Radiation hardness of GaAs: Cr and Si sensors irradiated by 20 MeV electron beam

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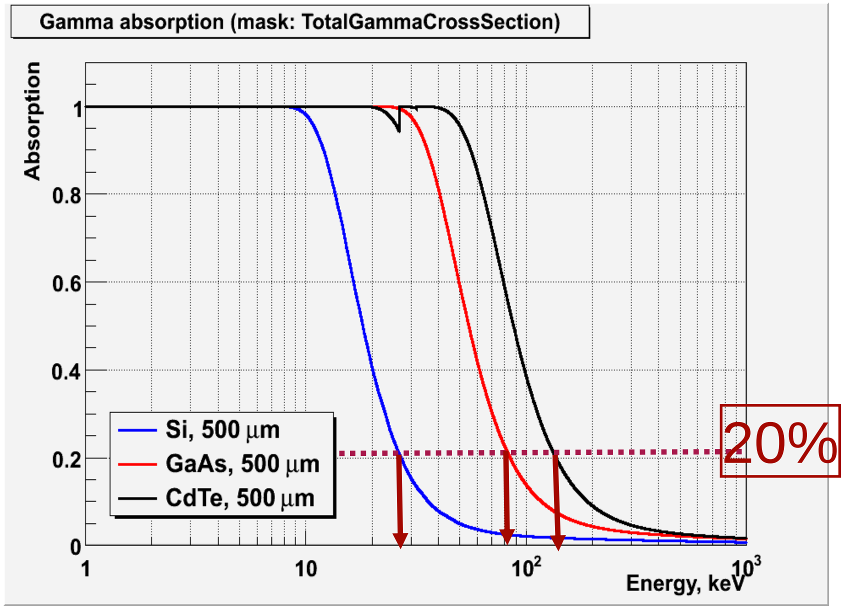
on behalf of the JINR group

Gallium arsenide as a detector material

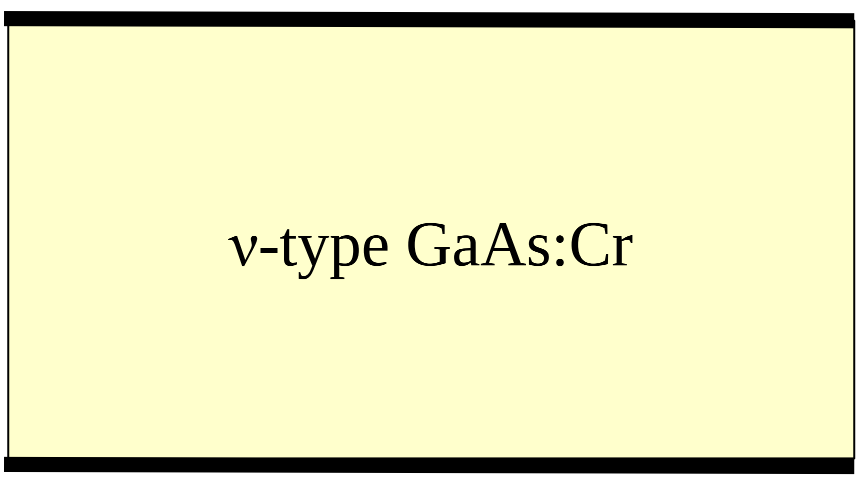
- GaAs is a well-known semiconductor, second widespread after silicon
- Limited use in particle detection because of low resistivity, low CCE and high intrinsic noise
- New modification of GaAs, compensated by Cr (GaAs:Cr), has been invented in Tomsk State University in 2000-2005
  - suitable for detector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

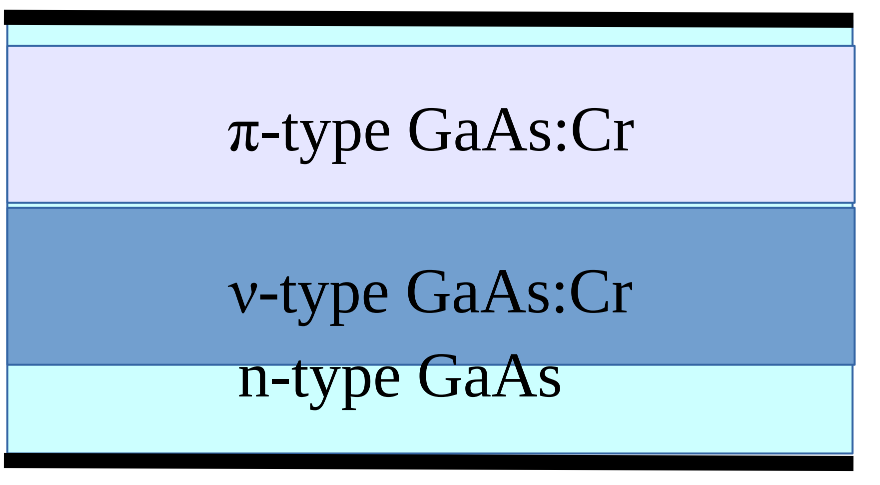


Material	main charge carriers	electron drift length	bulk resistivity	active sensor thickness	intrinsic noise
LEC SI-GaAs	holes	0.3-0.5 mm	$<2*10^8$ Ω*cm	<300 μm	high
GaAs:Cr	electrons	0.7 – 2 mm	$\sim 10^9$ Ω*cm	up to 1 mm	low

Two types of GaAs:Cr detectors

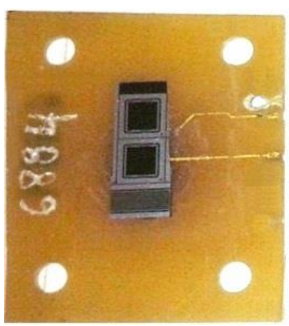
- ‘High Resistive' GaAs:Cr
  - resistivity ~10^9 Om*cm
  - active thickness up to 1 mm
  - electron drift length up to 2 mm
- πν junction structure
  - active thickness is determined by πν junction (depending on Ubias)
  - resistivity and CCE are similar.





GaAs:Cr and Si sensors

N	Type	Producer	Holder	Size, x y z, mm^3	Sensitive area, mm^2
1	GaAs:Cr (n^+-π-ν-n) barrier	TSU (Tomsk, Russia)	Plastic	5x5x0.3	5x5
2	GaAs:Cr high resistive	TSU (Tomsk, Russia)	PCB	5x5x0.3	4.5x4.5
3	Si *(p^+nn^+)* n-type 1	RIMST (Zelenograd, Russia)	Plastic	5x5x0.25	13
4	Si n-type 2	Hamamatsu HPK(USCS, USA)	PCB	10x10x0.4	3.5x3.5



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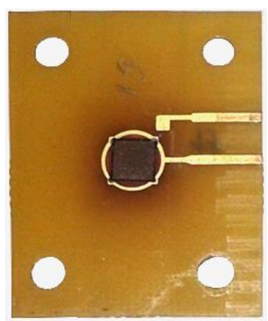

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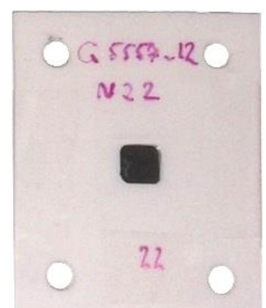

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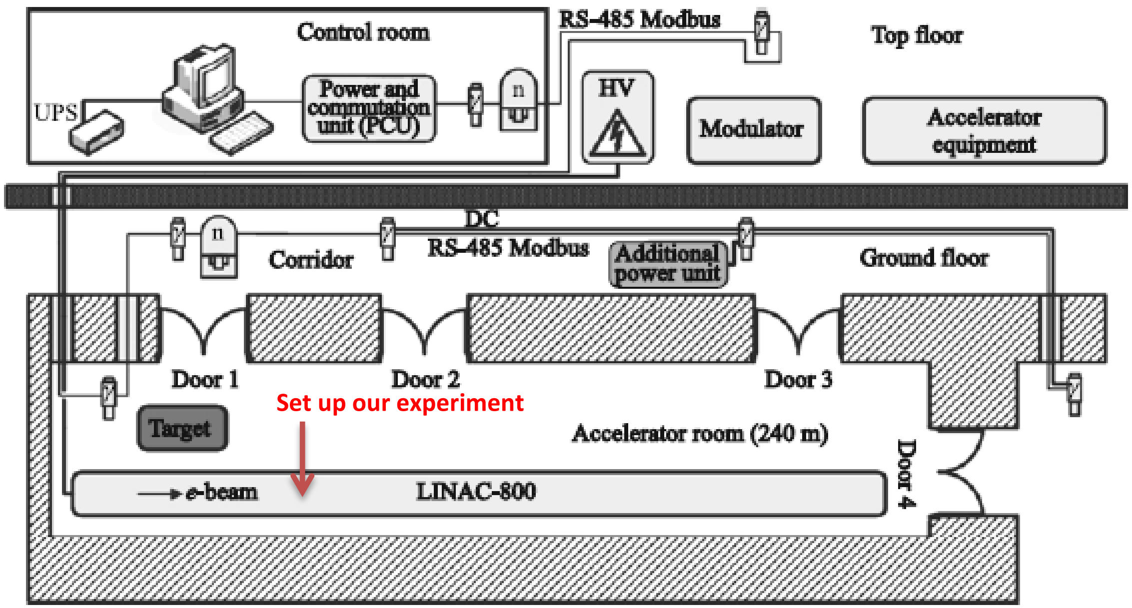
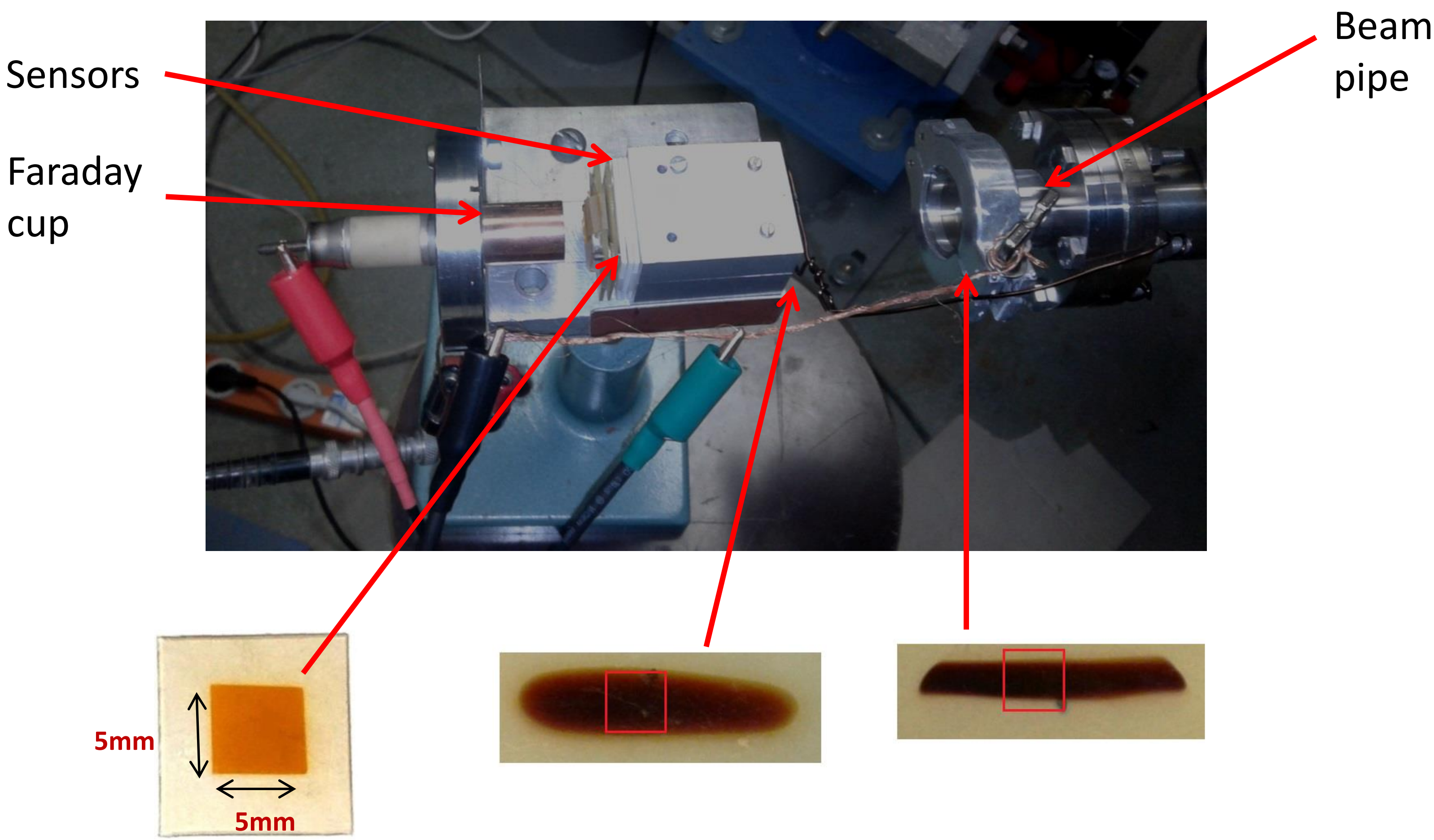
LINAC-800 e$^-$ accelerator



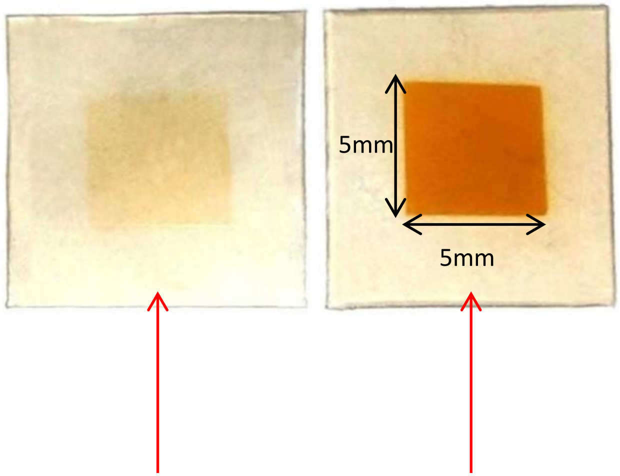
800 MeV electron linear accelerator (LINAC-800) is under construction at JINR. 20 MeV beam channel was used for sensors irradiation. Beam parameters:

- bunch current up to 10 mA,
- duration 2 μs,
- frequency from 1 to 10 Hz.

Irradiation beam control



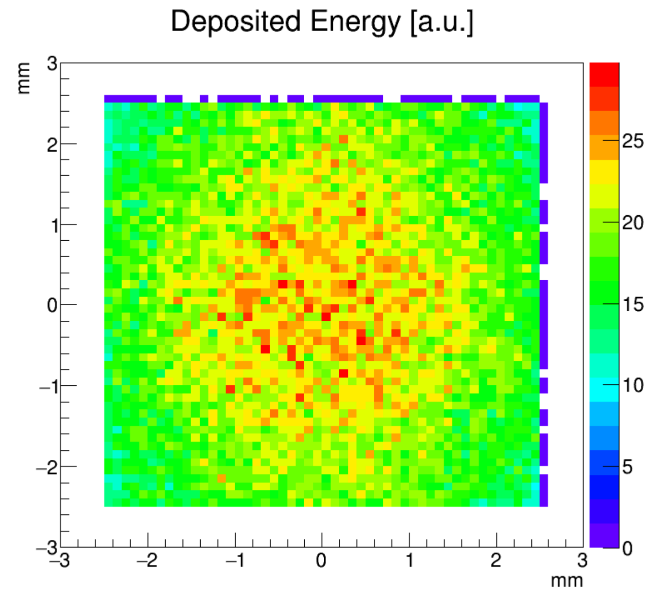
Irradiation control



48 kGy
($2.1x10^{14}$ e^-/cm^2)

194 kGy
(8.4×10^{14} e^-/cm^2)

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



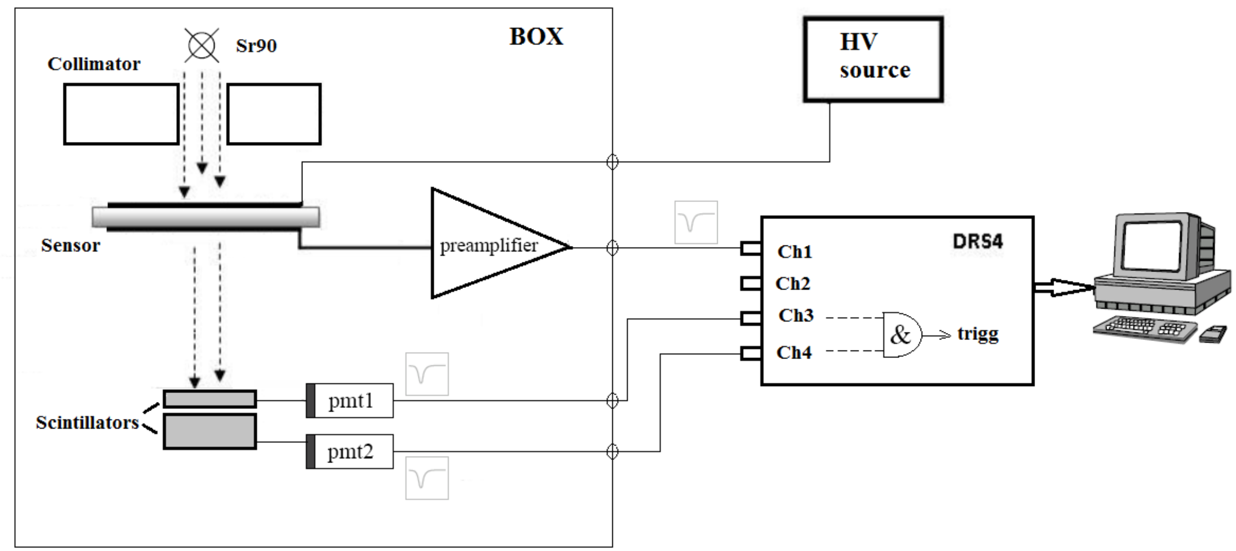
GEANT 4 simulation for the distribution of the deposited energy over the GaAs sensor 5x5x0.3 mm^2 area in e^--beam after collimator. Statistics $2x10^6$ e^-

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 for all types of sensors.

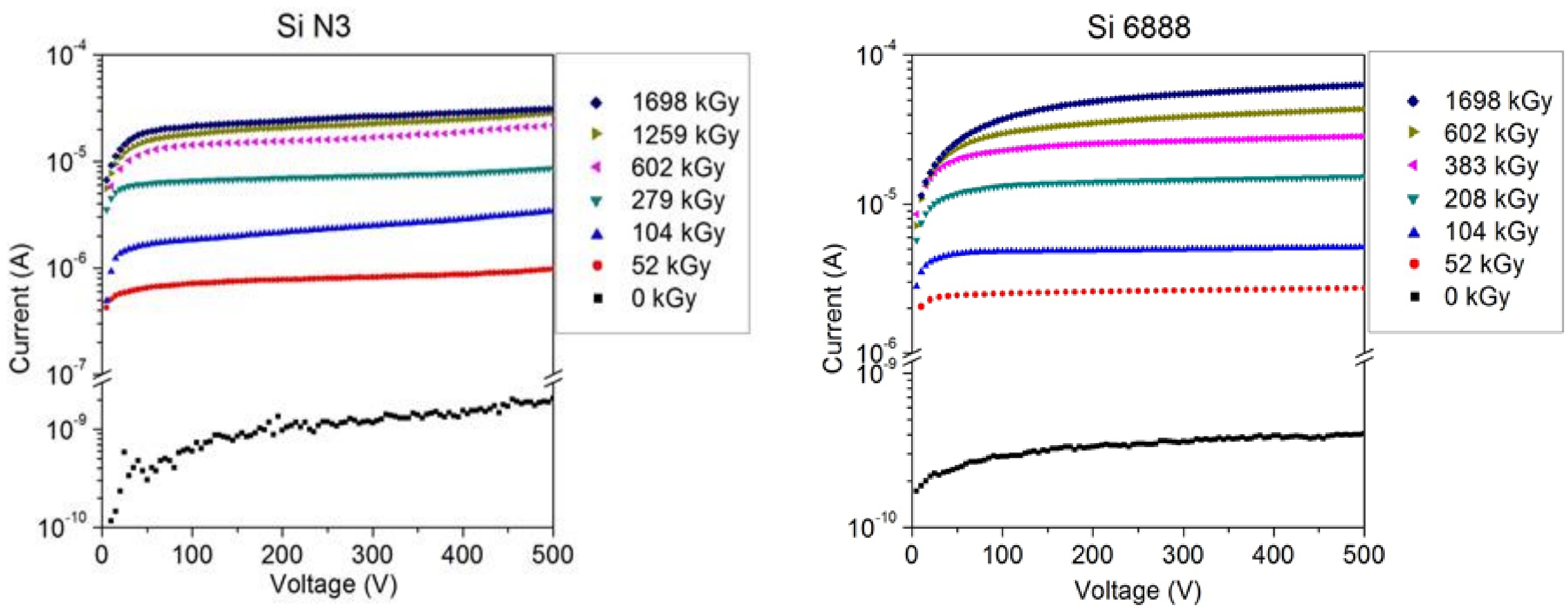
Configuration	Holder	Thickness [μm]	Absorbed dose to charge in Faraday cup [kGy/μC]		Error ,%
			1-st sensor	2-nd sensor	
GaAs (1)	Plastic	300	4.99	-	2.8
GaAs (2)	PCB	300	4.99	-	2.8
Si type1 (3)	Plastic	250	5.61	-	1.4
Si type2 (4)	PCB	400	5.68	-	1.4
(1)+ (1)	Plastic	-	5.14	4.87	2.7 – 2.8
(2)+ (4)	PCB	-	5.19	5.51	2.7 - 1.4

CCE(Charge collection efficiency) measurement setup



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

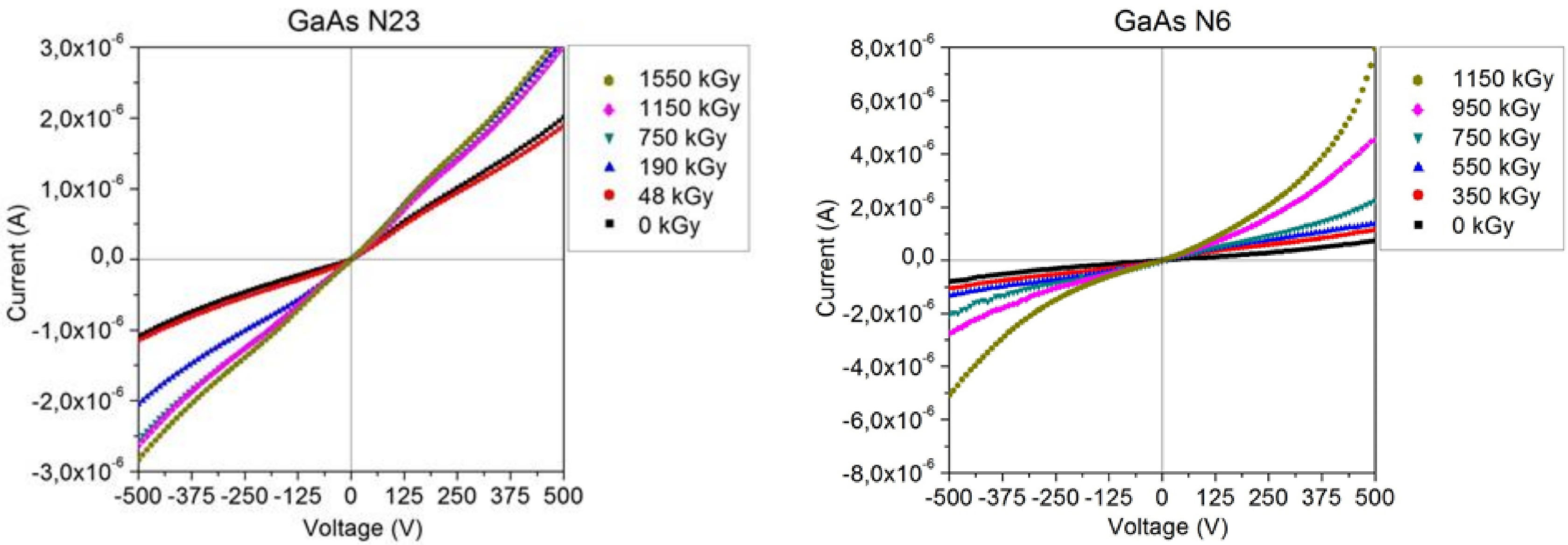
Results I-V Si



I-V characteristics of the normal n-type Si (N3) and radiation hard USCS Si (6888).

The dark current increased almost 4 orders of magnitude after the absorbed dose of 1.5 MGy

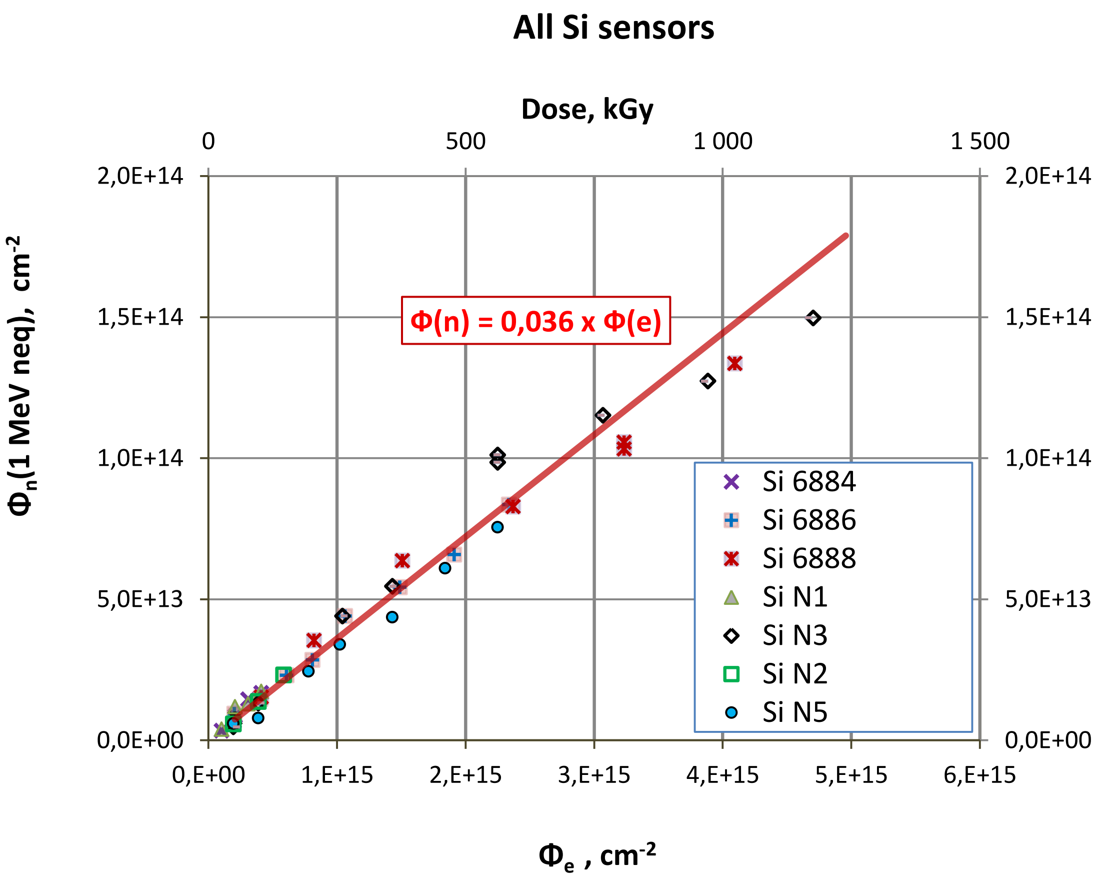
Results I-V GaAs:Cr: πν junction and HR



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

Resistivity of GaAs:Cr sensors is about 2-5*10^9 Ohm*cm, the dark current increased only 3 times for the high resistive and 4-5 times for the barrier GaAs:Cr.

1-MeV neutrons equivalent fluence for Si



For neutrons in Si

$$I = \alpha \times \Phi_n \times V$$

α = 5 x 10^{-17} (A/cm), current damage constant in Si

Φ_n – 1 MeV neq

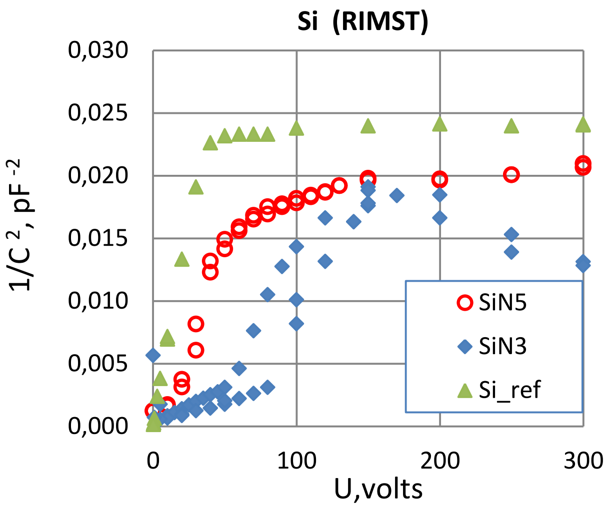
V *– sensor volume*

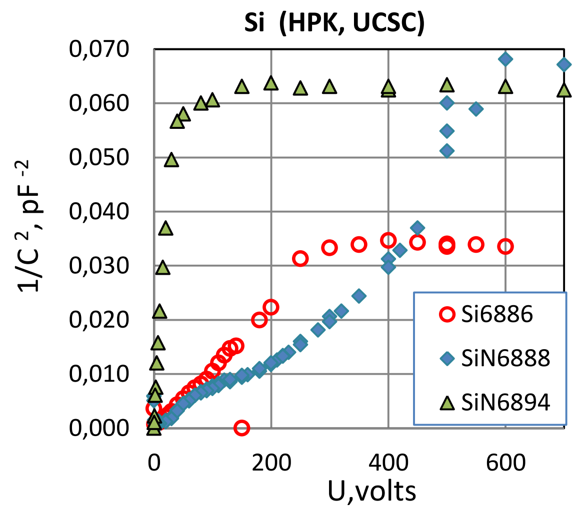
D = 1.5 MGy 20 MeV e

Φ_e ~ 6.7 x10^{15} cm^{-2} e^-

Φ_n ~ 2 x10^{14} cm^{-2} neq

C-V



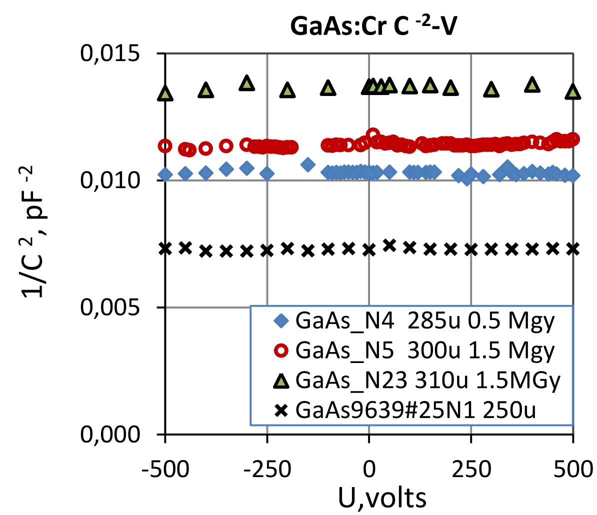


C $^{-2}$-V for Si type1(left) Si type2 (right) GaAs:Cr (down):

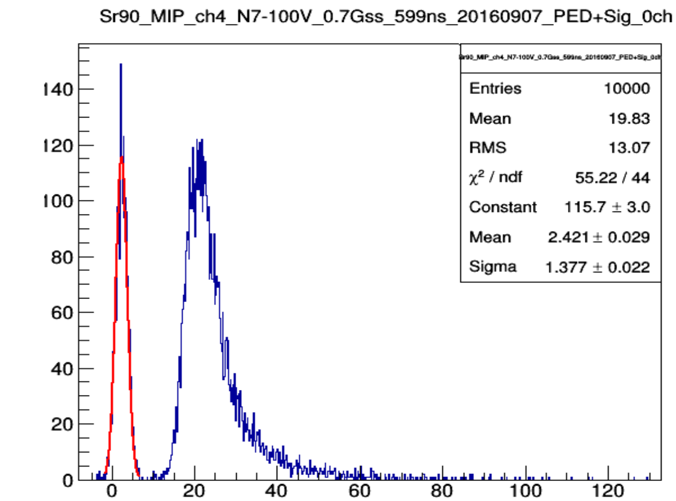
Unirradiated Si_ref, Si_6894 U_{fd}<40V;

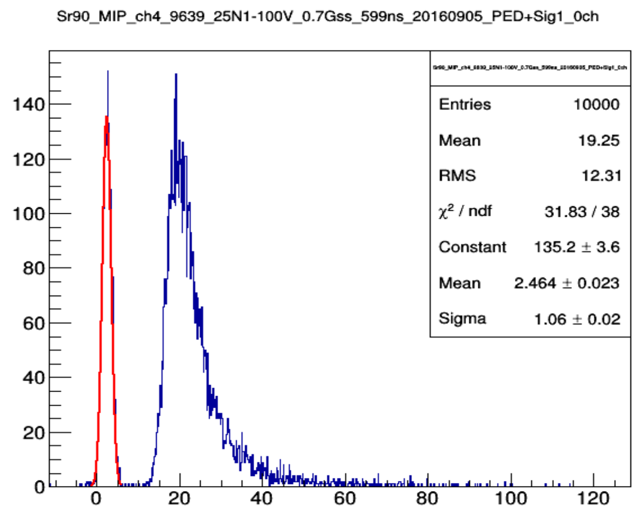
0.5 MGy Si_N5(type1) U_{fd}=100V;
Si_6886(type2) U_{fd}=300V;
GaAs:Cr_N4 (barrier)

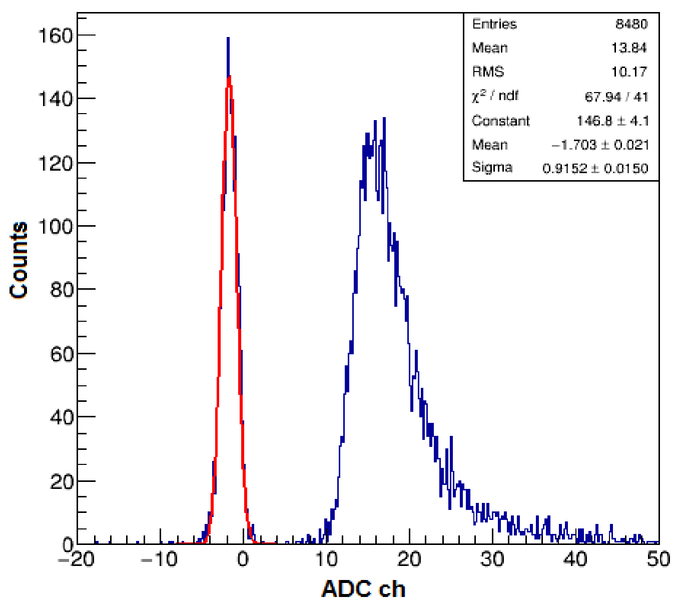
1.5 Mgy Si_N5(type1) U_{fd}=150V
Si_6888(type2) U_{fd} >600V;
GaAs:Cr_N5 – barrier type;
GaAs:Cr N23 – high resistive type;



MIP spectra for GaAs and Si sensors before irradiation





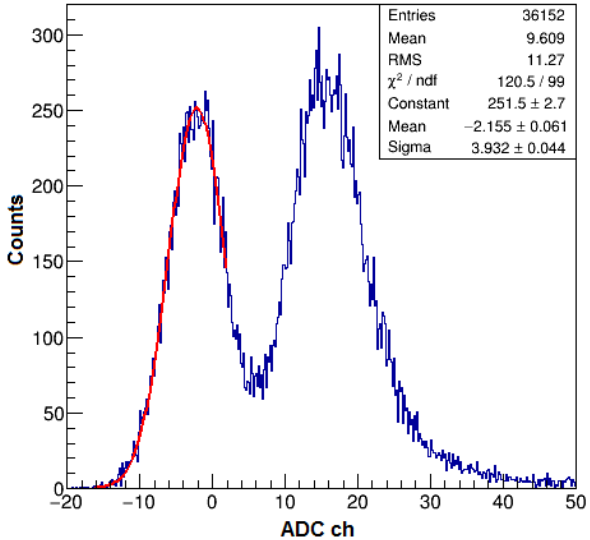


MIP spectrum from Sr^{90} ß-source for sensors, measured with Ubias =100V:

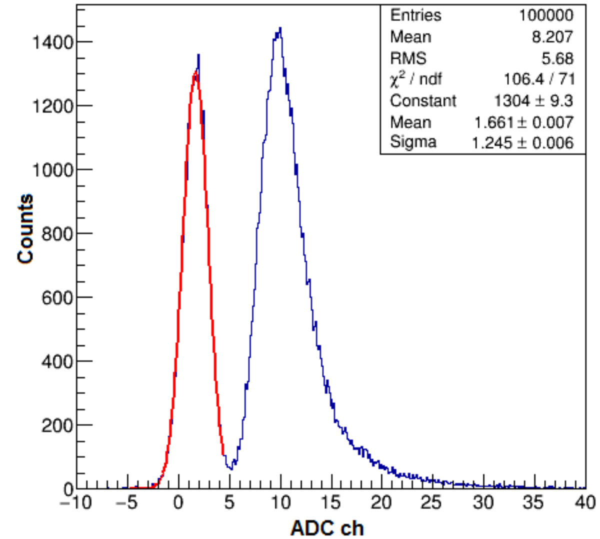
- *HR GaAs:Cr (left)*
- πν-junction *GaAs:Cr (right)*
- *Si type1 (down)*

MIP for Si & GaAs:Cr after 0.5 MGy

Type 1 Si_N5; 0.5 MGy ; T= 16°C



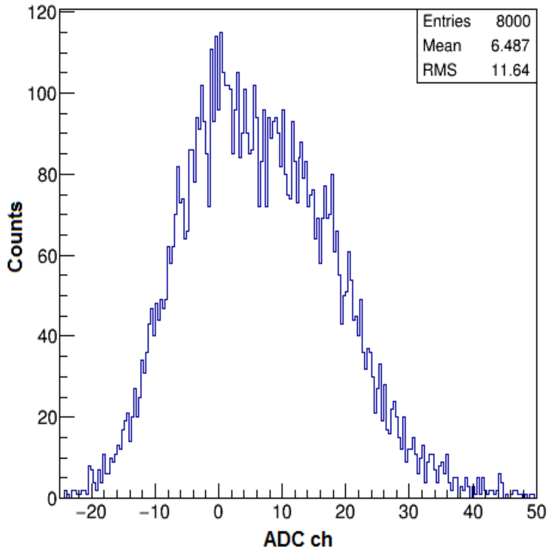
Barrier GaAs_N4: 0.5 MGy ; T =22°C



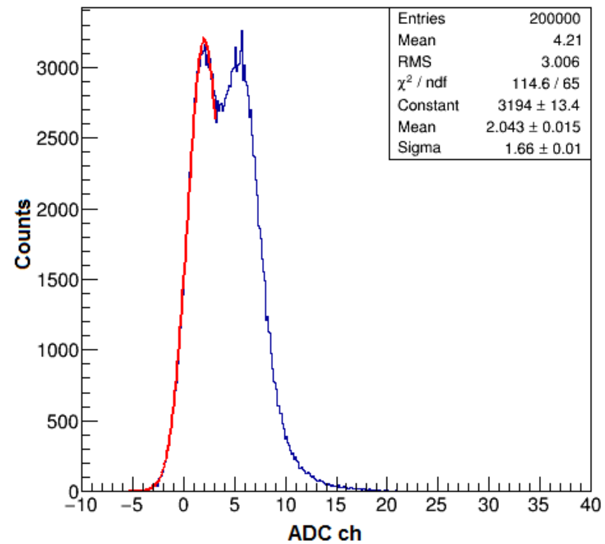
A slight cooling of the sensor Si for 5°C improves the MIP-signal and pedestal separation, but it is still worse than GaAs:Cr.

MIP for Si & GaAs:Cr after 1.5 MGy

Type 1 Si_N3: 1.3 MGy ;
Ubias=100V: T =22°C

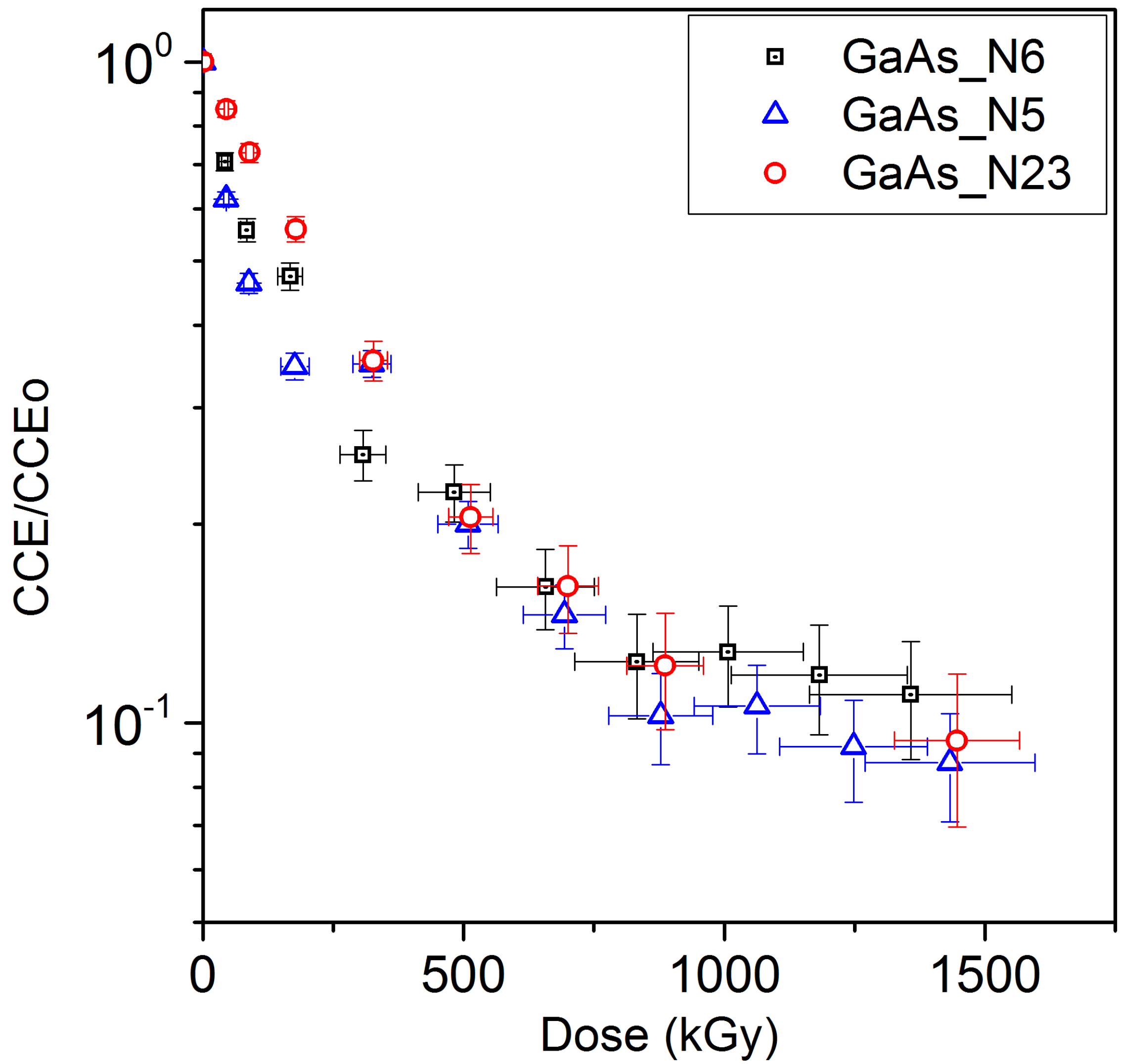


Barrier GaAs:Cr_N6: 1.5 MGy ;
Ubias=500V; T =22°C



After 1.5 MGy the MIP-signal and the pedestal are hardly separated.

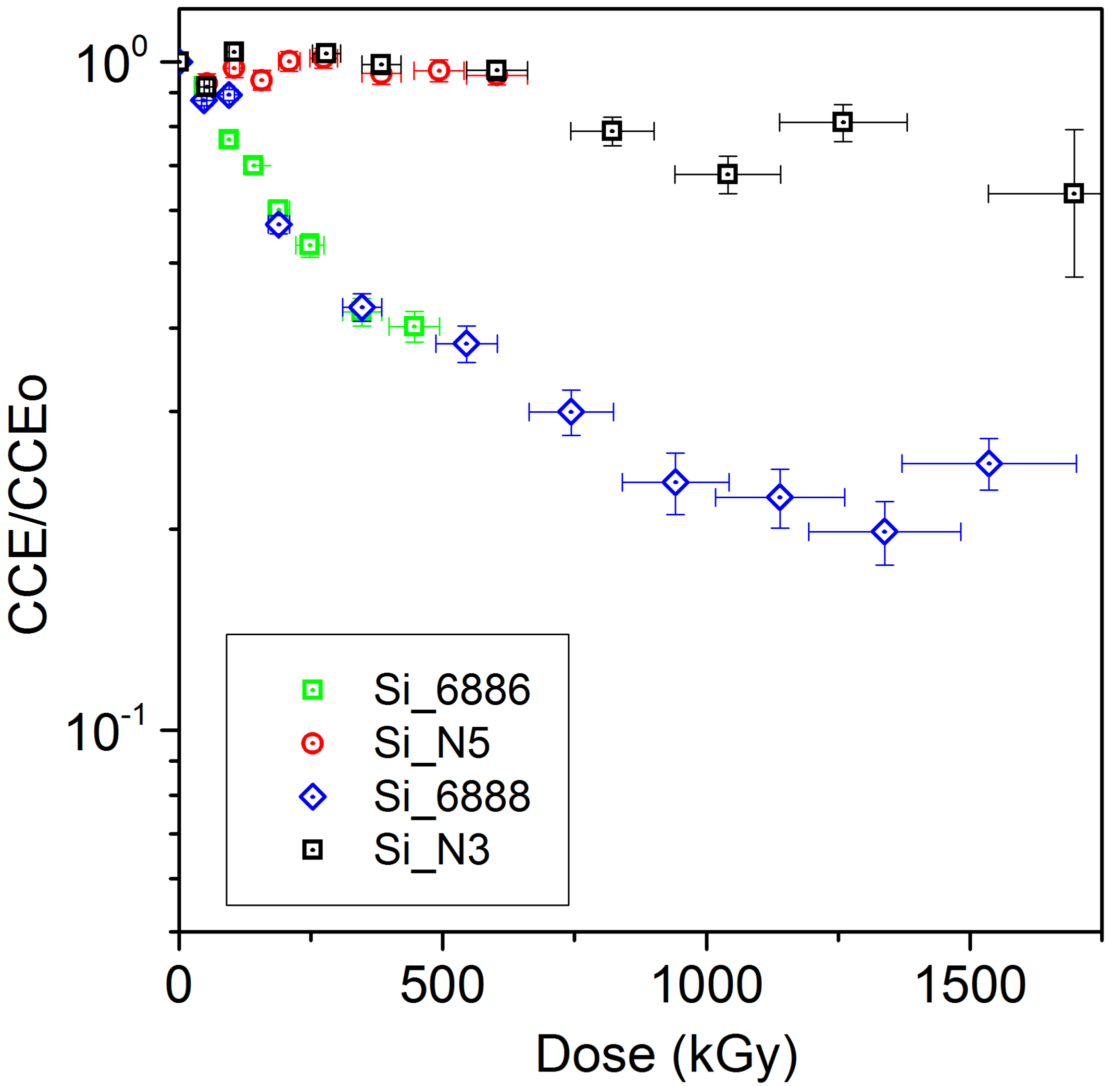
GaAs:Cr CCE vs Dose



In GaAs:Cr the CCE falls monotonously and abruptly until to dose 1MGy, but then it decreases slowly up to the maximum irradiation dose.
It was observed for both sensor types:

- N5,N6 - barrier GaAs:Cr
- N23- high resistivity GaAs:Cr

Si CCE vs Dose

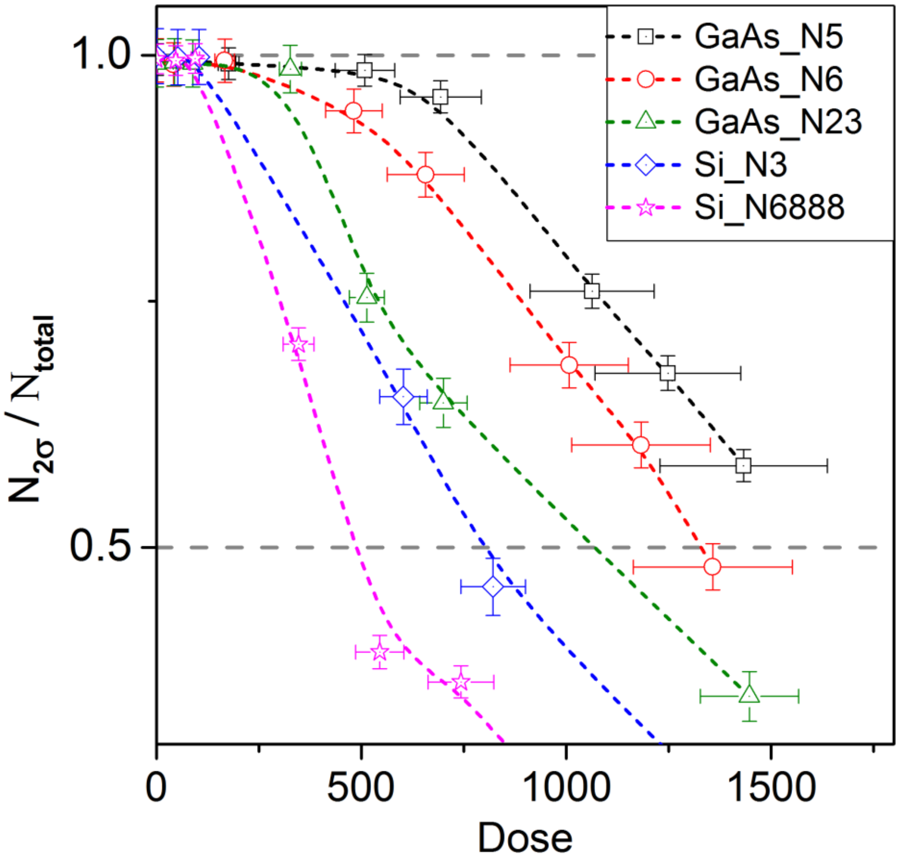


Due to increasing of the dark current the pedestal considerably broadened and the measurement becomes difficult for doses higher 0.5 MGy.

N3,N5 – Si type 1;

6886, 6888 – Si type 2;

GaAs:Cr and Si sensor resolution.



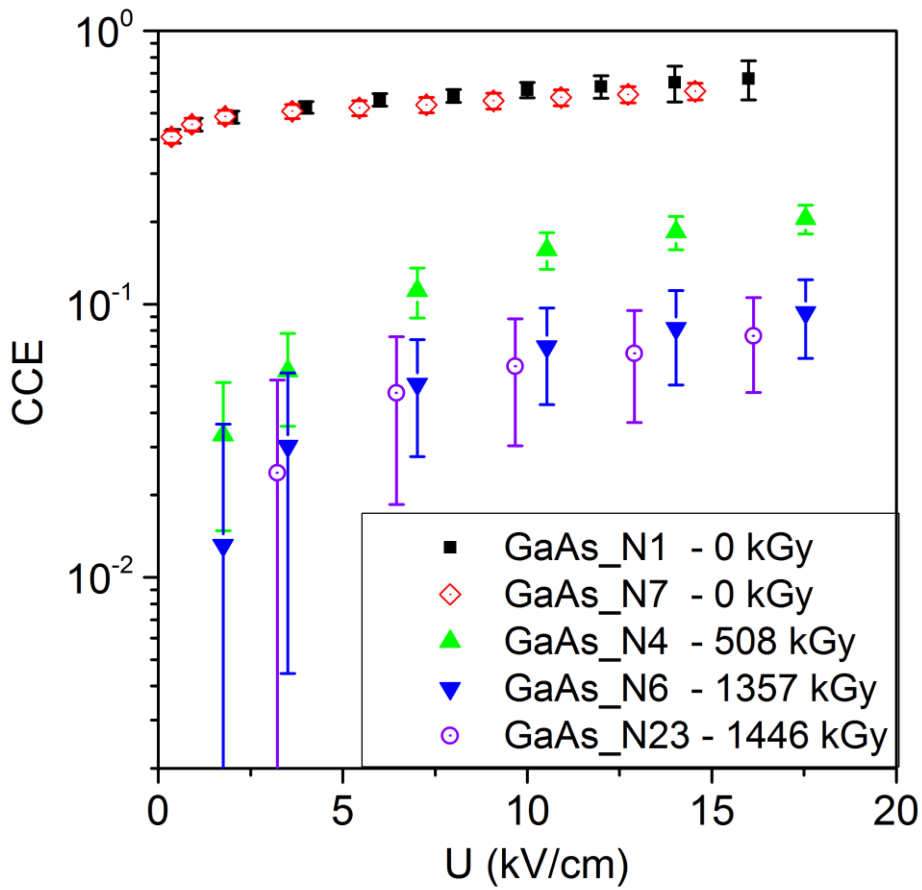
2σ-criterion was applied for a correct comparison of GaAs and Si sensors performance.

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

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

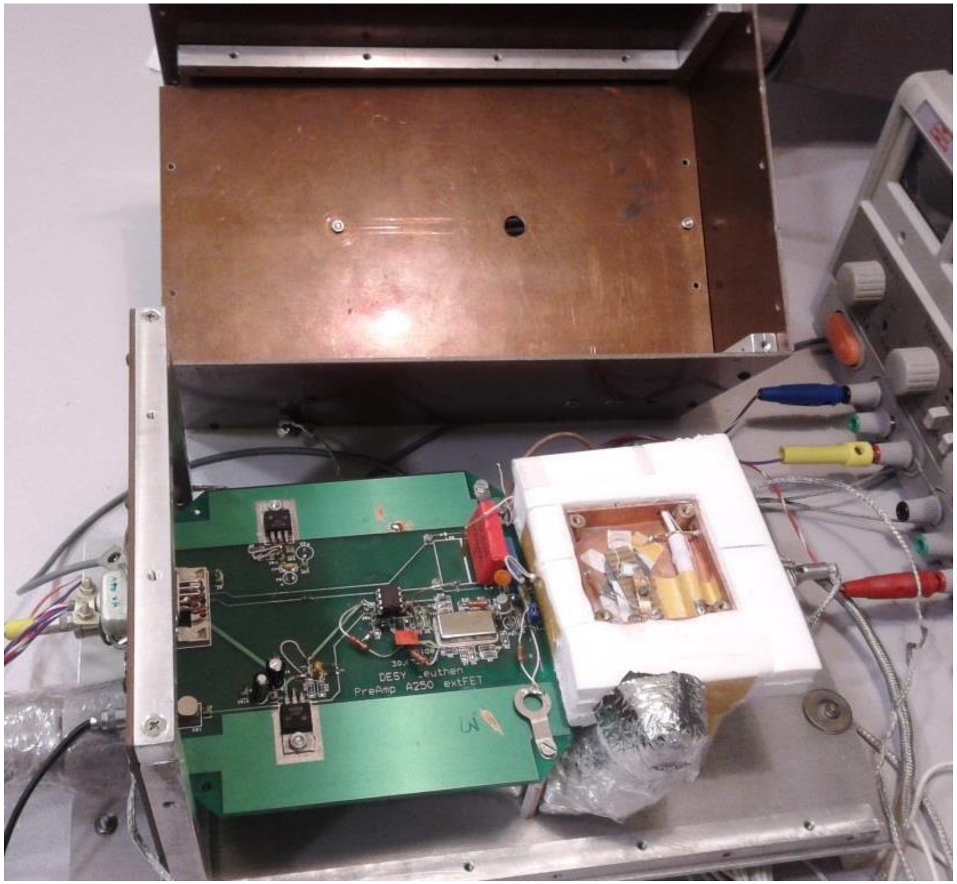
The greater ***K***, the better the signal and pedestal separation for MIP-spectrum.

GaAs:Cr CCE - V_{bias} dependence.



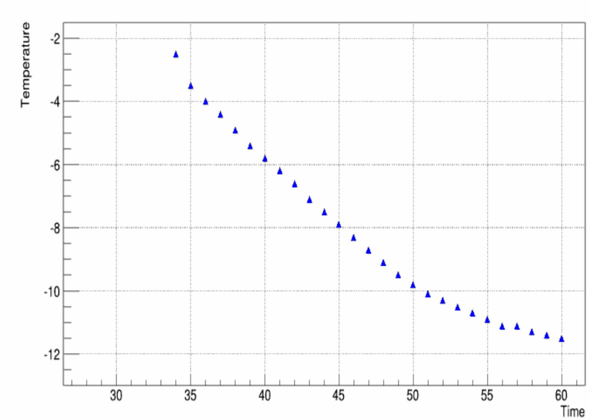
For the irradiated GaAs:Cr sensors CCE increases significantly with the field strength up to **20 kV / cm**, while the unirradiated sensors reach saturation at **1 kV/cm**

Cooling



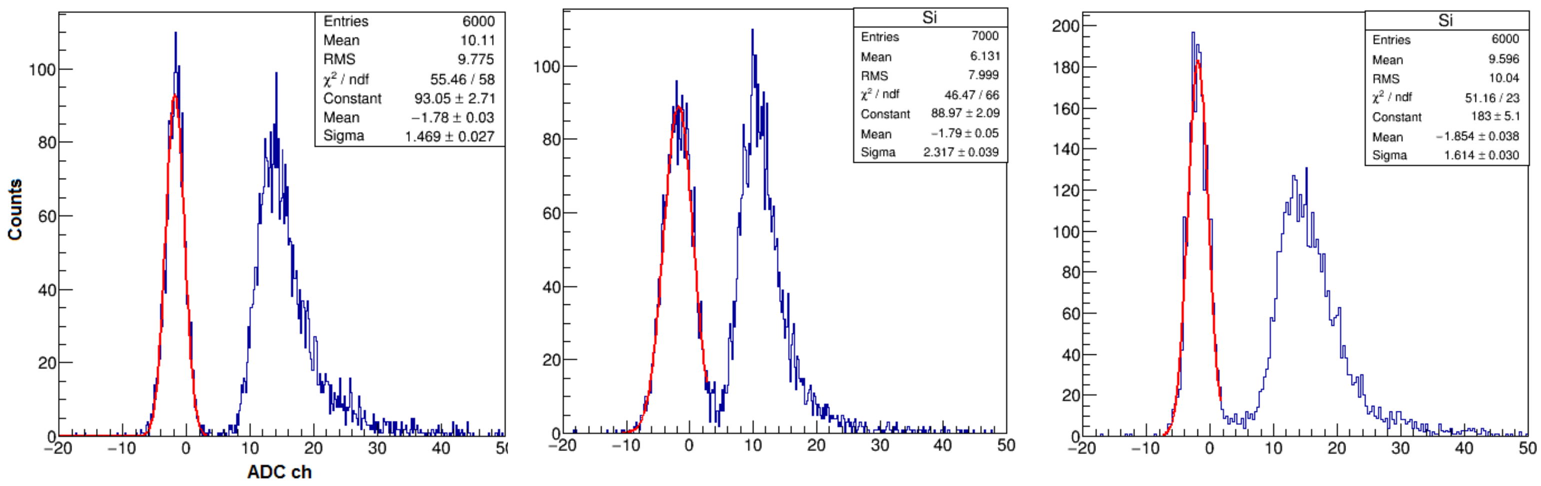
Measurement setup was modified for cooling.

Allow to measure I-V and CCE sensors with T from room temperature to -50°C



Si cooling: MIP spectrum

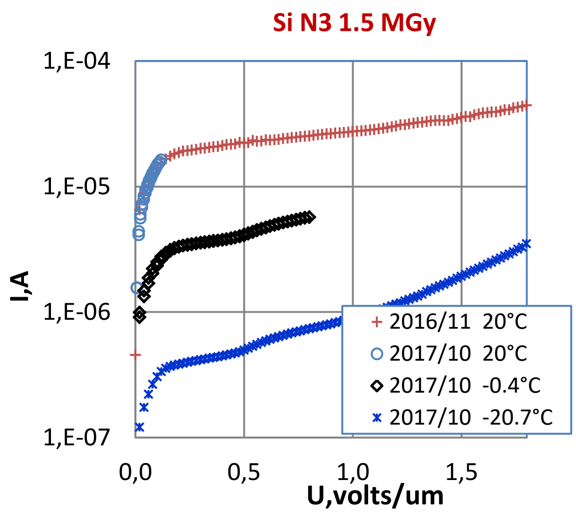
Si N5 0.5 MGy ; Ubias = 100V | **Si N3 1.5 MGy ; Ubias = 100V** | **Si 6888 1.5 MGy ; Ubias = 400V**

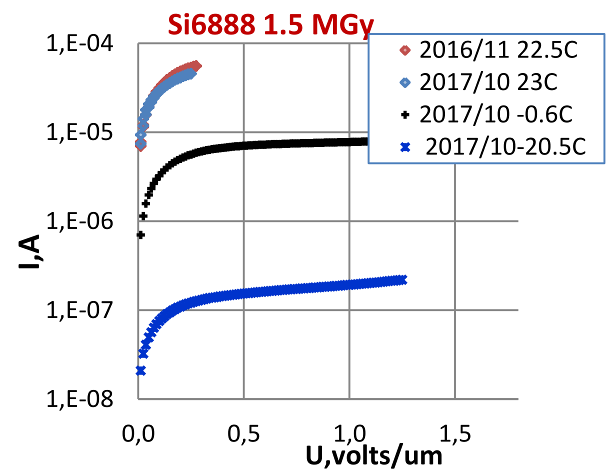


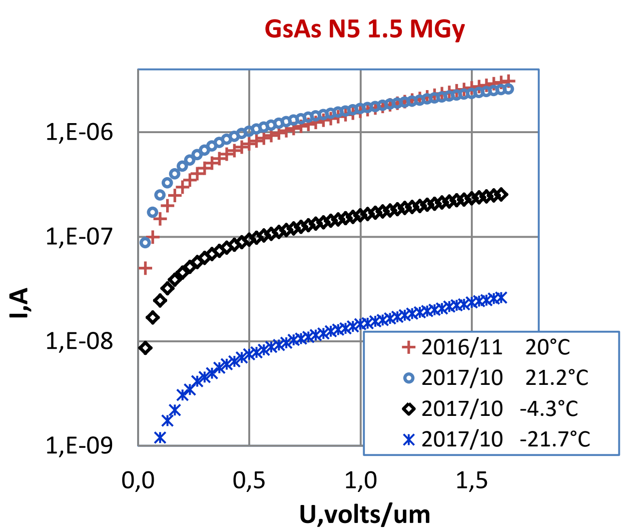
MIP spectra for Si type1: 0.5 MGy (left) 1.5 MGy (center). Type2 1.5 MGy (right).

The pedestal is visible on the left. Measurement temperature **-21^{o}C**.

Sensors cooling: I-V



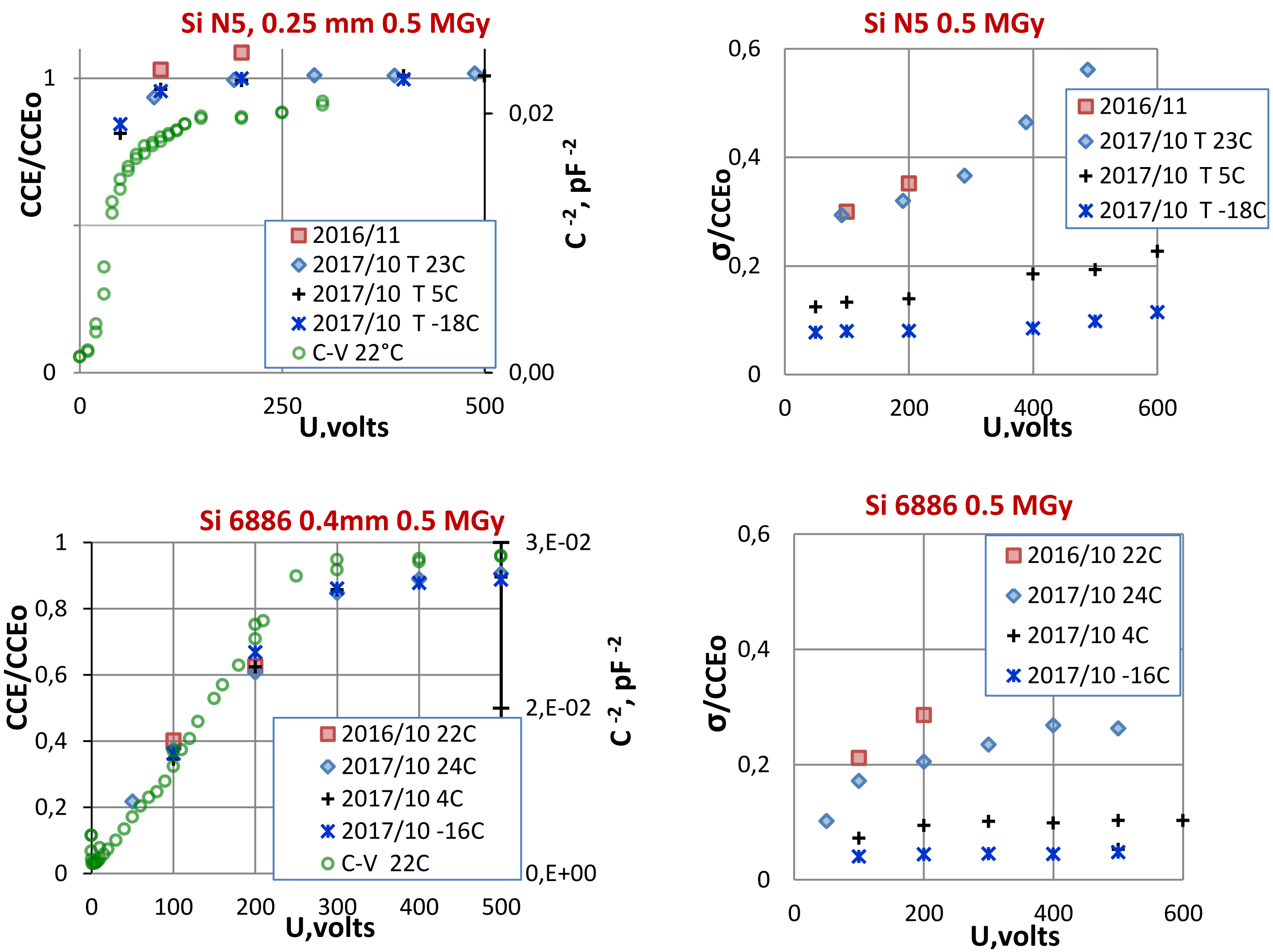




I-V characteristics, measured with different sensor temperatures:

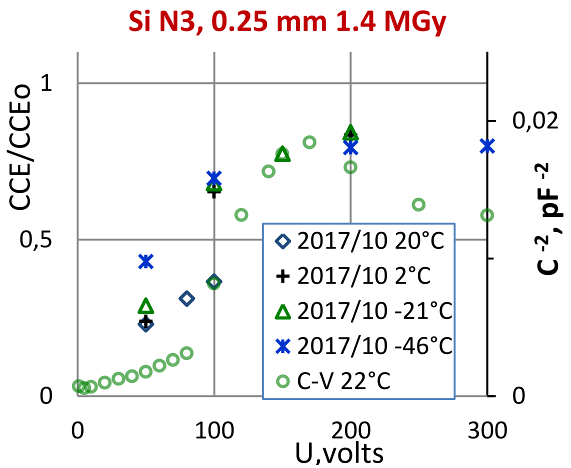
- Si_N3 (type1) 1.4 MGy
- Si_6888 (type2) 1.5 MGy
- GaAs:Cr_N5 (barrier) 1.5 MGy

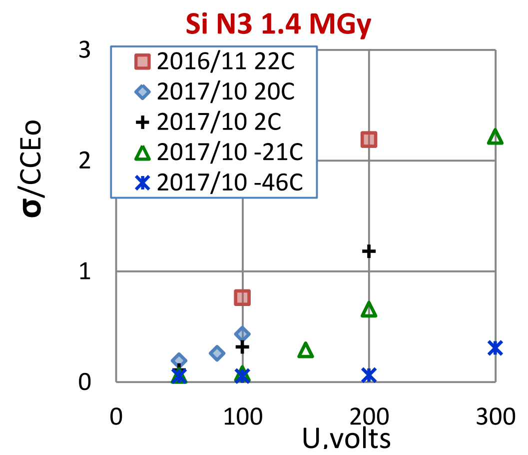
Si cooling 0.5 MGy: CCE-V, C^{-2}-V, σ-V

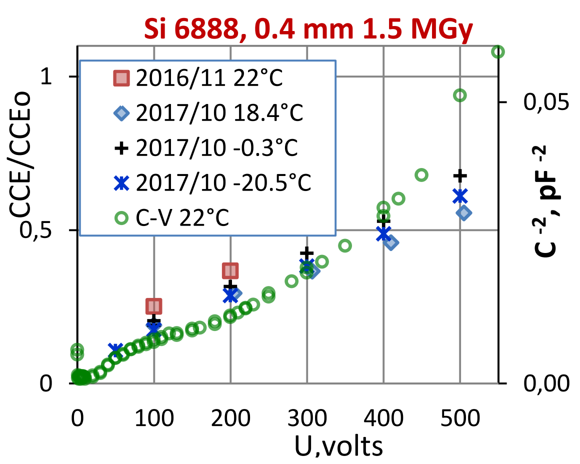


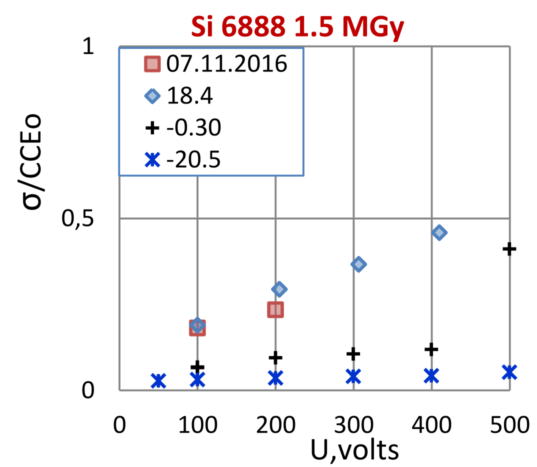
CCE, C^{-2}(left) and **σ** (right) as function of applied voltage for Si sensor after irradiation dose 0.5 MGy (2.5×10^{15} e^-/sm^2). Si N5 – type1, Si 6886 – type2.

Si cooling 1.5 MGy: CCE-V, C^{-2}-V , σ-V



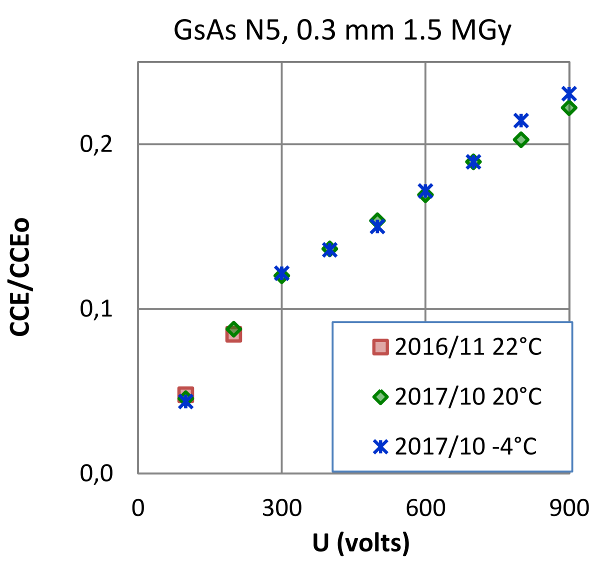


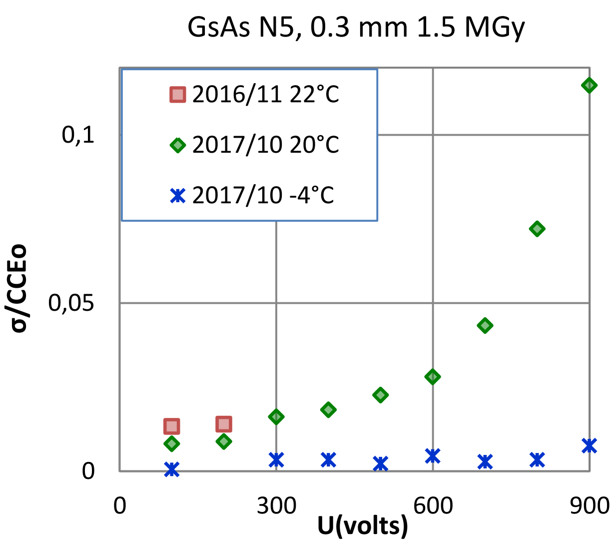




CCE, C^{-2}(left) and **σ** (right) as function of applied voltage for Si sensor after irradiation dose 1.5 MGy ($7x10^{15}$ e^-/sm^2). Si N3 – type1, Si 6888 – type2.

GaAs cooling 1.5 MGy: CCE-V, σ-V





CCE (left) and **σ** (right) as function of applied voltage for GaAs:Cr N5 sensor after irradiation dose 1.5 MGy (7x10^{15} e^{-}/sm^{2}).

Summary

- Two types of GaAs:Cr together with n-type Si sensors were irradiated to dose 1.5MGy by 20 MeV electron beam.
- Irradiation leads to different results in GaAs:Cr and Si sensors: strong increasing of the dark current in Si and dropping CCE in GaAs:Cr.
- A significant difference between two types of GaAs:Cr sensors is not found.
- 2-σ criterion was applied in order to estimate irradiated sensors resolution.
- After dose 1.5 Mgy signal magnitude drops to 10-20 % of initial in GaAs:Cr.
- Si sensors require cooling and rising $U_{bias} > U_{fd}$ more strong for sensors from Hamamatsu.