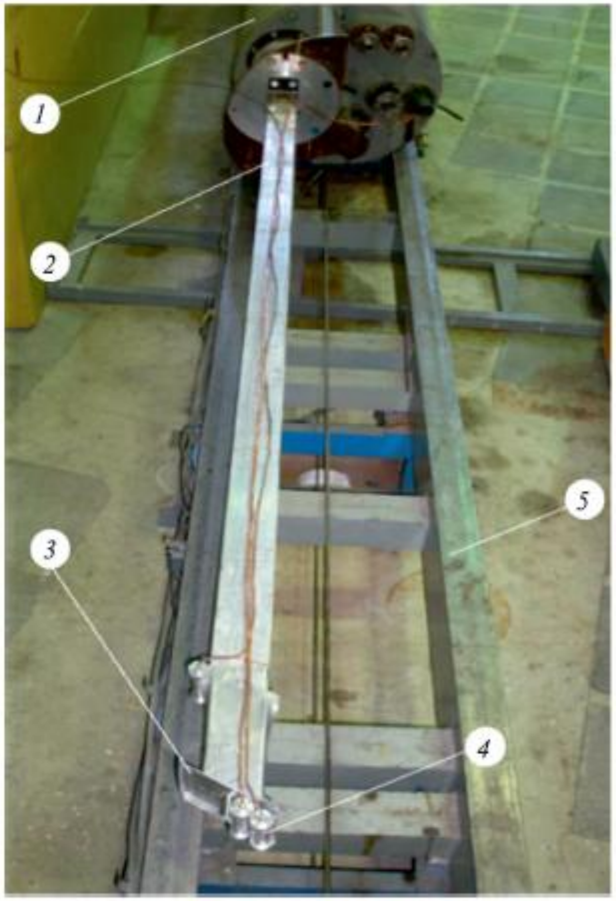


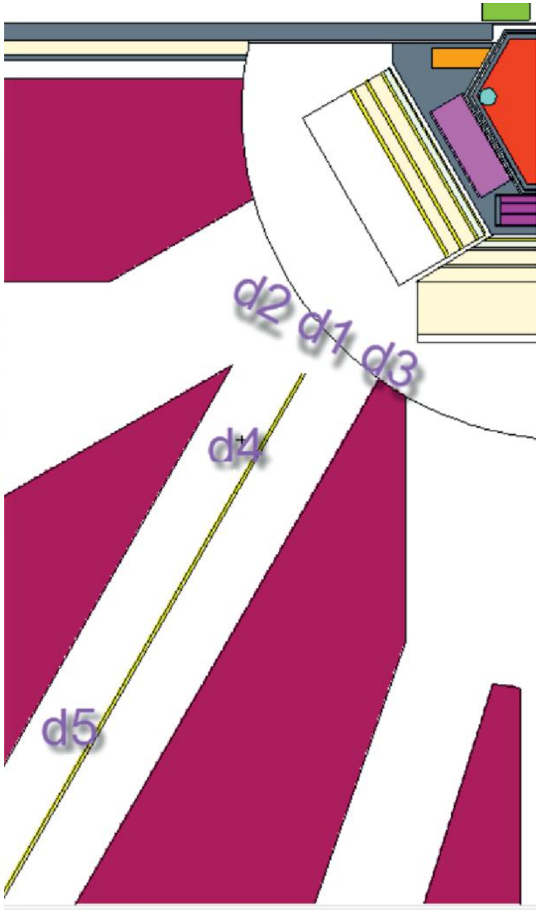
1

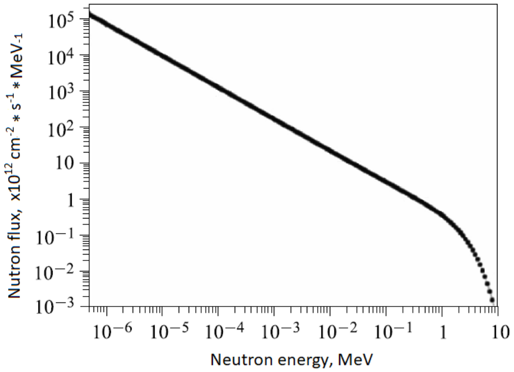
Si (№1,2,3,4,5,6) Nov’16

2

Irradiation setup of the IBR-2 reactor.







Neutron spectra in channel №3, measured in d1-d3.

Irradiation setup on channel No. 3 of the IBR-2, view from the side of biological protection:
1 - massive part of the irradiation facility; 2 - transport profile;
3 - metal container for fixing samples; 4 - samples; 5 - rail track;

1 MeV NIEL equivalent fluence measurement.

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:

$$\Delta I = \alpha_I \times \Phi_{eq} \times V$$

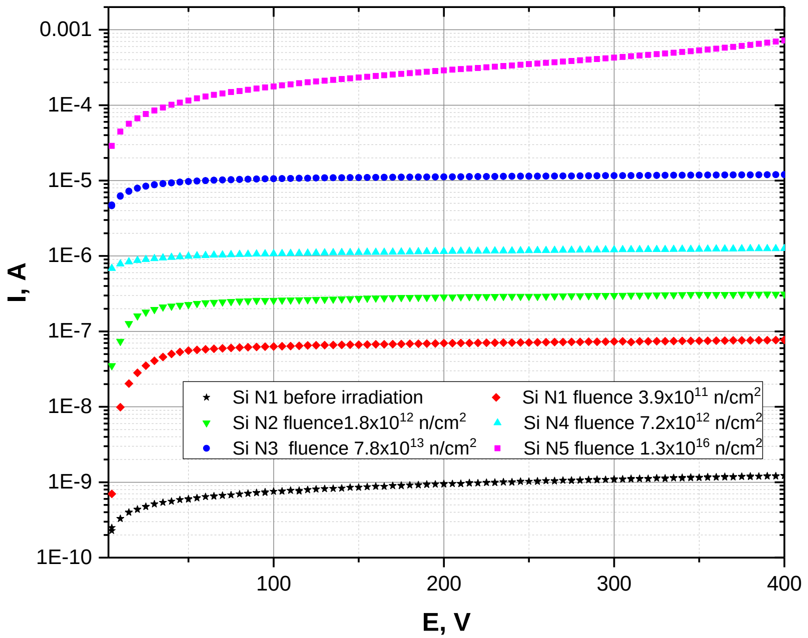
ΔI = $I - I_0$ is the measured reverse dark detector current increment after irradiation;
Φ_{eq} (cm^{-2}) - is the 1-MeV fast neutron fluence equivalent;
α_I = $(5 \pm 0.5) \times 10^{-17}$ (A/cm) - is the current damage constant for silicon and fast neutrons with an energy of 1 MeV normalized to +20°C without regard to self annealing;
V - is the sensitive detector volume under the full depletion voltage,

The concept of this method is scaling of nonionizing energy losses (NIEL) normalized to equivalent damage in silicon produced by neutrons with an energy of 1 MeV. This provided an opportunity to compare radiation damage produced by various types of radiation with different energy spectra. The fluence of a given radiation type is related to the 1-MeV neutron fluence equivalent in silicon damage as follows:

$$\Phi_{eq}\,(1\ \text{МэВ/Si}) = k \times \Phi$$

***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.

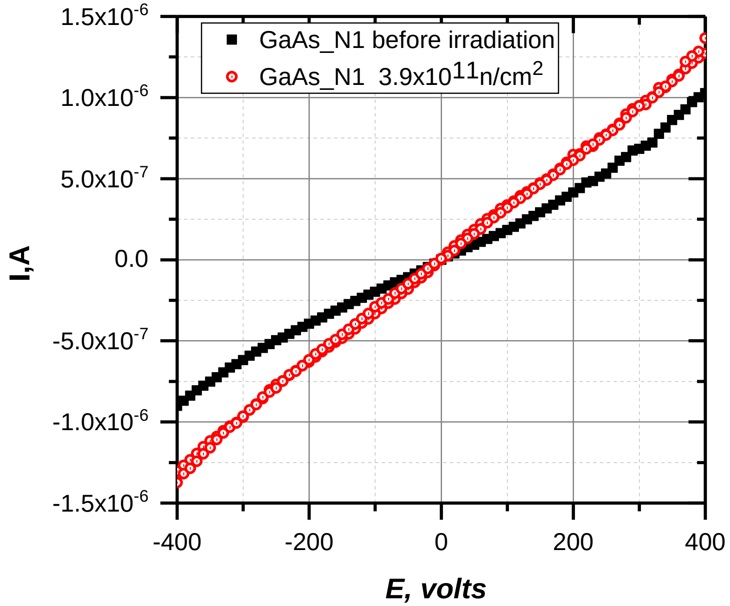
Irradiation of Si and GaAs:Cr sensors at the IBR-2 reactor.

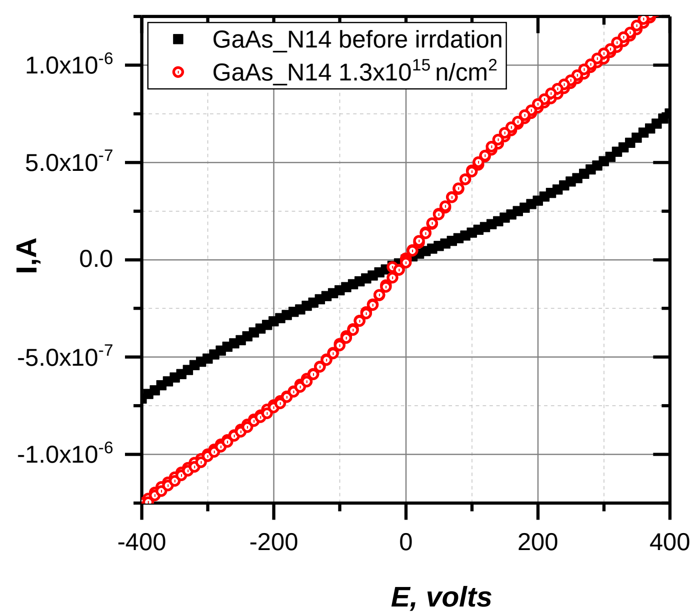


Sample №	n-fluence, n×cm^{-2} by NAA method	n-fluence, n×cm^{-2} by Si monitor
№1	$5{,}5\cdot10^{11}$	$3{,}91\times10^{11}$
№2	$2\cdot10^{12}$	$1{,}83\times10^{12}$
№3	$4{,}5\cdot10^{13}$	$7{,}76\times10^{13}$
№4	$4{,}7\cdot10^{12}$	$7{,}22\times10^{12}$
№5	$1{,}1\cdot10^{16}$	$1{,}32\times10^{15}$
№6	-	$3{,}72\times10^{16}$

I-V characteristics for Si detector before and after neutron irradiation at temperature 20ºC.
Irradiation of six sets of samples with fast neutrons on the channel No. 3 IBR-2 reactor.
Flux density measured by neutron activation analysis using a nickel satellite (NAA method) and by using of Si monitors (1 MeV (Si) equivalent).

GaAs:Cr I-V after irradiation.

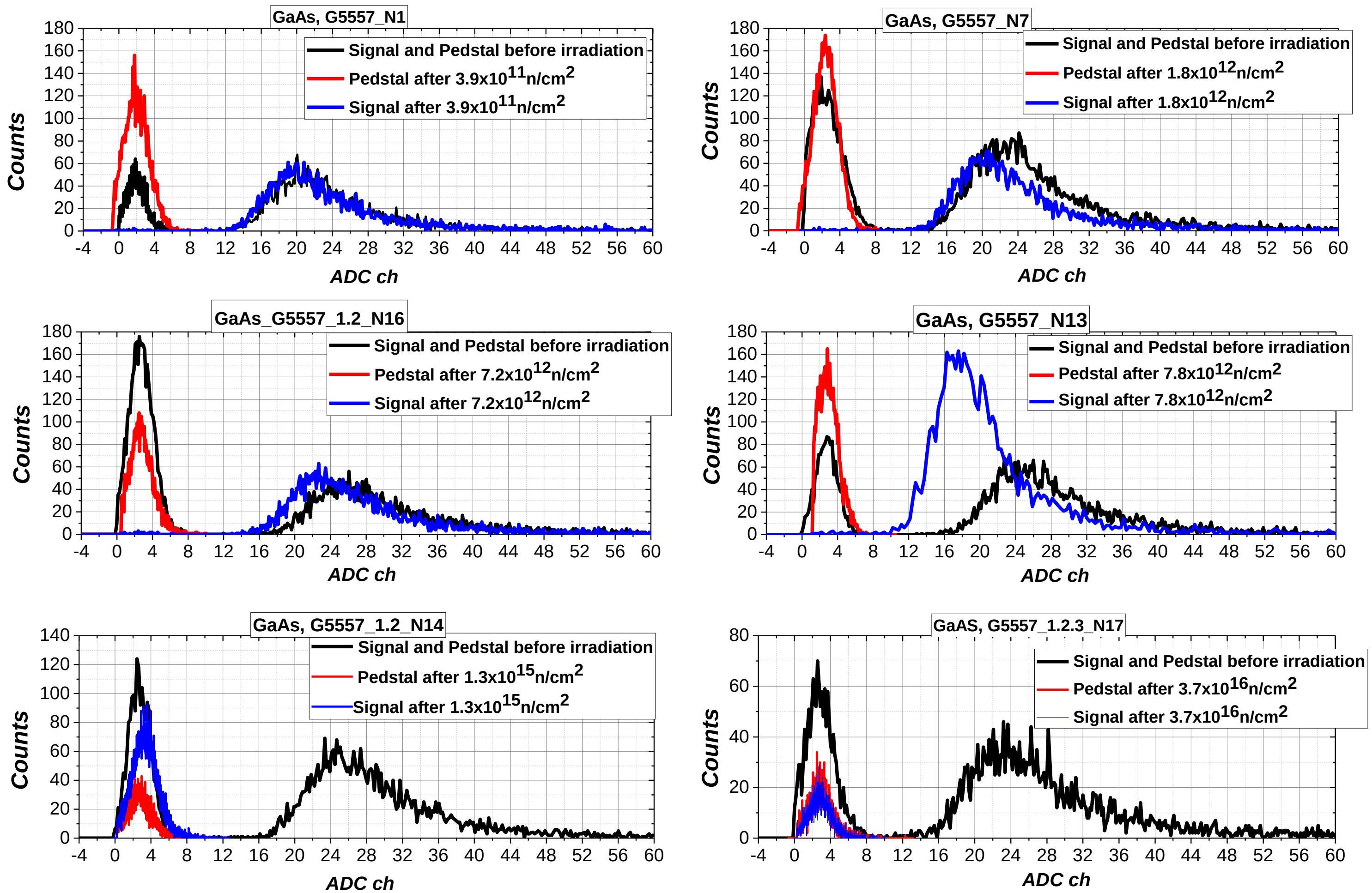




I-V characteristics for GaAs:Cr N1 (right) and number 14 before and after irradiation at temperature 20ºC.

After neutron fluence 4.7×10^{11} n/cm^2 the dark current increases slightly, but with fluence 6.1×10^{15} n/cm^2 we can see the dark current increased more than one order of magnitude .

GaAs:Cr CCE after irradiation.



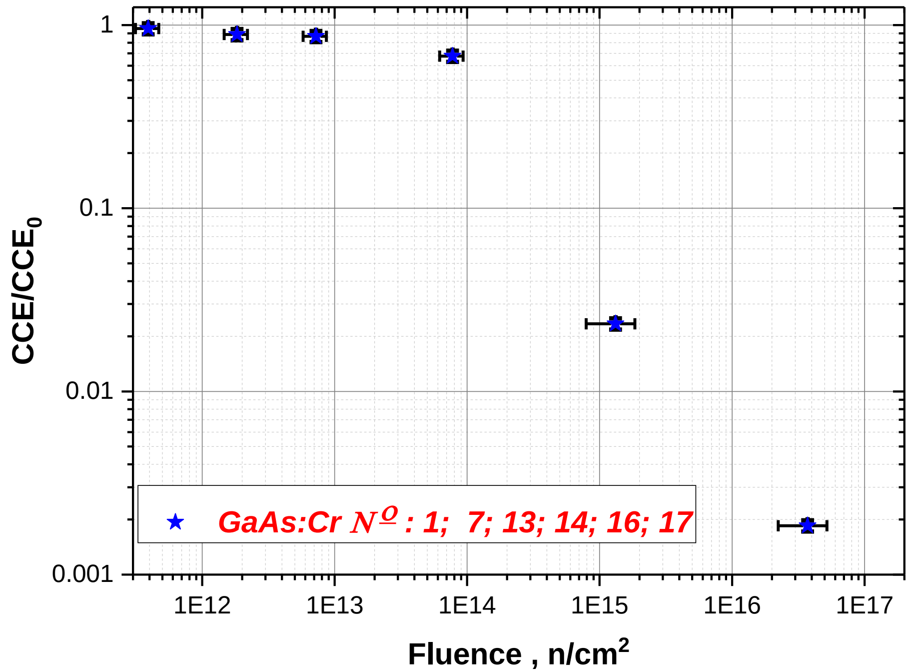
MIP spectra for GaAs:Cr , irradiated by neutron with fluence up to 3.7×10^{16} n/cm^2, U_{bias}=-200V, T = 20^{o}C.

With increase the neutron fluence, the signal peak gradually shifts to the pedestal ,

at fluence $3.9\text{x}10^{11}$ n/cm^2, the signal practically at the same position;

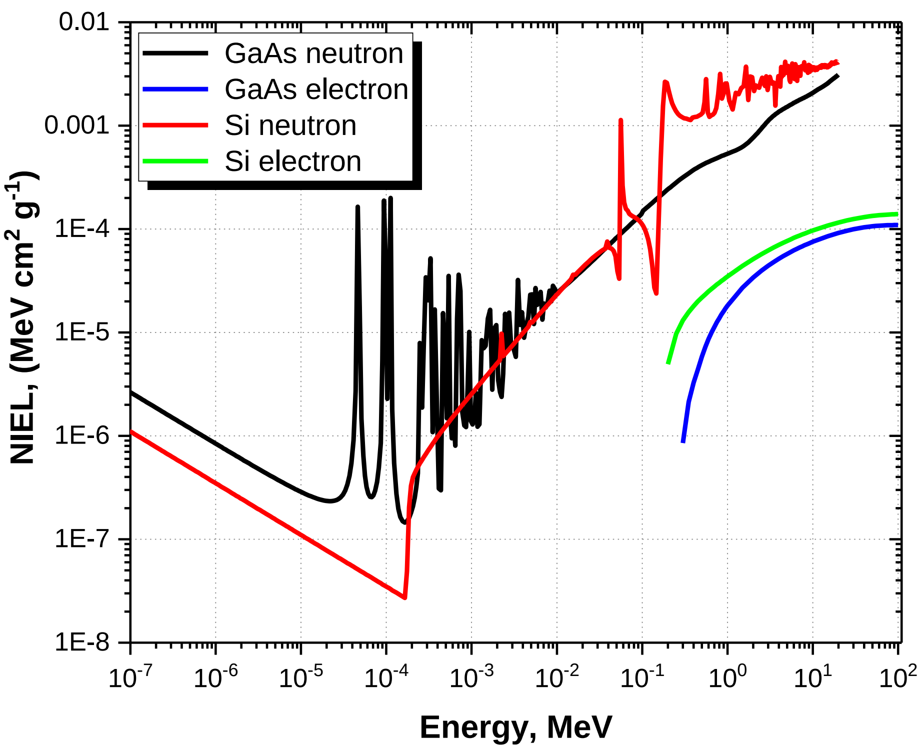
at high neutron fluence $3.7\text{x}10^{16}$ n/cm^2 the signal and pedestal at the same position, this means that the sensor has completely lost its detecting properties;

GaAs:Cr after irradiation. CCE - Fluence.



Dependence of CCE on neutron fluence, U_{bias}=-200V, T = 20^{o}C.

NIEL equivalent for Si and GaAs.



Displacement Damage NIEL Doses (MeV cm^2/g) for Si and GaAs subjected to irradiation with neutrons and electrons.
http://www.sr-niel.org/
Data taken from MS-02 Milano Bicocca group, INFN, Italy

As well known by NIEL it is possible to convert neutron fluence to electron fluence as a function of radiation damage it is very clear especially for Si and pure GaAs.
To convert between 1 MeV neutrons and 21 MeV electrons by NIEL, the coefficient for pure GaAs:

$NIEL_{(1\ MeV\ \ n)}/NIEL_{(21\ MeV\ e)}$ ~ **5.5**

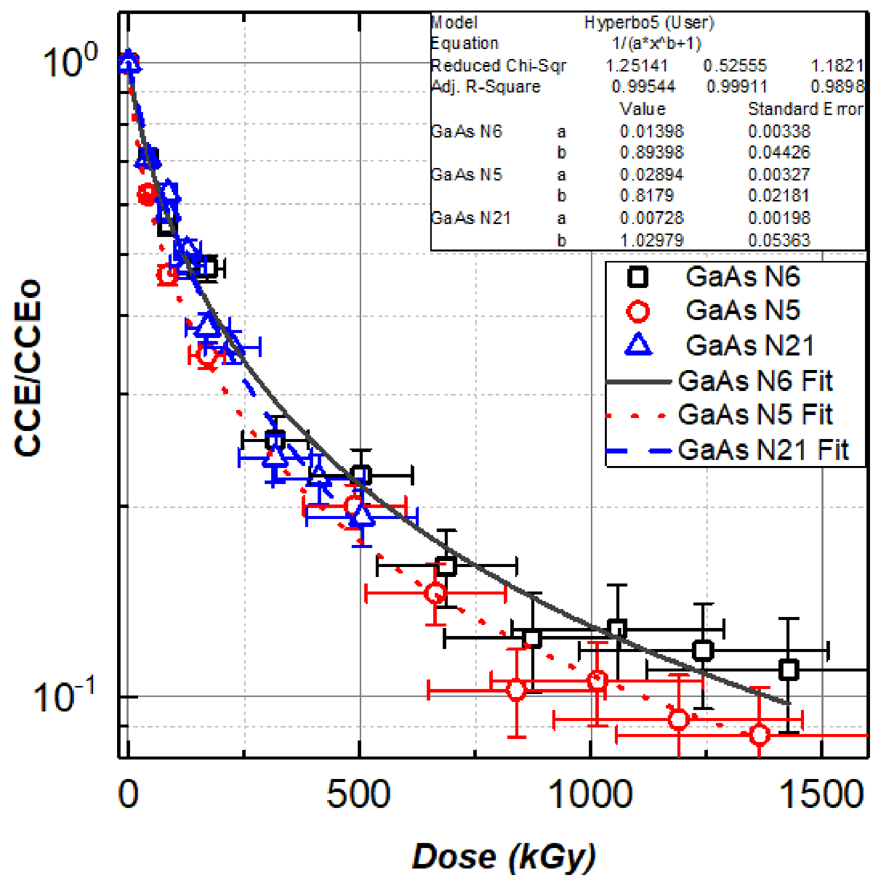
But the next questions arise:

Can this calculated by NIEL ratio be used for GaAs:Cr ?

Can this ratio be used to estimate the charge collection drop in GaAs:Cr sensors after neutrons or electrons irradiation?

GaAs:Cr after 21 MeV electron irradiation;

Radiation hardness of GaAs: Cr and Si sensors irradiated by electron beam
U. Kruchonak et al.,
NIM, A 975 (2020) 164204, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2020.164204.

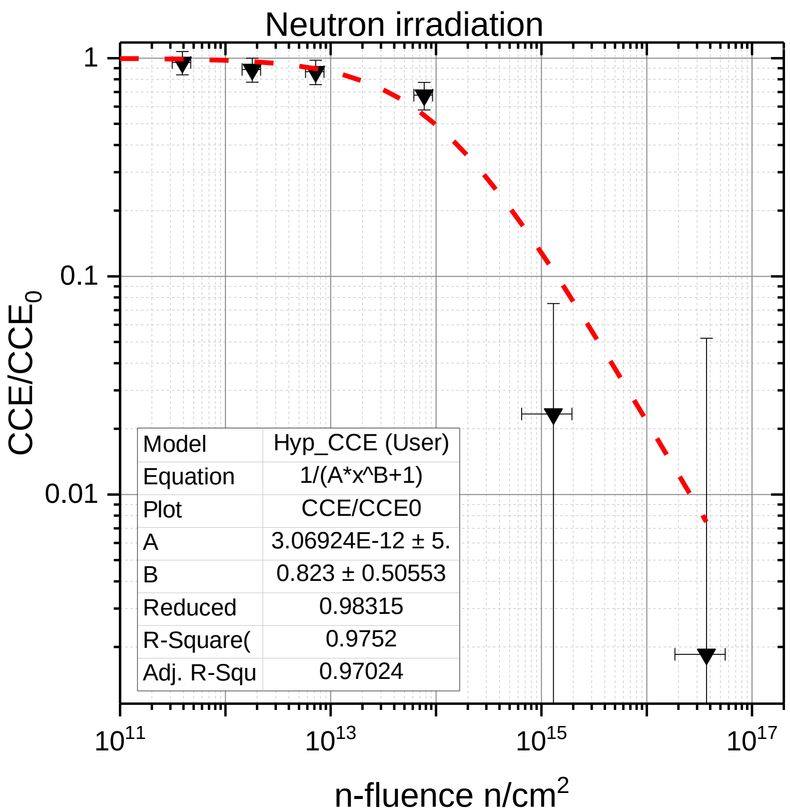


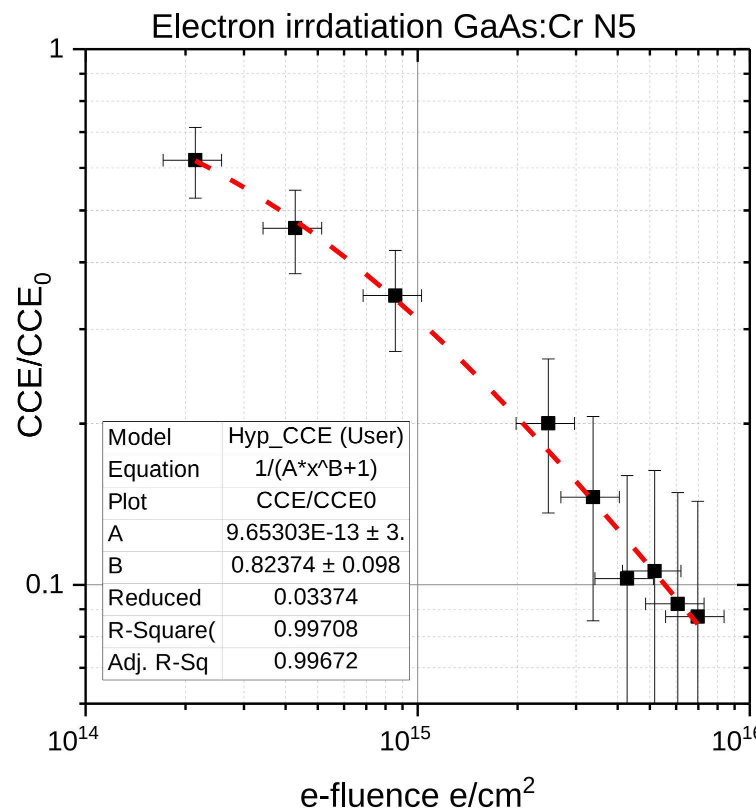
The experimental dependence of CCE on absorbed dose for GaAs:Cr sensors irradiated with 21 MeV electrons can be approximated by the next formula:

$$CCE = \frac{1}{a \times D^b + 1}$$

where **D** - is the dose (kGy);
a and **b** - are normalization factors.

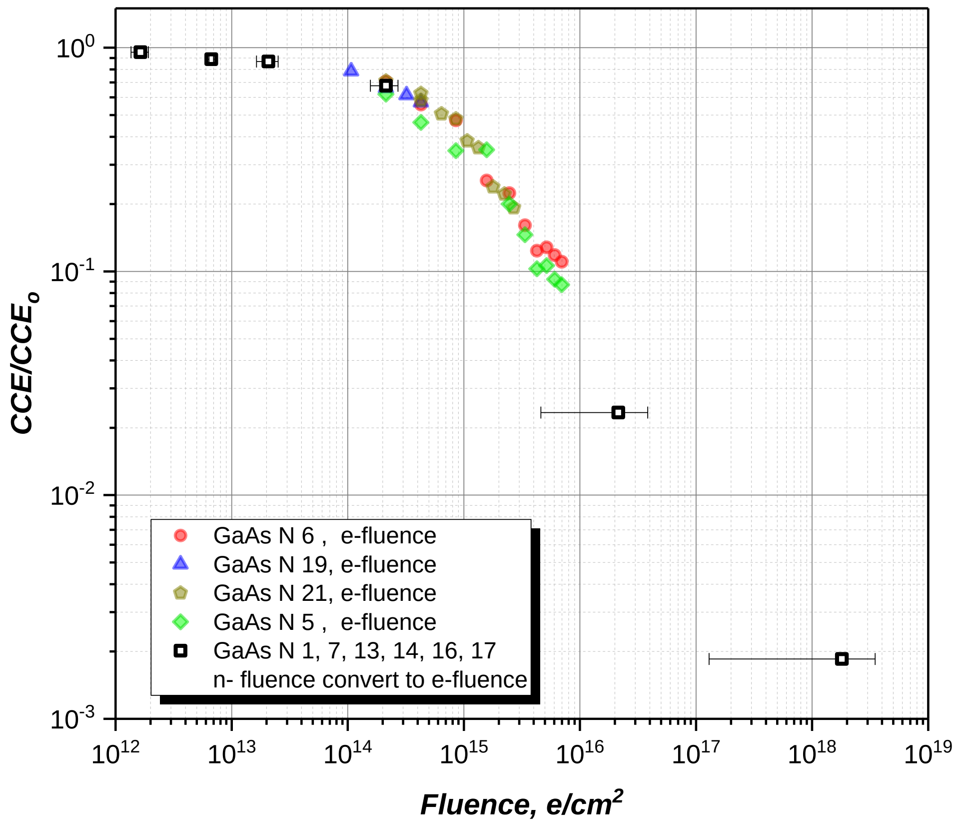
Comparison of neutron and electron irradiation for GaAs:Cr;





Dependence of CCE on fluence for GaAs:Cr sensors irradiated by neutrons (left) and GaAs N5 irradiated by 20.8 MeV electrons (right);
Measurement U_{bias}=-200V, T = 20°C.

Conversion between neutron and electron irradiation for GaAs:Cr;



$$\Phi_e = k \times \Phi_n$$

hardness coefficient:
k = 3.5

Comparison of CCE dependences for GaAs: Cr sensors irradiated with 21MeV electrons and with fast neutrons. For samples irradiated with neutrons the flux is reduced to the equivalent electrons flux by formula using the hardness coefficient k=3.5 .

Conclusions

- Irradiation of 6 sets of silicon and GaAs:Cr sensors with neutrons was carried out at the IBR-2 reactor in JINR. I-V and CCE characteristics of irradiated sensors were measured.

- Results were compared with irradiation of GaAs:Cr sensors with 21 MeV electrons (published in NIM, A 975 (2020) 164204, ISSN 0168-9002).

- The dependence of CCE on the fluence can be approximated by the same formula for both electrons and fast neutrons, which makes it possible to compare the damage in GaAs:Cr sensors irradiated with fast neutrons and electrons.

- Using GaAs:Cr sensors an empirically calculated hardness coefficient **k = 3.5** was obtained. It can be used for damage estimation of GaAs:Cr sensors under irradiation with 21 MeV electrons and fast neutrons.

Thank you
for attention !