Overview about radiation hardness materials

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2022

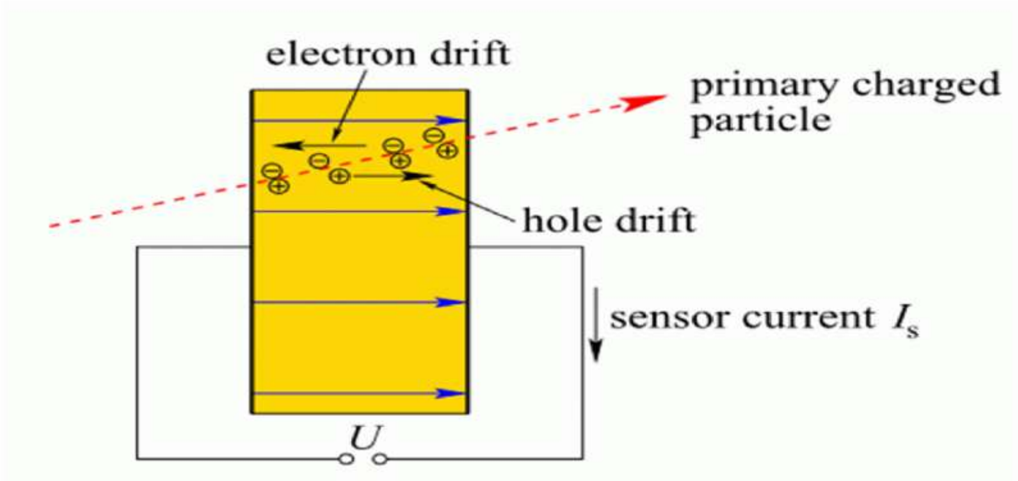
- **Semiconductor detectors are widely used in nuclear physics and high energy physics experiments.**

- **the application of semiconductor detectors could be limited by their ultimate radiation resistance.**

- **the increase of radiation defects concentration leads to significant degradation of the working parameters of semiconductor detectors.**

- **The investigation of radiation defects properties in order to enhance the radiation hardness of semiconductor detectors is an important task for successful implementation of a number of nuclear physics experiments**

Solid state detectors with direct electrical signal readout (not scintillators, gas or liquid detectors)



Detector functions
As a solid state
Ionisation chamber

Charge carriers are
Generated by a particle
And then drift in a E field
Signal is readout by an
amplifier

Some information about GaAs, Si, Diamond and Sapphire

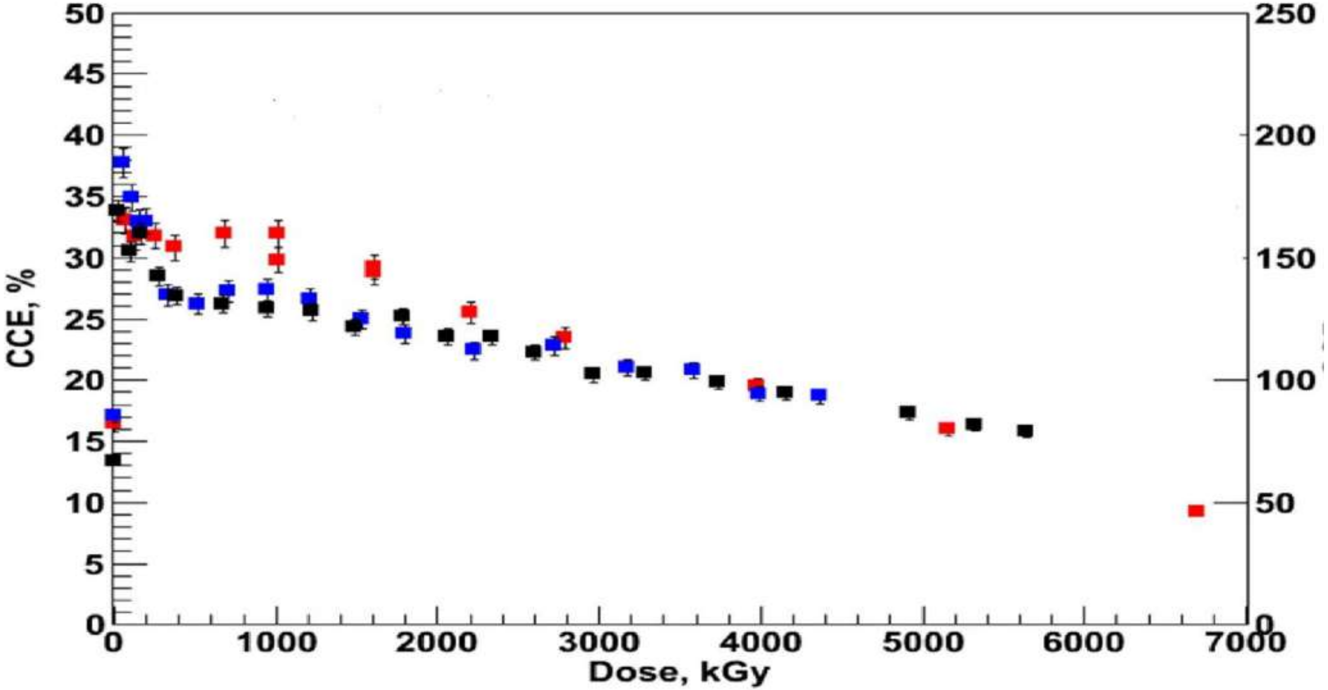
	GaAs	Si	Diamond	Sapphire
Density	5.32 g/cm^3	2.33	3.51	3.98
• Pair creation E	4.3 eV/pair	3.6	13	24.6
• Band gap	1.42 eV	1.14	5.47	9.9
• Electron mobility	8500 cm^2/Vs	1350	2200	>600
Hole mobility	400 cm^2/Vs	450	1600	-
• Dielectric const.	12.85	11.9	5.7	9.3-11.5
• Radiation length	2.3 cm	9.4	18.8	
Ave. E_{dep}/100 μm (by 10 MeV e^-)	69.7 keV	53.3	34.3	
MPV pairs/100 μm	15000	7200	3600	2200
Structure	p-n or insul.	p-n	insul.	insul.

Diamond

- Diamond can operated up to 10 MGy at 10 MeV electrons.

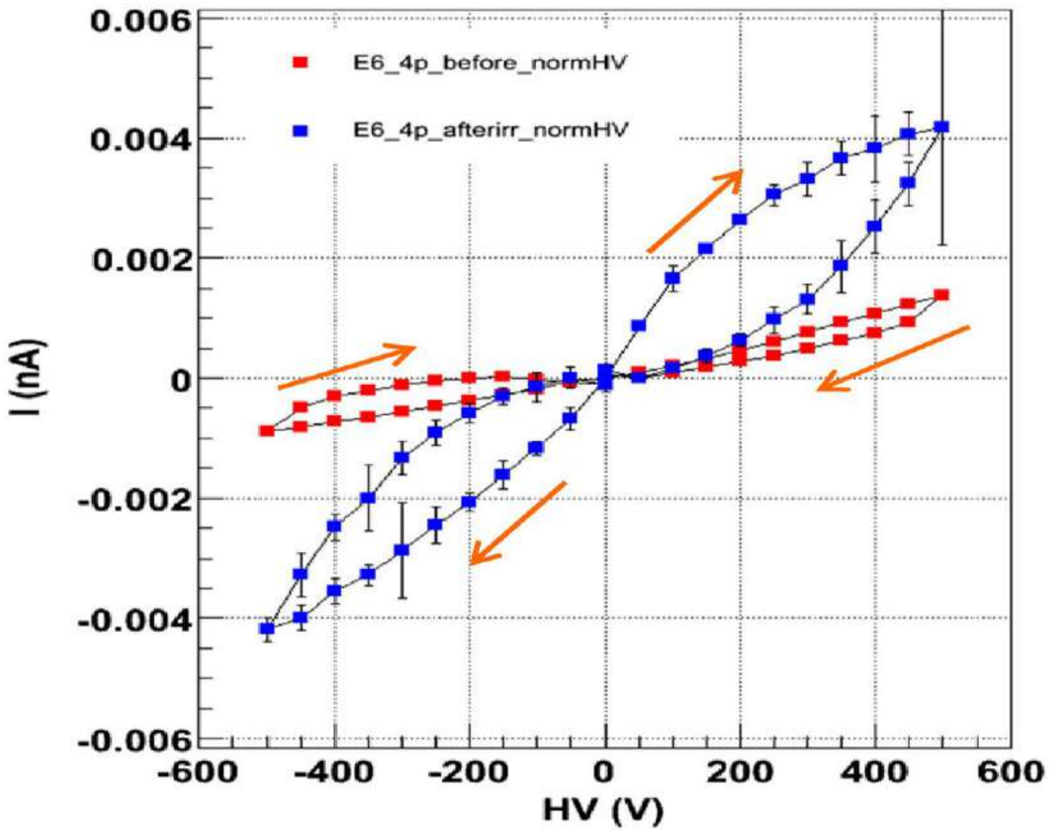
- Diamond initially has small signal , because   he has larger band gap and the ionization energy losses leads to few charge carriers production in compression with Si or GaAs.

CCE for Diamond , 10 MeV electron beam



At 7 MGy still operated about 10%

10 MGy for Diamond roughly about 10^{16} n/cm^2 for Si



Slight increase in dark current, but still in pA range up to dose 7 Mgy electron irradiation

properties

- **High radiation hardness**
- **availability on wafer scale**

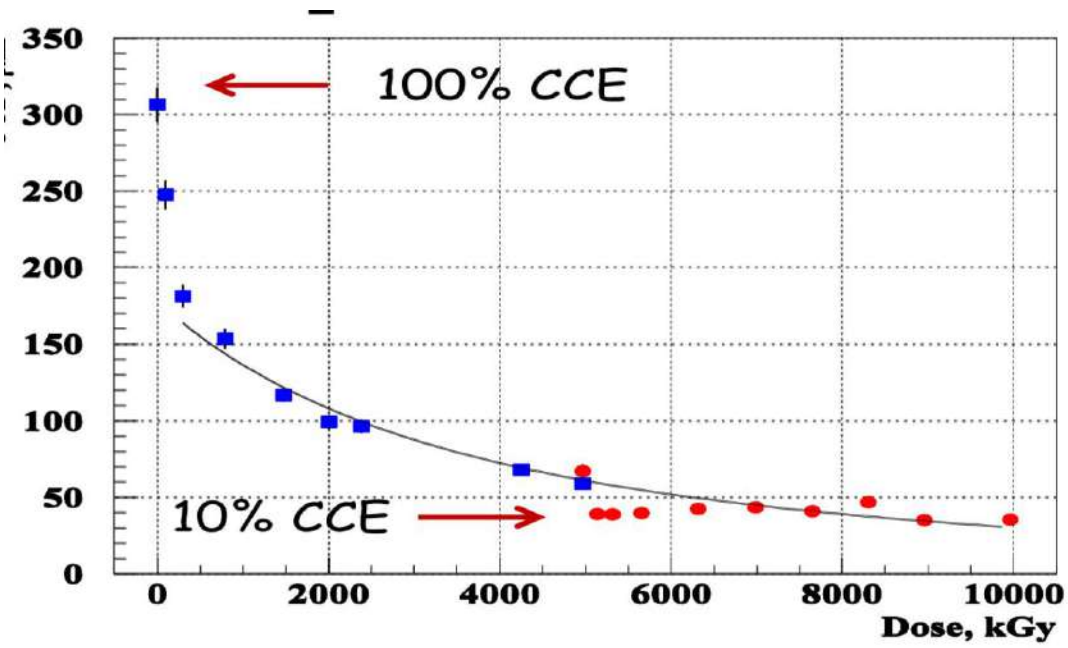
- **The problem, Price is too high for large-scale production**

Sapphire

Sapphire initially has charge collection at the level of 1%, also has some of defects.

we can say the radiation hardness of Sapphire about some of MGy. But the problem small signal .

- Single crystal Al2O3 grown by Czochralski process
- Large scale production: crystals up to 500 kg
- Positive: Cheap, large area, wide bandgap
- Negative: small response to MIP (about 2200 eh pairs per 100 um)
- Low charge collection efficiency



At 10 MGy still operated about 10%

Dark current about pA before and after irradiation

- **Sapphire (single crystal Al_2O_3) is a very promising wide-bandgap material .**

- **Produced in large quantities for industrial purposes, large size wafers are available (25 cm, up to 40 cm diameter is possible), not expensive .**

- **Perfect electrical properties, excellent radiation hardness, but presently low charge collection efficiency (~ 5%, probably due to high level of impurities)**

CdTe

CdTe: also used as radiation hardness detector .

the registration efficiency of CdTe is high in compression with another radiation hardness materials

Some information about CdTe

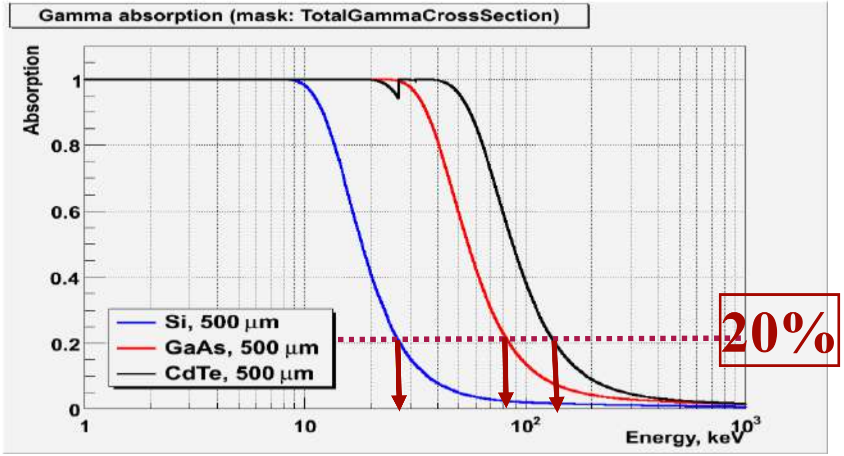
Density	5.85 g/cm^3
Melting Point	1092°C
Boiling Point	1130°C
Band gap Eg (300 K) Single crystal	1.5 eV
Electron –hole production	4.28–4.5 eV

Summary of previous measurements

- GaAs:Cr detectors have the same or better radiation hardness comparing with the other radation hardness detectors
- No information about the tested systematically GaAs:Cr in electron beams.
- A few information about the dependence of the radiation degradation on the irradiation rate for GaAs:Cr detector

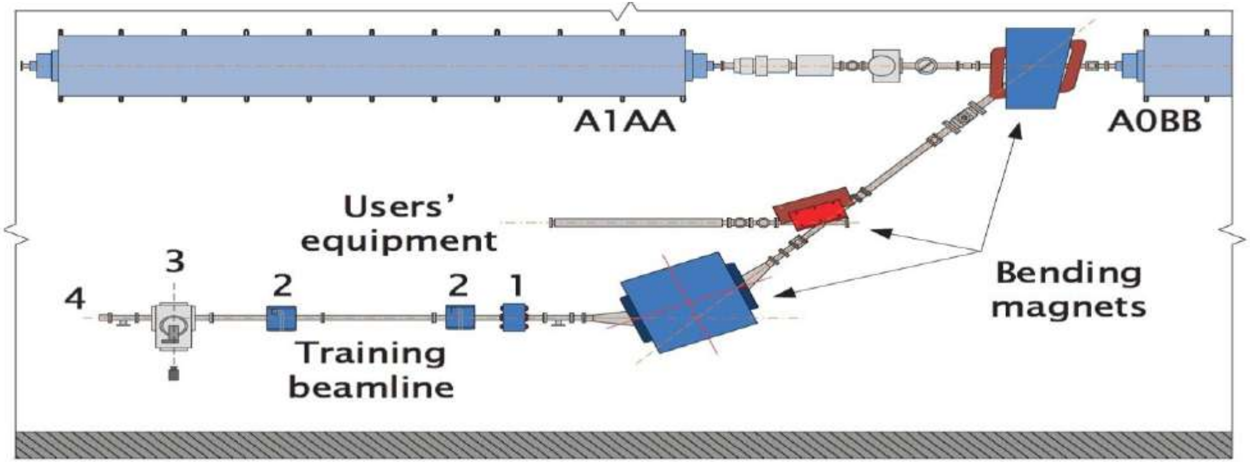
GaAs: Cr

- 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 efficiency



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	$\sim10^9$ Ω*cm	up to 1 mm	low

LINAC-200



energy 10-25 MeV in this channel , E 20.9 MeV

electron energy resolution about ±200 keV

pulse current 10 mA

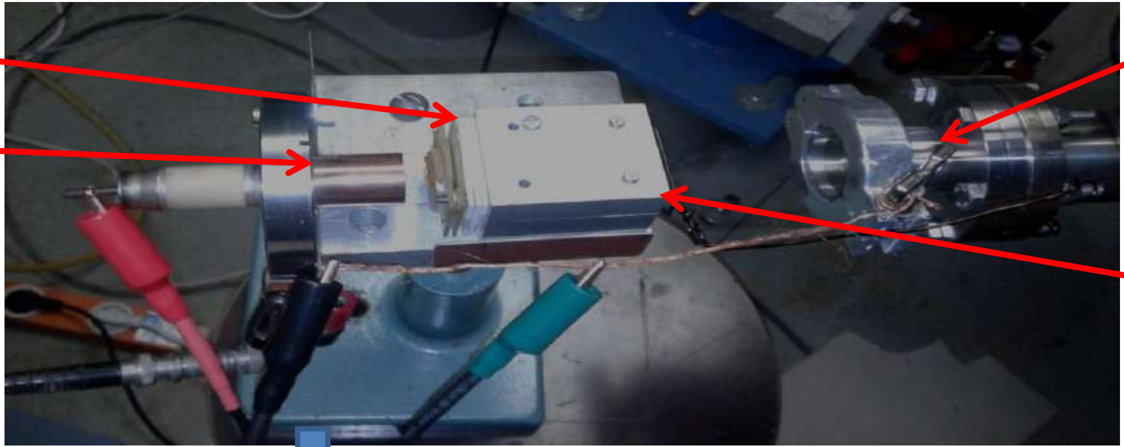
pulse duration 2 µs

frequency 1 - 25 Hz

Irradiation setup

Sensors

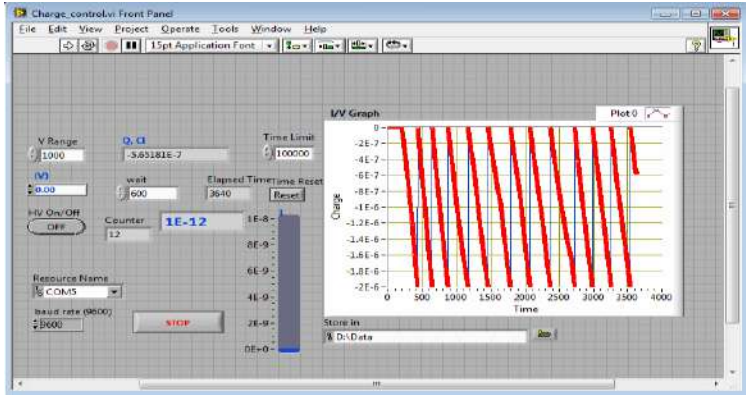
Faraday cup



Beam pipe

Collimator

Keithley 6517

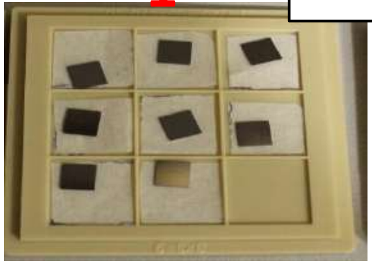


GaAs: Cr and Si sensors for irradiation

type	№	fram	size($мм^3$)	Area ($мм^2$)	flux($см^{-3}$)
(1) GaAs:Cr	N1,N4,N5,N6	Plastic	5x5x0.3	5x5	$\sim 10^{17}$
(2) GaAs:Cr	N7,N21,N23	PCB	5x5x0.3	4.5x4.5	$\sim 10^{17}$
(3) Si (1) (RIMST)	N3, N5	Plastic	5x5x0.25	3.6x3.6	$(0.8\text{-}1.6)\times10^{11}$
(4) Si (2) (HPK)	6886, 6888	PCB	5x5x0.4	3.5x3.5	$(1.3\text{-}3.5)\times10^{11}$

GaAs:Cr

1



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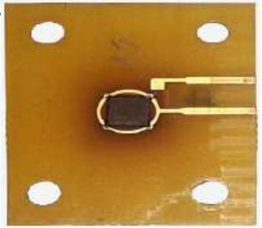
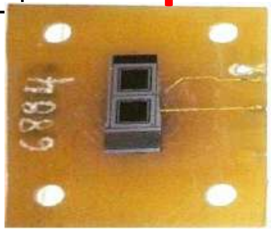


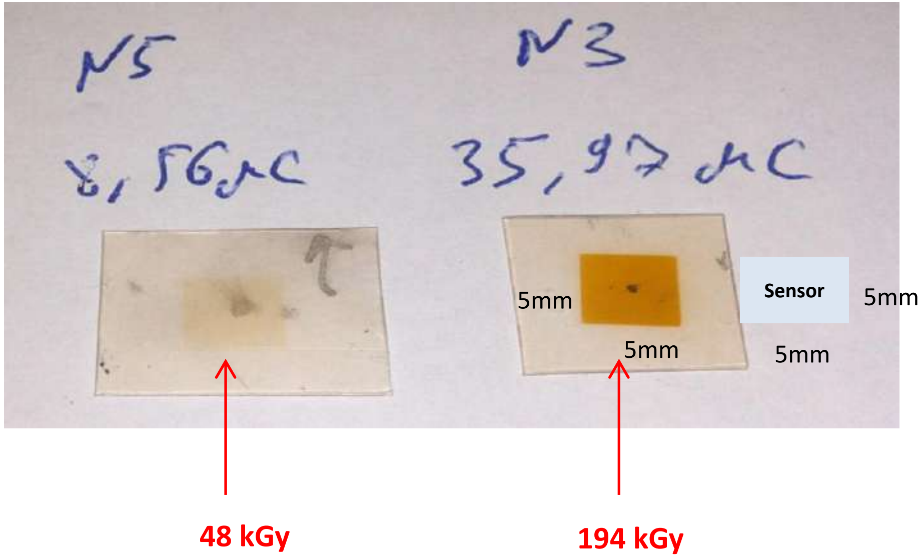
Si

3

4



Irradiation control



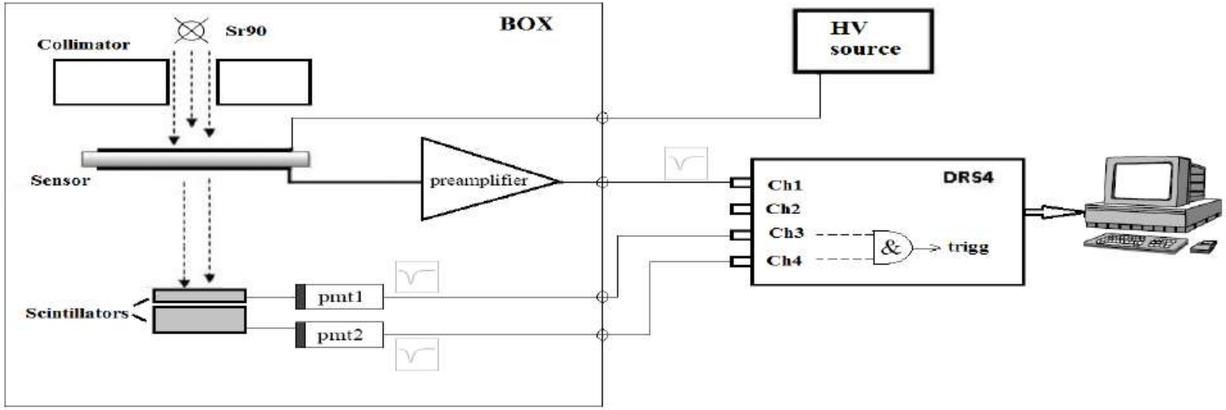
The radiation sensitive film was placed behind the sensor to control the absorbed dose, and the uniformity of electron flounce during irradiation.

GEANT 4 simulation

The electron transport through the irradiation setup was simulated by GEANT4 in order to obtain the ratio of registered by Faraday cup charge to absorbed dose in the sensor.

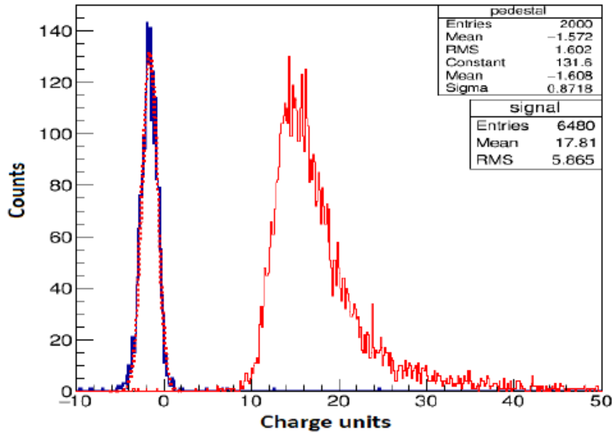
Sensor	Holder	Thickness, um	Energy deposit by one e, MeV	Absorbed dose to charge in Faraday cap, kGy/uC	Error
GaAs	Plastic	300	0.2218	5.56	0.04
GaAs	PCB	300	0.2238	5.61	0.04
Si	Plastic	300	0.1064	6.09	0.06
Si	PCB	300	0.1066	6.10	0.06

CCE(Charge collection efficiency) measurement set up

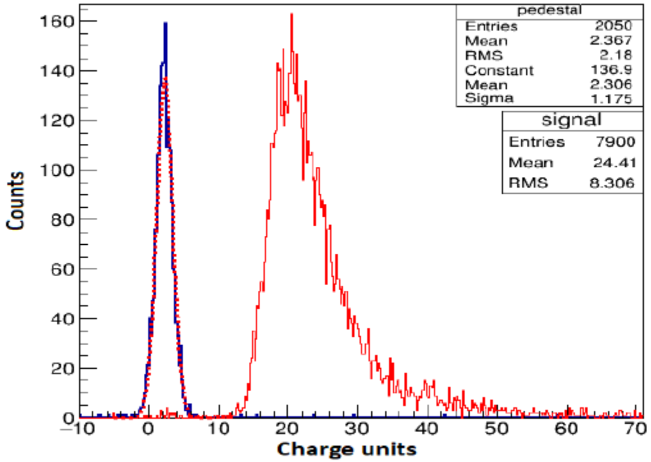


electrons from Sr^{90} source well collimated and triggered by 2 scintillators. It allows to cut and measure signal only from electrons passed throw the sensor with energy from 1 to 2.2 MeV which is close to MIP electrons

Si

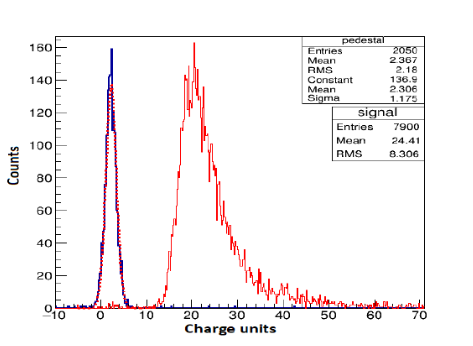
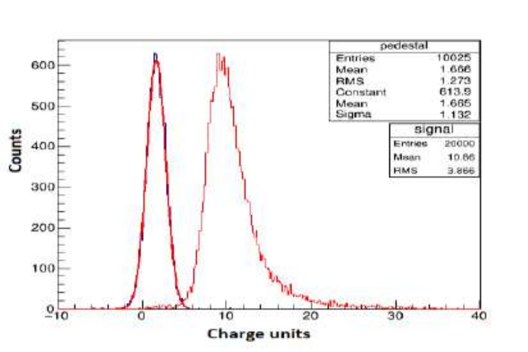
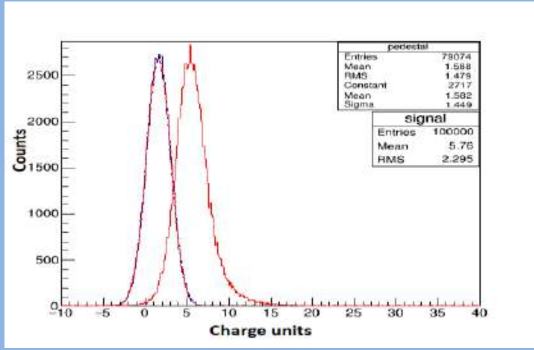
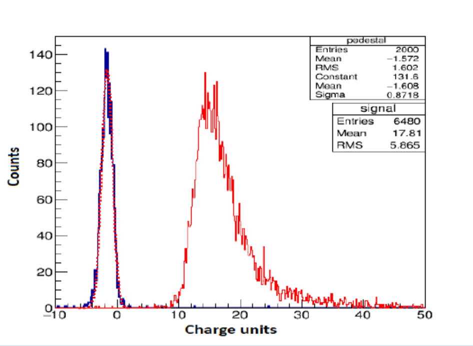
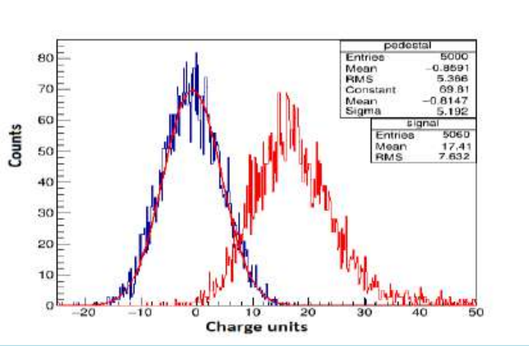
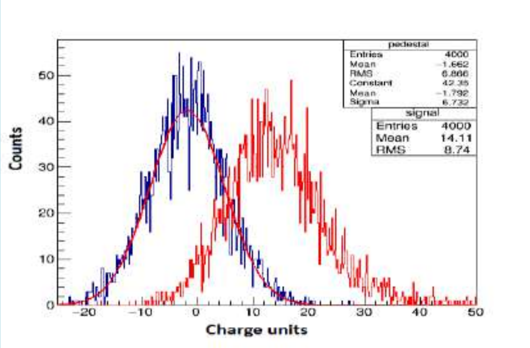


GaAs

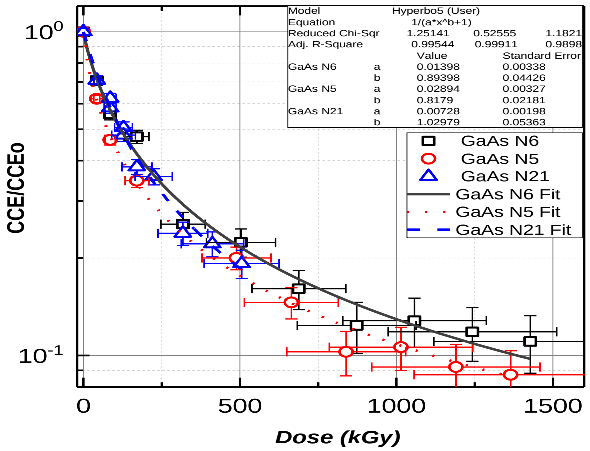


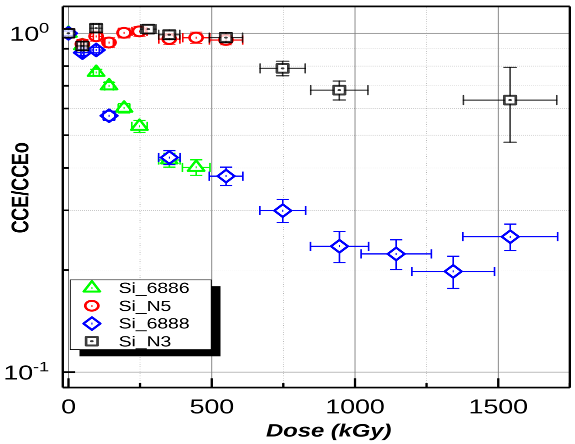
MIC spectra: Si (250 µm), Ubias = 100V, GaAs: Cr (300 µm), Ubias = -200V The pedestal is fitted with a Gaussian

MIP spectra of irradiated sensors at room temperature

	0 MGy	0.5 MGy	1.5 MGy
GaAs:Cr			
Si			

CCE irradiated sensors



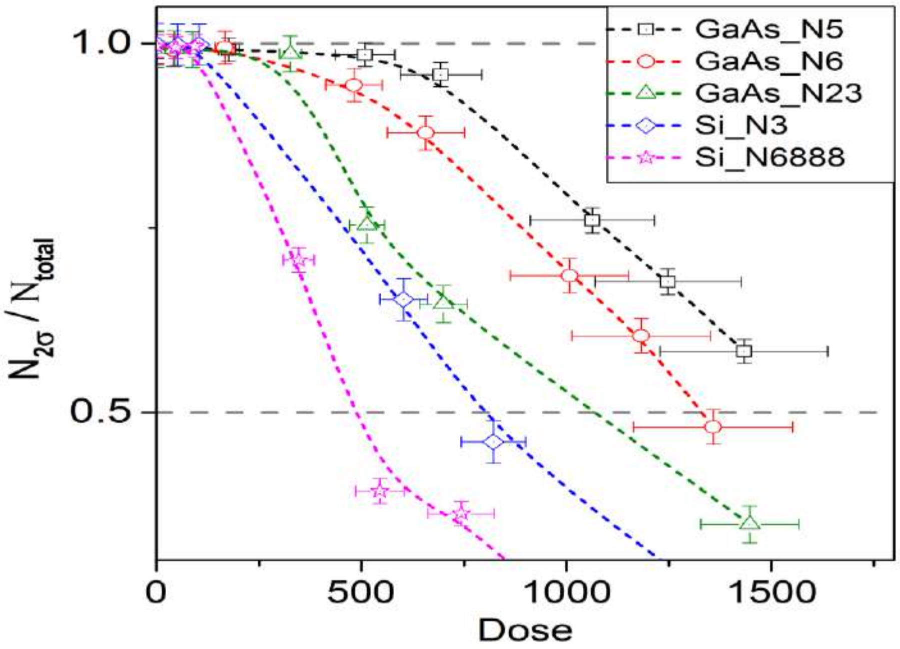


Dependences of CCE on absorbed dose for GaAs: Cr and Si at room temperature. For GaAs: Cr, the dose dependence of CCE was approximated by the formula:

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

where D is the dose, a and b are the normalization coefficients

The compression of GaAs: Cr and Si sensors using the 2σ criterion



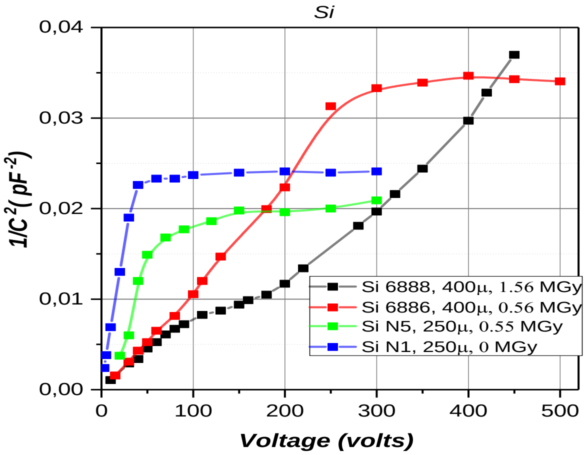
2σ-criterion was applied for a correct comparison of GaAs and Si sensors performance.

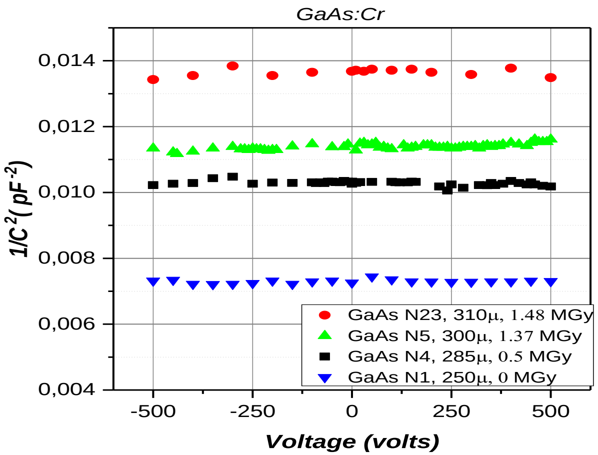
$$K = \frac{N_{2\sigma}}{N_{total}}$$

<u>K</u> is the ratio of events departed greater than the total number 2σ from pedestal to the total number of events in MIP-spectrum.

The greater <u>K</u>, the better the signal and pedestal separation for MIP-spectrum.

C-V characteristics of irradiated sensors





C -V for sensors Si type1 : N1, N5; Si type 2: 6886, 6888

GaAs: Cr irradiated with various doses.

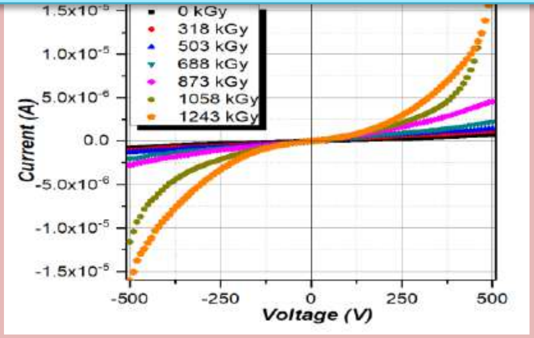
Frequency 10kHz, temperature 21C°.

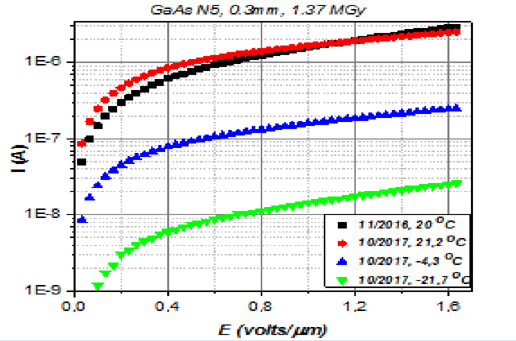
Temperature dependences of the I - V characteristics of irradiated sensors

I-V T = 20 °C

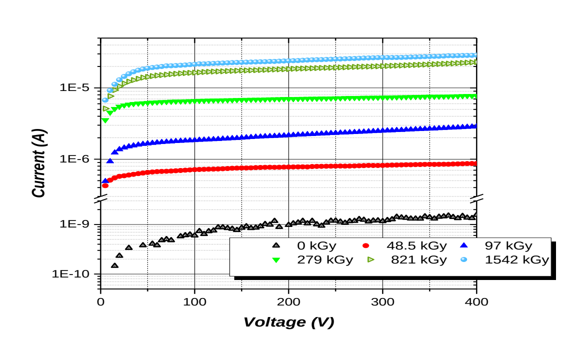
I-V Coolling

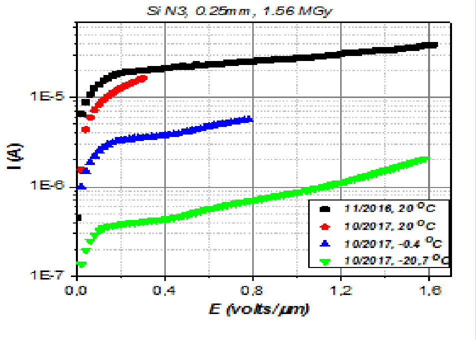
GaAs:Cr





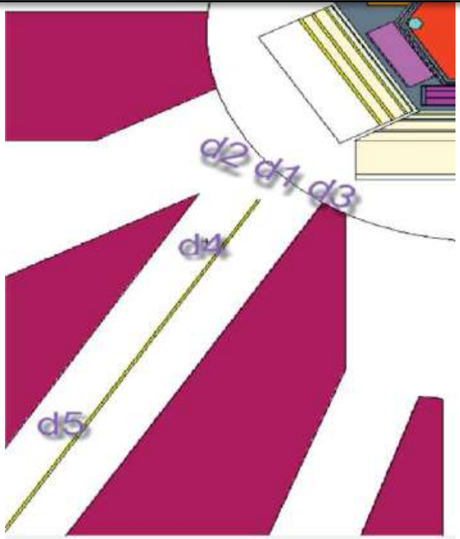
Si

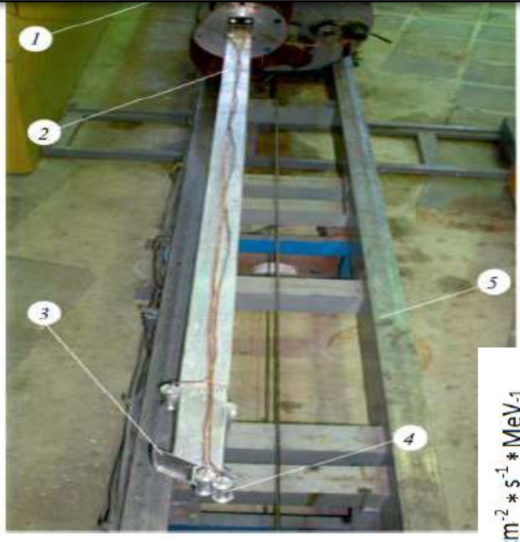




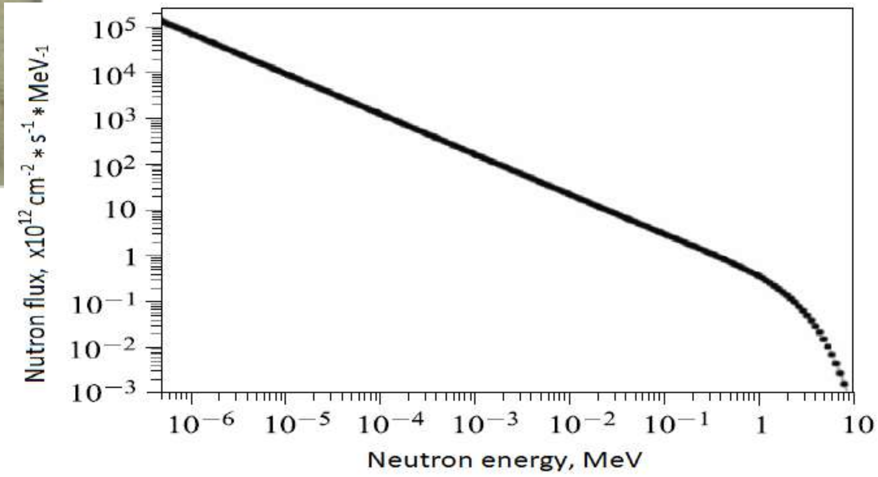
Si - dark current increases by 4 orders of magnitude!
GaAs: Cr - the dark current has increased insignificantly (3-7 times).

radiation hardness of GaAs: Cr under neutron irradiation at IBR-2 reactor

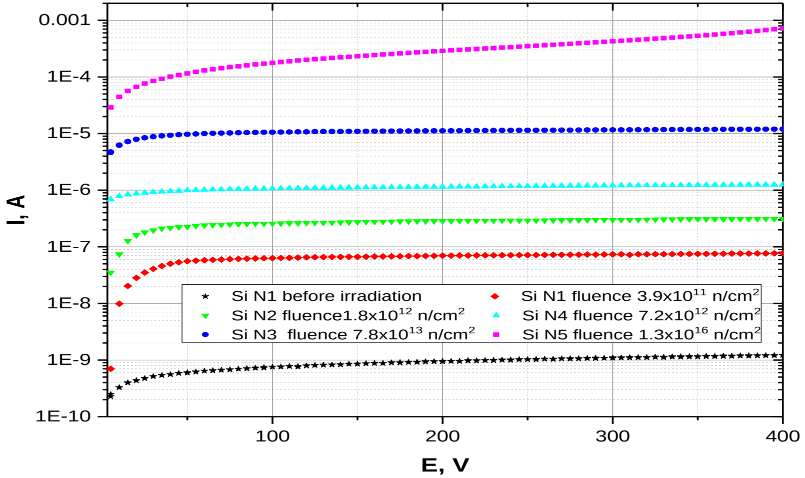




Neutron spectrum in channel No. 3 of the IBR-2 reactor, measured at points d1-d3.



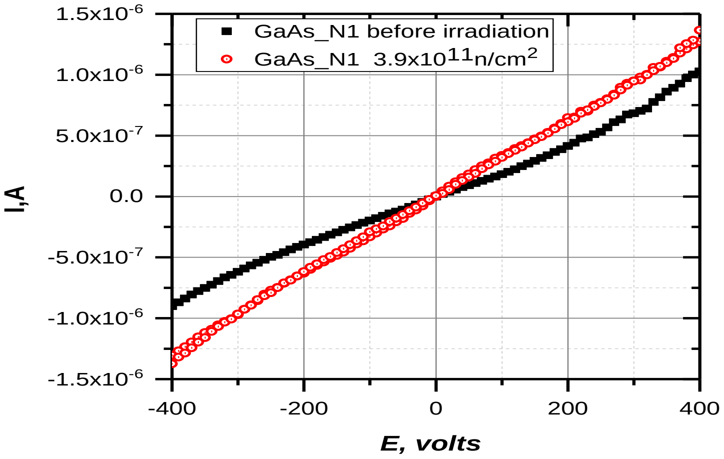
I - V characteristics of Si sensors after neutron irradiation

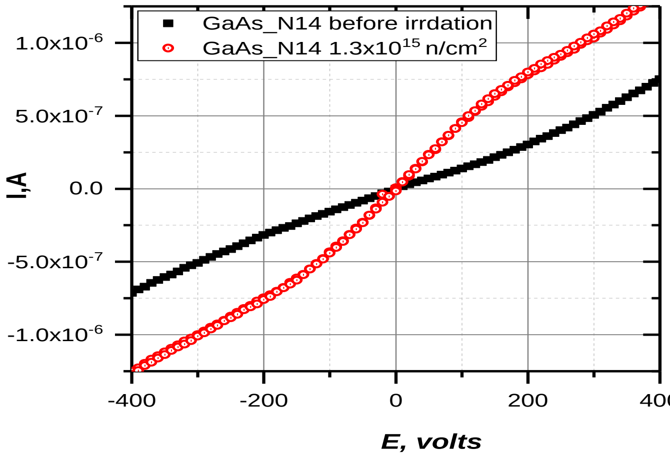


Sample №	n-fluence, n×cm^{-2} by NAA method	n-fluence, n×cm^{-2} by Si monitor
№1	$5{,}5\cdot10^{11}$	$3{,}91\times10^{11}$
№2	$2\cdot10^{12}$	$1{,}83\times10^{12}$
№3	$4{,}5\cdot10^{13}$	$7{,}76\times10^{13}$
№4	$4{,}7\cdot10^{12}$	$7{,}22\times10^{12}$
№5	$1{,}1\cdot10^{16}$	$1{,}32\times10^{15}$
№6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

I - V characteristics of Si sensors before and after irradiation with fast neutrons at a temperature of 20 C^{o} at channel 3 of the IBR-2 reactor. The fluence was measured by 2 methods: neutron activation analysis using a nickel (NAA method) with Si monitors (1 MeV (Si) equivalent)

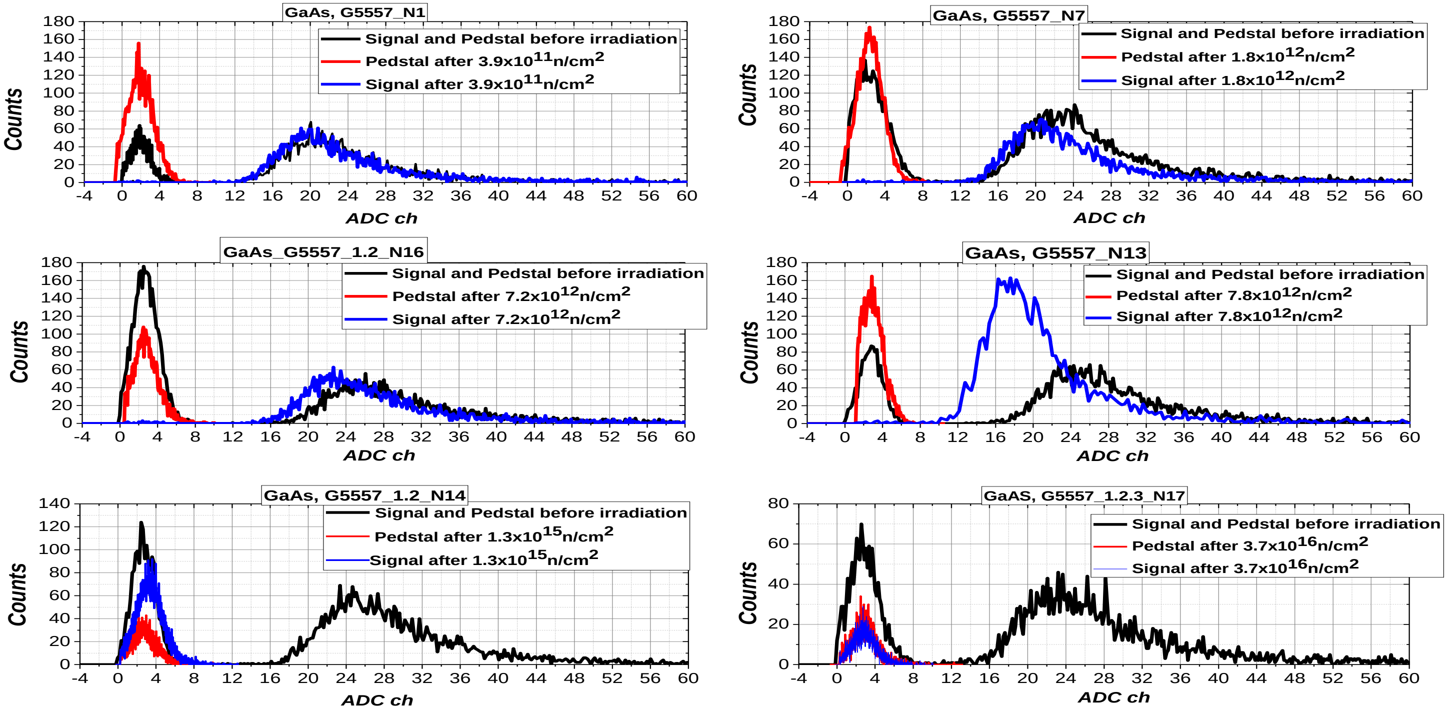
I - V characteristics of GaAs: Cr sensors after neutron irradiation





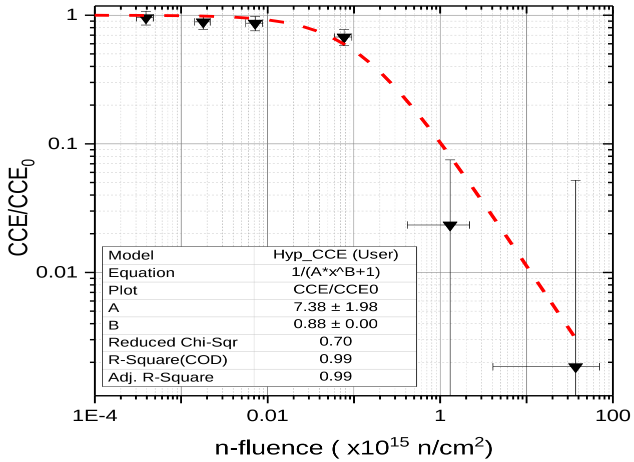
I - V characteristics of irradiated GaAs: Cr sensors No. 1 (left) and No. 14 (right) at a temperature 20 C^{o}.
After a 3.9 × 10^{11} n /cm^2, the dark current increased
after 6.1 × 10^{15} n / cm^2, the dark current increased 4 times.

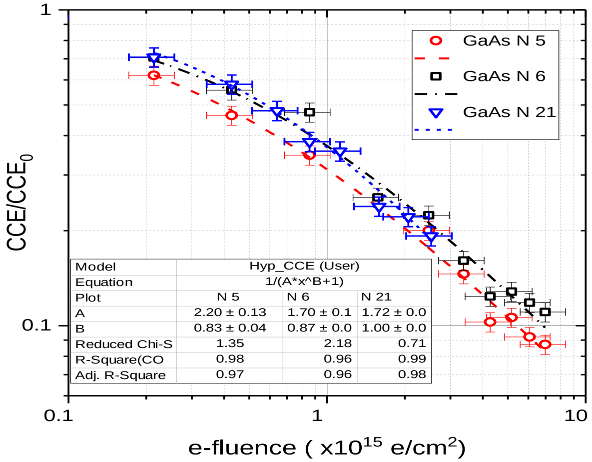
charge collection efficiency (CCE) GaAs: Cr sensors after irradiation



MIC spectra of GaAs: Cr sensors after irradiated by neutron at different doses , Ubias = -200V, T = 20 ° C.

Comparison of CCE for GaAs: Cr sensors irradiated by neutrons and electrons





Dependence of CCE on the fluence of neutrons (left) , electrons 20.9 MeV (right) for GaAs: Cr sensors. Ubias = -200V, T = 20 C°.

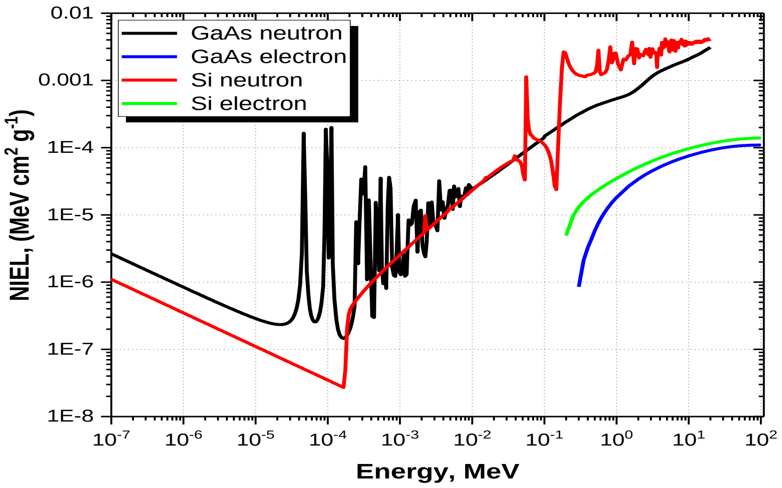
To approximate the dependence of CCE on the neutron and electron fluence in GaAs: Cr sensors,

the following formula was applied:

$$CCE = \frac{1}{\alpha \times \Phi^b + 1}$$

Φ - fluence of particles, electrons or neutrons; α, b - parameters of normalization;

Non-ionizing energy loss of Si and GaAs:Cr



Calculation of non-ionizing energy loss NIEL electrons and neutrons for GaAs and Si.

In order to correctly compare the radiation damage of the detector material by electron and neutron , we use non-ionizing energy loss (NIEL)

• the interaction of radiation with materials lead to energy losses in 2 ways :

-nuclear-elastic

- nuclear-inelastic this leads to interactions with lattice atoms and produce vacancy-interstitial , displacement, damage in the crystal lattice .

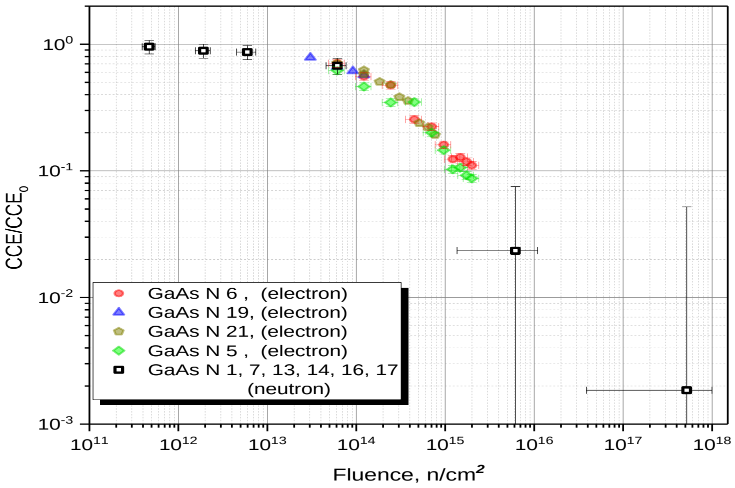
in order to compare between electron and neutron defect we use this coefficient is used:

$$k = NIEL_{(21\ MeV\ e)} / NIEL_{(1\ MeV\ n)}$$

Then the electron fluence can be reduced to an equivalent neutron fluence of 1 MeV:

For GaAs, the coefficient. : $k = NIEL_{(21\ MeV\ e)} / NIEL_{(1\ MeV\ n)} = 0.28 \pm 0.03$

Electron Fluence converted to neutron fluence



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

$$k_{\mathrm{GaAs:Cr/eq}} = 0.28$$

Comparison of the CCE dependences for GaAs: Cr sensors irradiated with electrons and neutrons.

publications

1. Beam energy measurement on LINAC-200 accelerator and energy calibration of scintillation detectors by electrons in range from 1 MeV to 25 MeV / Nuclear Inst. and Methods in Physics Research -- 2019 -- A.935 -- p.83-88 -- ISSN 0168-9002

2. Analysis of radiation effects on some properties of GaAs: Cr and Si sensors exposed to a 22 MeV electron beam / Nucleus -- 2018 -- Vol. 64, p.4-9 -- ISSN 0864-084X

3. Radiation hardness of GaAs:Cr and Si sensors irradiated by 21 MeV electron beam / Journal of Instrumentation -- 2020 -- 15 C06003

4. Radiation hardness of GaAs: Cr and Si sensors irradiated by electron beam / Nuclear Inst. and Methods in Physics Research -- 2020 -- A 975 164204 -- ISSN 0168-9002

5. Investigation of the radiation hardness of GaAs:Cr semiconductor detectors irradiated with fast neutrons at the reactor IBR-2 / Journal of Physics: Conf. Ser. -- 2020 -- 1690 (2020) 012042 -- doi:10.1088/1742-6596/1690/1/012042

6. study of radiation damage in GaAs:Cr-based detector exposed to 20 MeV electron beam .in press.

Prize:

Первое место конкурса научных работ ЛЯП 2020

Поощрительная премия конкурса научных работ ЛЯП 2019

- The last 5 years more than 30 students from different country (maximum from Egypt) participate in course (Radiation protection and safety from radiation sources) in our lab.