Development of Thin, Thermally Stable n-type Junctions for Segmented HPGe Detectors via Pulsed Laser Melting

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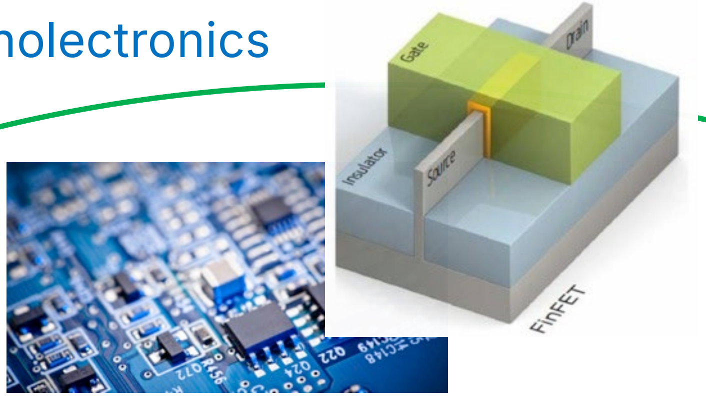
https://web.infn.it/gamma
https://www.agata.org

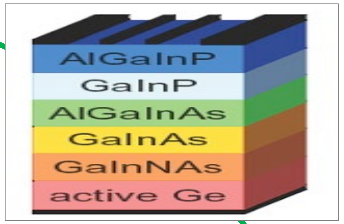
Outline

Germanium material for….

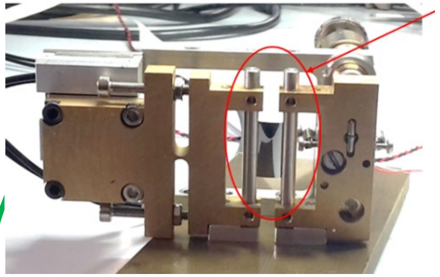
Nanolectronics

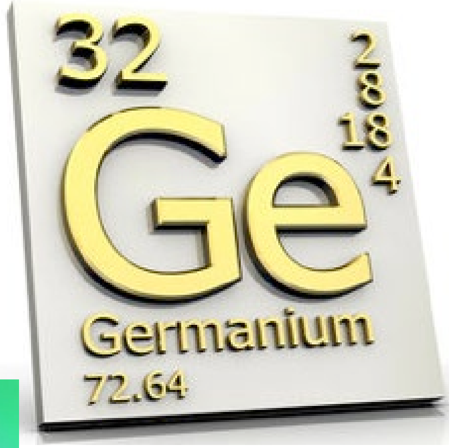


Photodetectors

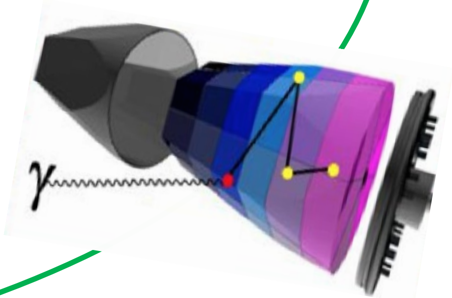


Channeling and
crystalline undulators





γ-Ray detectors



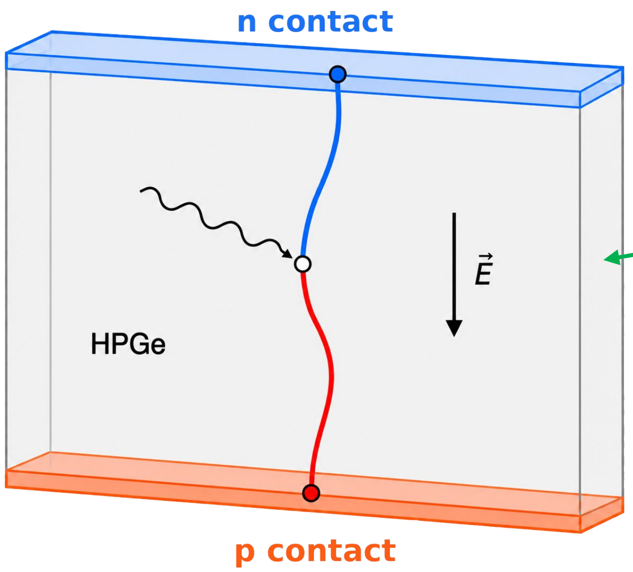
Solar
cells

Lasers

What is an HPGe Detector?

High-Purity Germanium detectors HPGe:
reverse-biased p-i-n semiconductors used to detect gamma-rays.

n^+ Li doped = 0.9 mm
Thermal diffusion
(electron collection)



Surface passivation

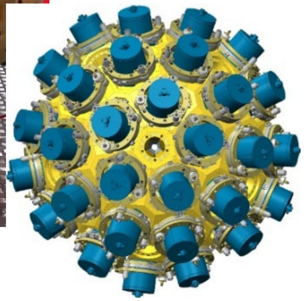
p^+ B doped = 0.3 μm
Ion implantation
(holes collection)

HPGe
Charge carrier density: 10^{10} cm^{-3}

Diameter: 40mm
Height: 20mm

Gamma detector state of the art
(AGATA in EU or GRETA/GRETINA in USA)

Advanced GAmma Tracking Array (AGATA)

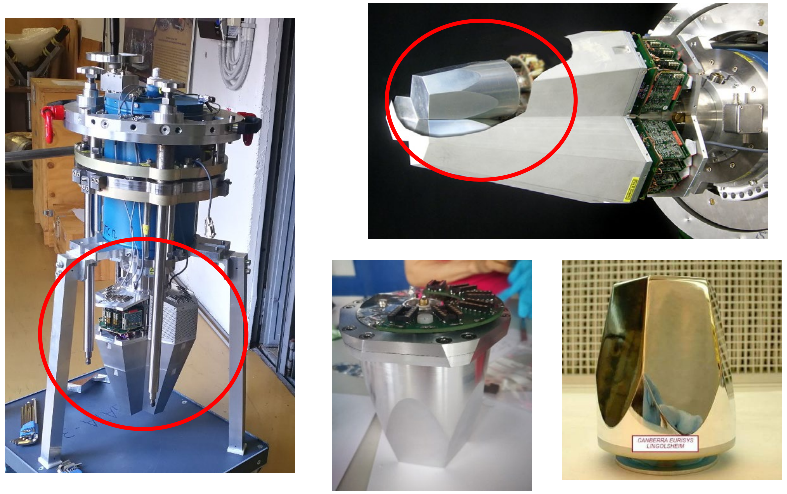


J.J Valiente al. **NIM** Phys. Res. A (2023) 1049

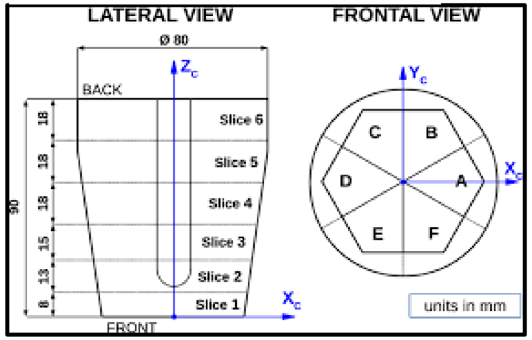
Gamma-Ray Tracking Array (GRETA)

Gamma detector state of the art
(AGATA in EU or GRETA/GRETINA in USA)

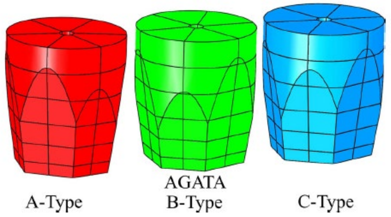
ATC (AGATA triple cluster detector)



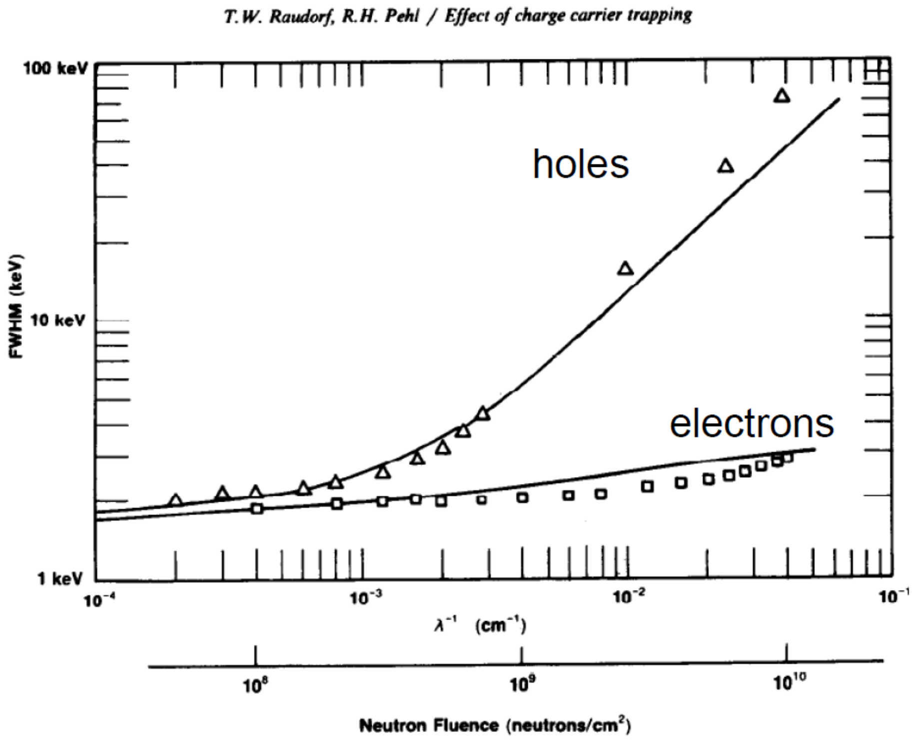
MIRION



3 asymmetrical HPGe detector

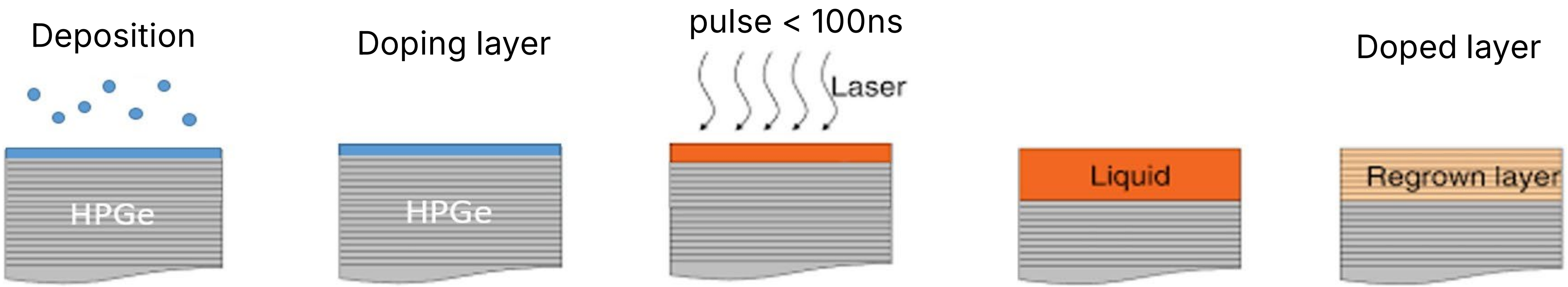


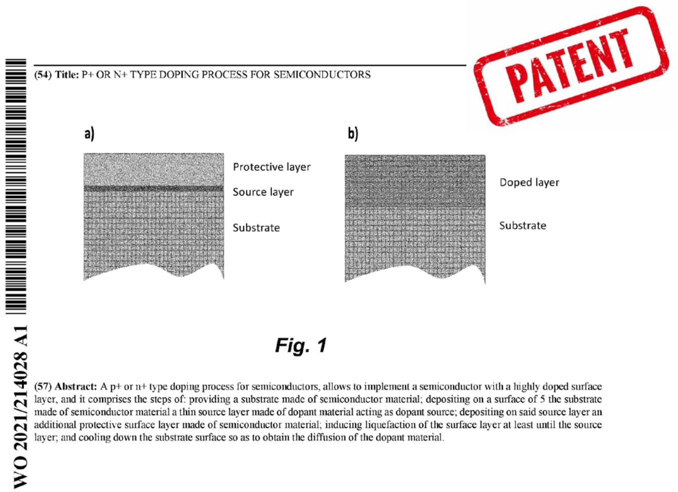
J. Eberth et al. Eur. Phys. J. A (2023) 59: 179



Encapsuleted coaxial segmented HPGe n-type detector:
2Kg weight
80 mm diameter
90mm long
1 core inner contact
36 segments

New contact/junction on HPGe: PLM (Pulse Laser Melting)




WO 2021/214028 A1

(54) Title: P+ OR N+ TYPE DOPING PROCESS FOR SEMICONDUCTORS

Fig. 1

(57) **Abstract:** A p+ or n+ type doping process for semiconductors, allows to implement a semiconductor with a highly doped surface layer, and it comprises the steps of: providing a substrate made of semiconductor material; depositing on a surface of 5 the substrate made of semiconductor material a thin source layer made of dopant material acting as dopant source; depositing on said source layer an additional protective surface layer made of semiconductor material; inducing liquefaction of the surface layer at least until the source layer; and cooling down the substrate surface so as to obtain the diffusion of the dopant material.

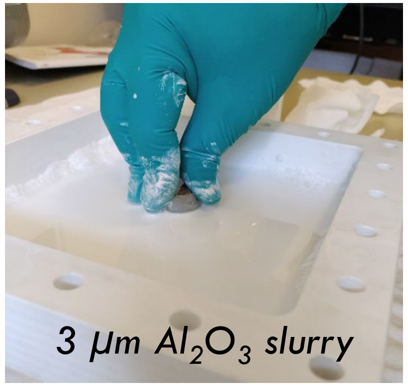
Autors:
D. De Salvador, G. Maggioni, D. Napoli, E. Napolitani

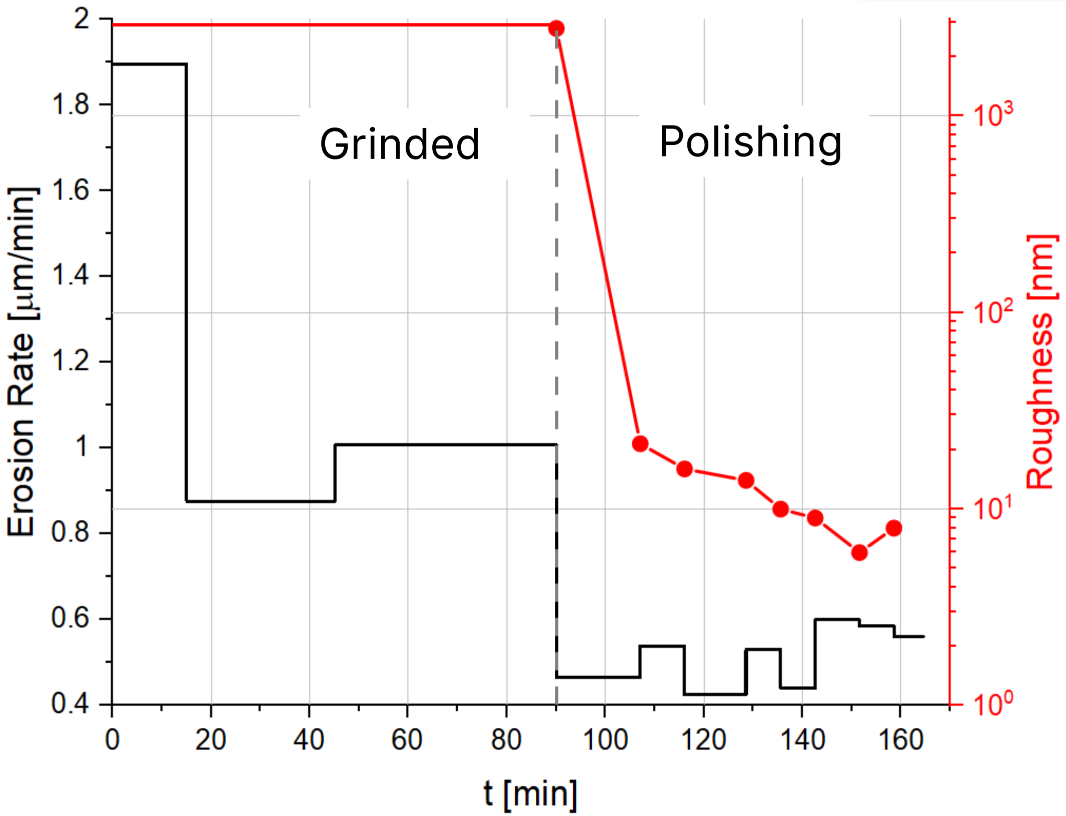
Advantages:

- Melting temperature is reached and maintained for a very short time (<100 ns)
- Only the surface (< 200 nm) is melted, the bulk is at room temperature
- High dopant concentrations with very sharp dopant profile
- Very clean process suitable for preserving the Ge hyperpurity
- Suitable for complex contact geometries (segmentation)

New PLM contact/junction on HPGe: Crystal surface preparation

Grinded surface (opaque)





Etched surface (High waviness, low roughness)

(3:1) HNO_3 : HF

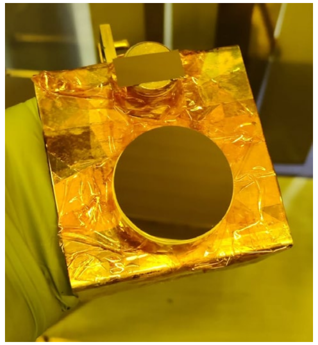
Polished surface (CMP) (Low waviness, low roughness)

rotating disc rinsed with H_2O_2 1% (pH 12 with KOH) Rate: ≈ 200 nm/min

(2025) + Colloidal Silica (30nm size) Rate: ≈ 400-600 nm/min

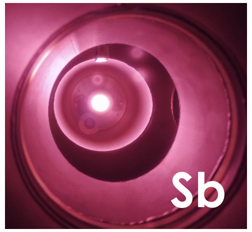
New contact/junction on HPGe: Sputtering deposition and laser PLM

Magnetron Sputtering deposition

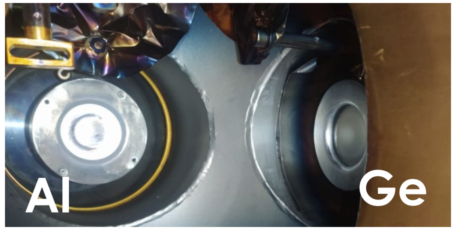


n^+	Sb	2 nm [illegible]
p^+	Al (Ge cap)	4 nm (10 nm) [illegible]

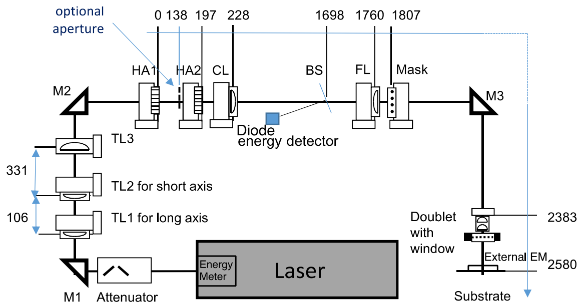
[illegible]

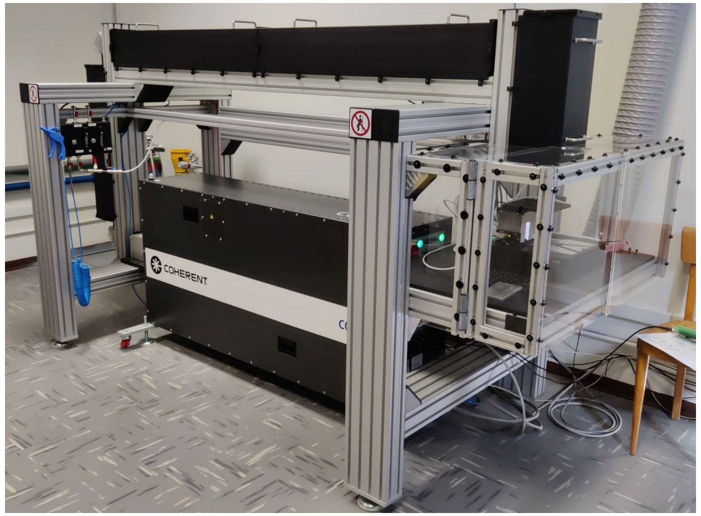


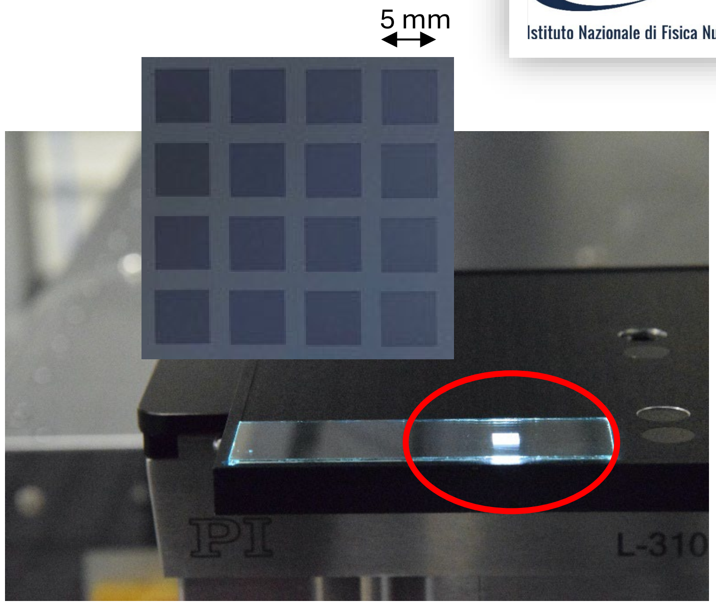
[illegible]



Excimer KrF laser



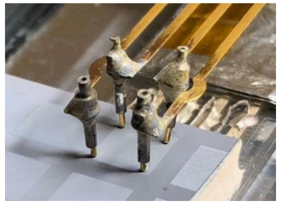


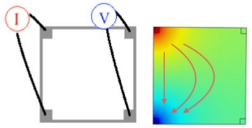


- λ=248 nm, 22 ns
- Frequency: 1-10 Hz
- ED= 50-1300 mJ/cm2
- Square 5×5mm2 spot
- Homogeneity: < 2%
- lateral resolution <30 µm
- Motorized XYZ stage

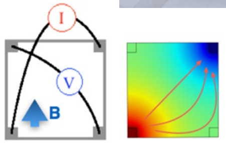
New PLM contact on HPGe: characterization

Van Der Pauw - Hall

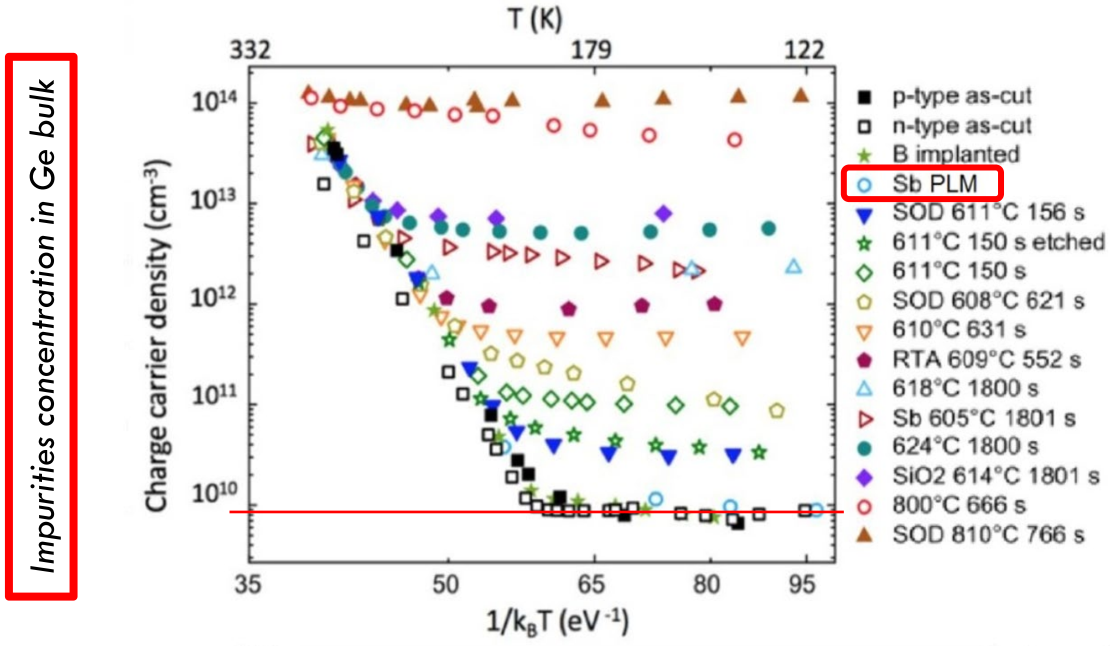





Sheet resistance

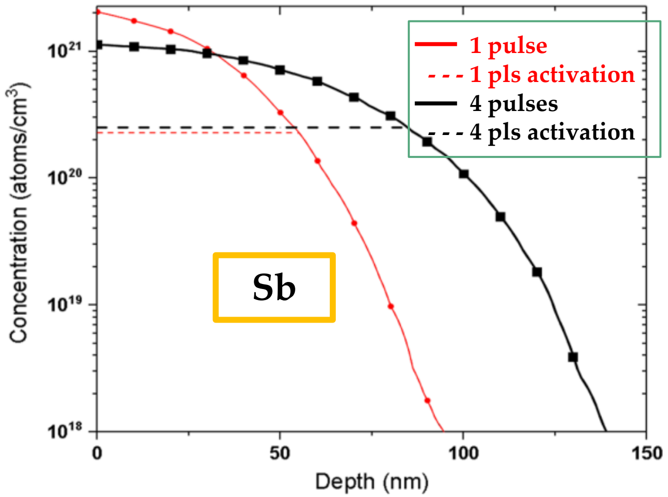


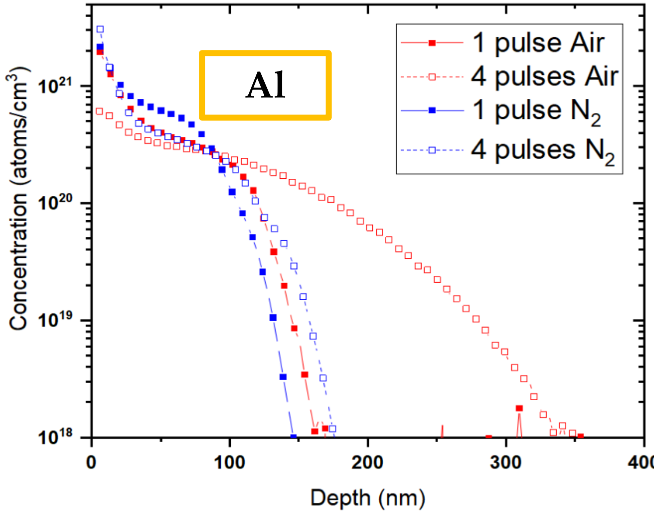
Charge carriers



V. Boldrini et al., **Journal of Physics D: Applied Physics** (2018) volume 52, 3

SIMS (Secondary Ions Mass Spectrometry)



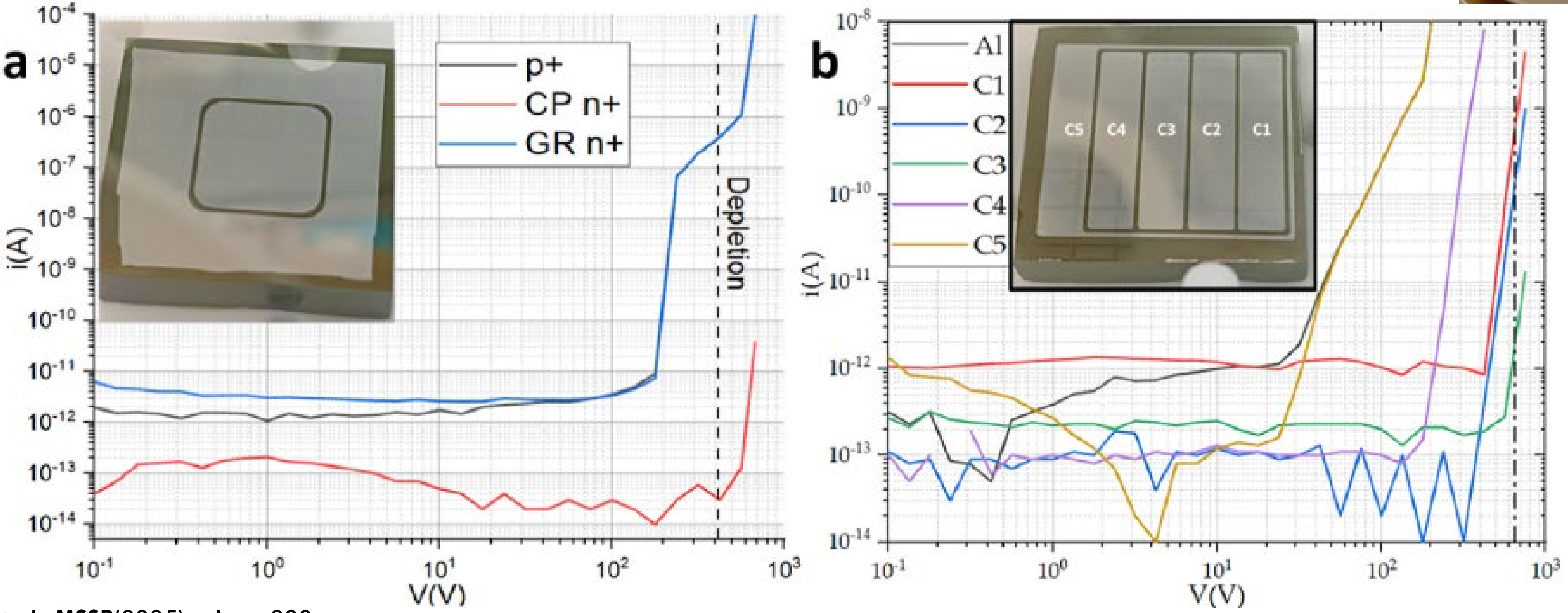


C. Carraro et al. "**Applied Surface Science**, 509 (2020)

HPGe PLM planar segmented detector: I-V characterization

Soft contact + Al plated (segmented)

Sb/p-HPGE/Al, $N=6\times10^{9}$ cm^{-3} L=28mm, t=10mm	Sb/p-HPGE/Al, $N=1.6\times10^{10}$ cm^{-3} L=33mm, t=8.5mm



S. Bertoldo et al., **MSSP**(2025) volume 200

HPGe PLM planar detector: Summary Process

HPGe p-type detector

Detector	d (mm)	N_A [10^{10} cm^{-3}]	V_D [V]	Process	V_B [V]	$\lvert \vec{E_B} \rvert$ [kV/cm]
D2-A	9.20	1.6	760	Dust-proofed equipment	15–25	0.2–0.3
D2-B	9.15	"	750	Aggressive solvents	20–40	0.3–0.4
D2-C	9.15	"	750	Au-free lithography	50–60	0.4–0.5
D2-D	9.10	"	740	Chemical-mechanical polishing	60–90	0.5–0.6
D2-E	8.8	"	690	Indium discs	80–110	0.5–0.6
D3	19.8	0.6	1320	Kapton foils contact	1200	1.3
D2-F	8.6	1.6	660	Mylar foils contact	150–300	0.7–1.1
D4	10	0.6	335	Thick Al plating and mylar foils contact	500–600	0.8–0.9
D2-G	8.6	1.6	660	Thick Al plating and mylar foils contact	400–600	1.2–1.5

S. Bertoldo et al., **MSSP**(2025) volume 200
https://doi.org/10.1016/j.mssp.2025.109967

Materials Science in Semiconductor Processing 200 (2025) 109967

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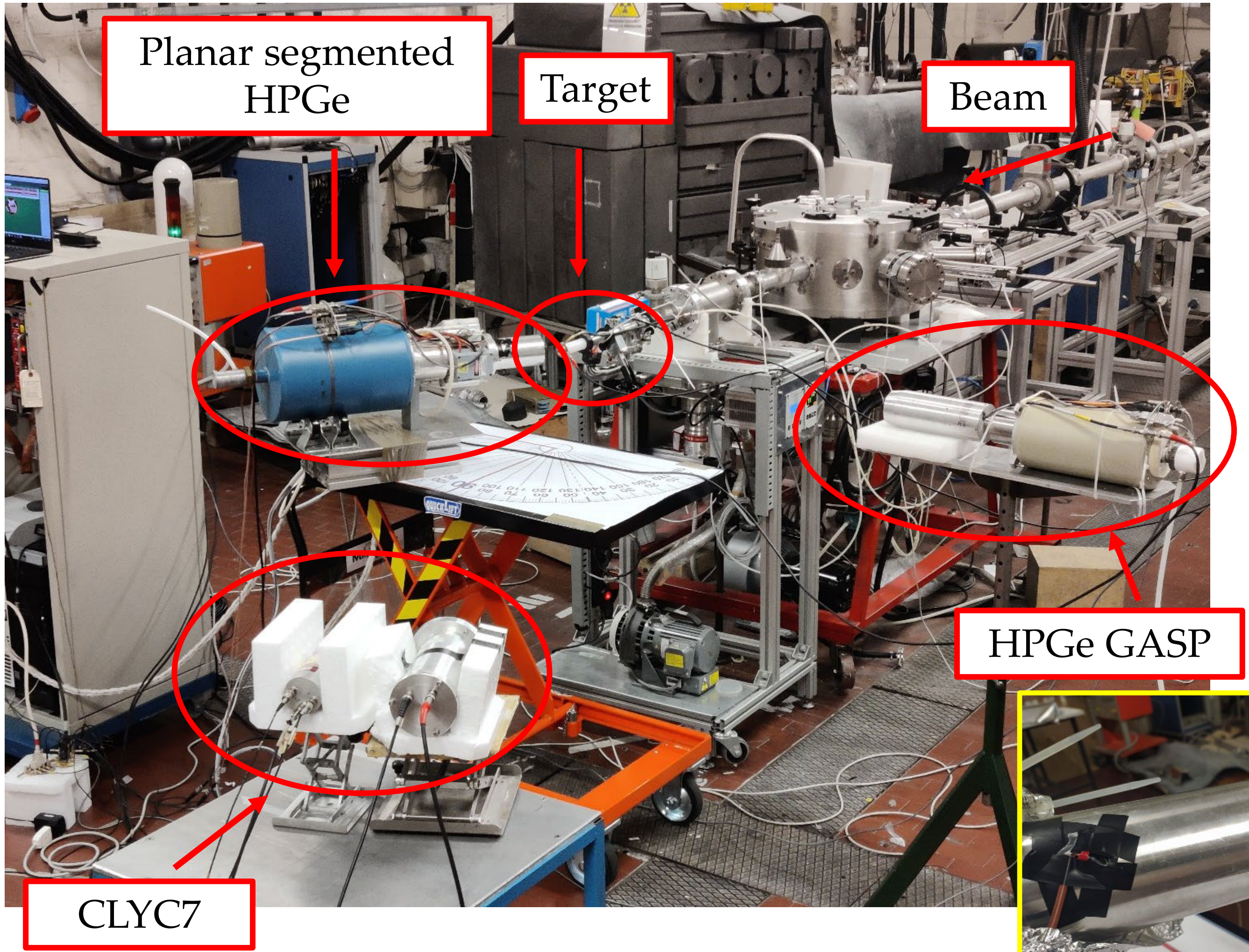
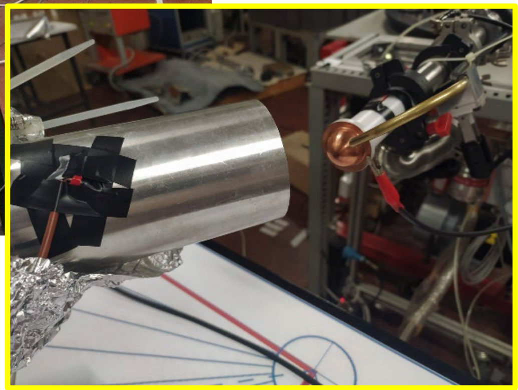
Lithium-free hyperpure germanium detectors with enhanced thickness, area, and segmentation via pulsed laser melting

HPGe PLM detector: Radiation Hardness (Neutron damage)





380nA 4MeV proton beam
^{7}Li target, 100µm

Reaction: ^{7}Li (p,n) ^{7}Be

Prototype detector is located at 30° 9.5 cm

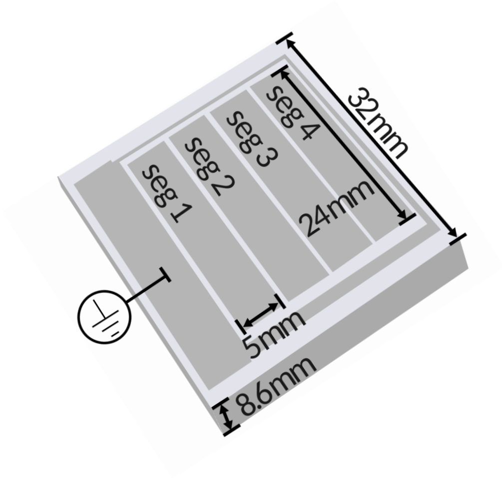
Neutrons are directly measured with

- CLYC7 scintillators, 30° 2 m
- GASP HPGe γ detector, 90° 1 m

$$^{7}Be + e^- \xrightarrow{53.3\ \text{days}} {}^{7}Li \rightsquigarrow 477.6\ \text{keV}$$

R. Escudeiro at all. "**Neutron radiation damage on a planar segmented germanium detector**" Acta Physica Polonica B Proceedings Supplement 17, 3-A14 (2024) DOI:10.5506/APhysPolBSupp.

HPGe PLM detector: Radiation Hardness (Neutron damage)



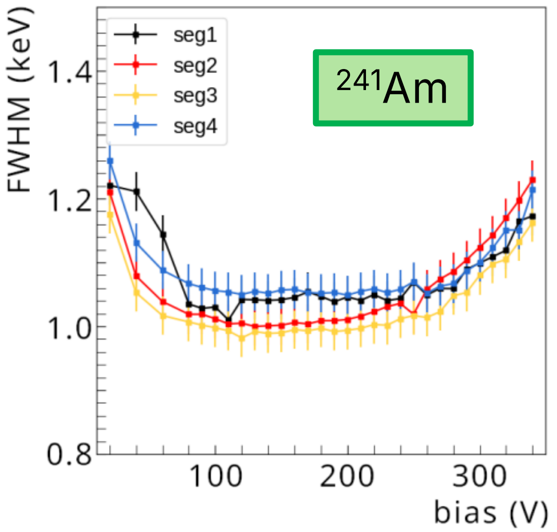
Detector prototype:

Sb/p-HPGe/Al L=

32mm, t= 8.6mm

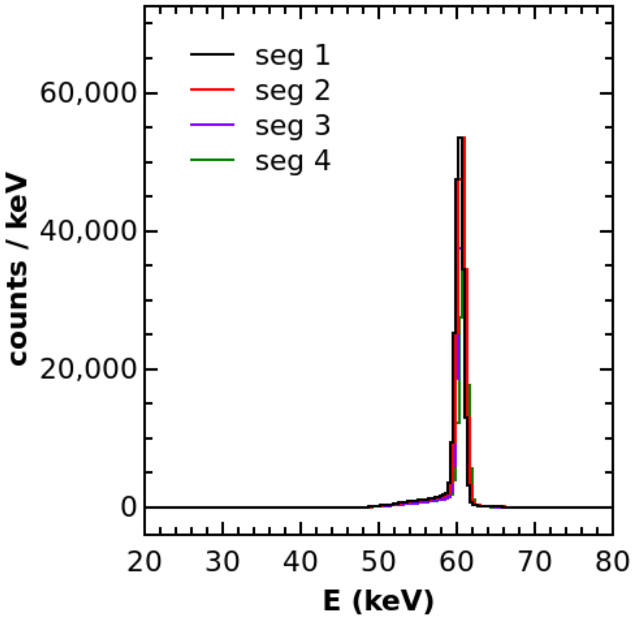
4 contacts + guard ring

Energy resolution



Starting resolution at 80V operational bias before the neutron damage run

^{241}Am
E = 59,5 keV
FWHM < 1,1 keV



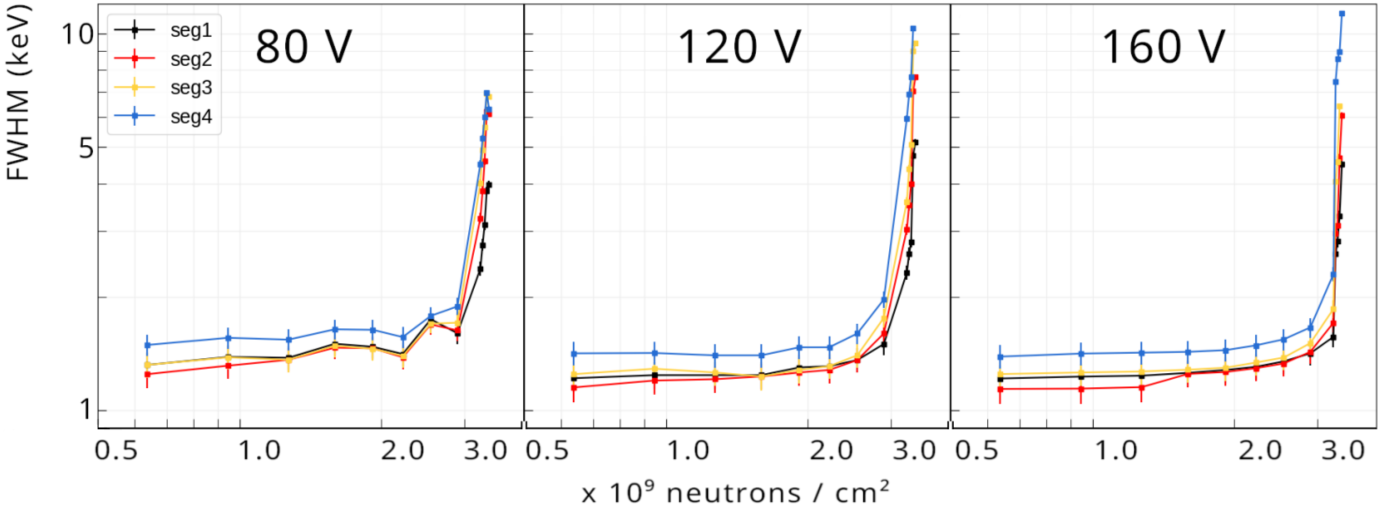
HPGe PLM detector: Radiation Hardness (Neutron damage)

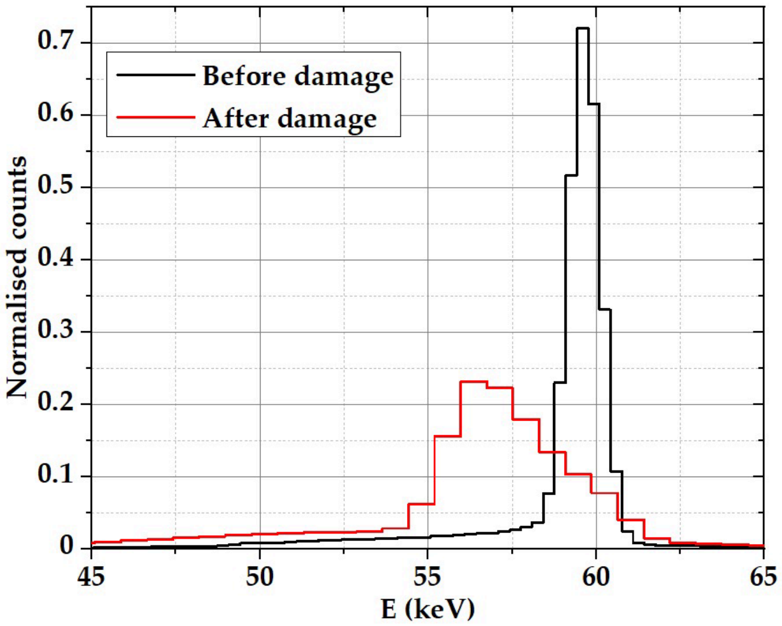
Operational Voltage 80-120-160V

Neutron irradiation for 20min and to 5 min runs with ^{241}Am to better characterize resolution worsening

^{241}Am
E = 59,5 keV
FWHM = 3,2 – 4,2 keV

Drastic drop in resolution after
≈ $3 \cdot 10^9$ neutrons/cm^2 irradiation fluence

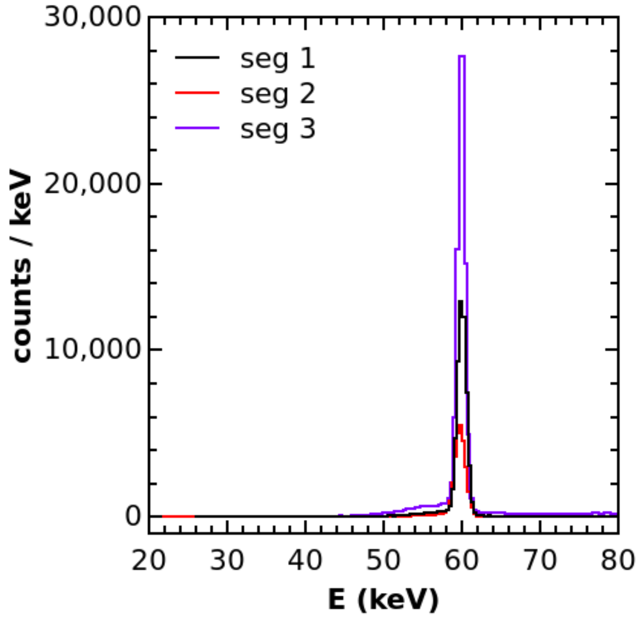


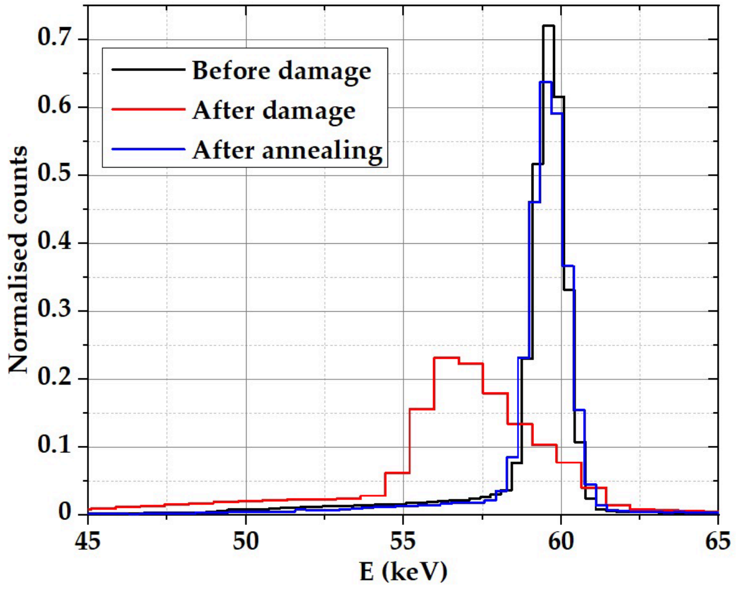


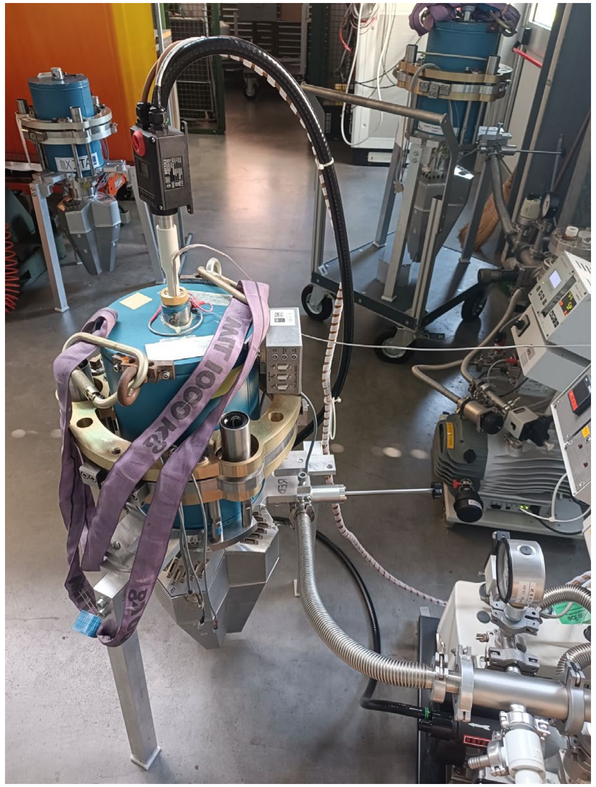
HPGe PLM detector: Radiation Hardness (Recovery)

Annealing: 40h at 105°C continuously pumped inside the cryostat

^{241}Am
E = 59,5 keV
FWHM < 1,6 keV







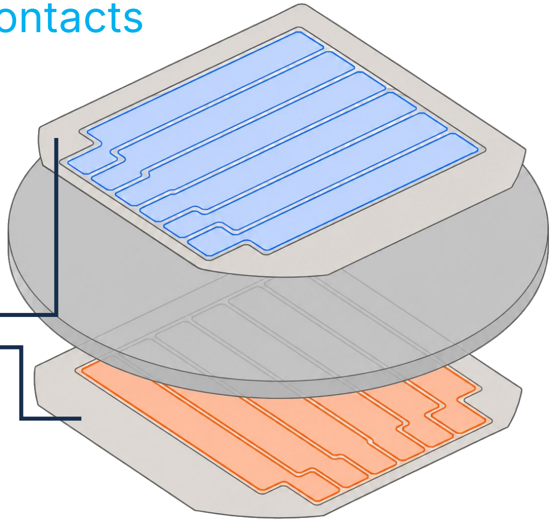
Design and Fabrication of DSSD HPGe detector

Planar Double Sided Strip Detector (DSSD)

2inch - 2mm HPGe
p-type wafer
6.0 ± 0.3 E9 cm^{-3}

6 Sb-PLM
n+ contacts

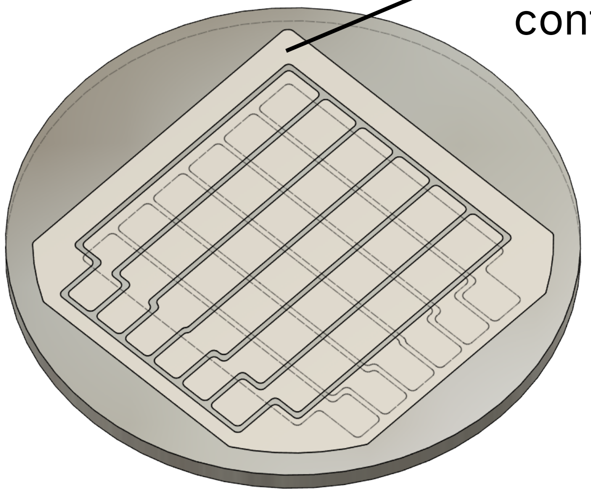
guard
rings



6 Al-PLM
p+ contacts

TOTAL AREA

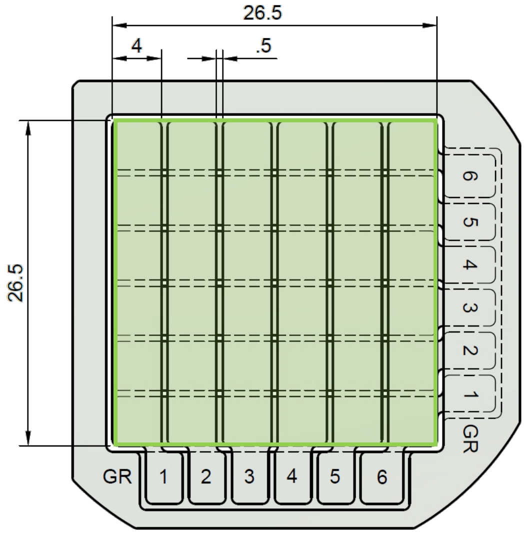
guard rings
for edge-field
control



six readout
electrodes per side

ACTIVE AREA

0.5 mm gap

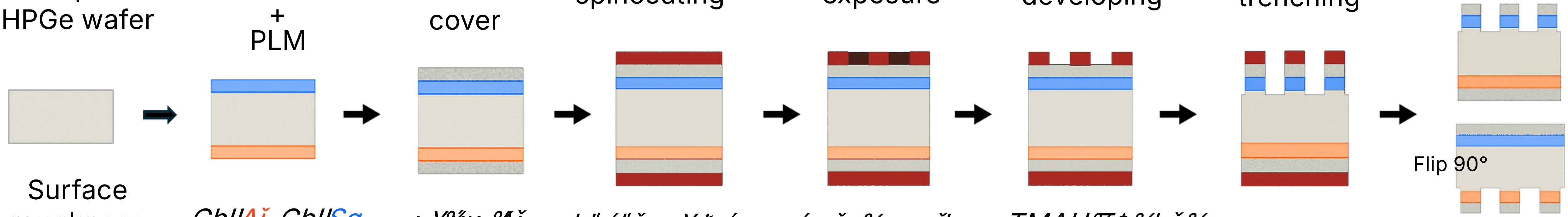


36 VOXELS
$4 \times 4 \times 2$ mm^3

Scan me to see photolithography animation

Design and Fabrication of DSSD HPGe detector

from prime HPGe wafer | sputtering + PLM | Al metallic cover | spincoating | exposure | developing | trenching | lift-off



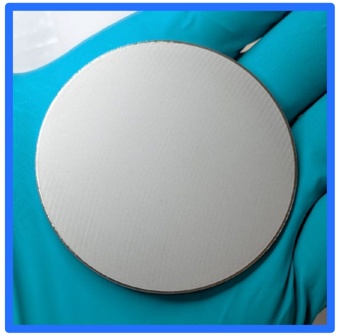
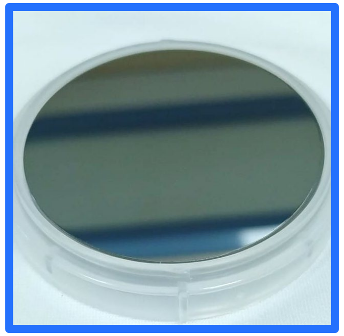
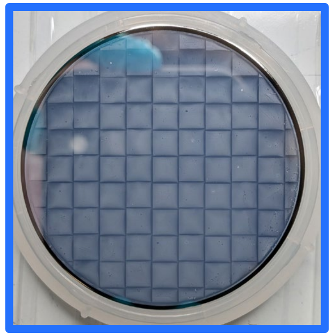
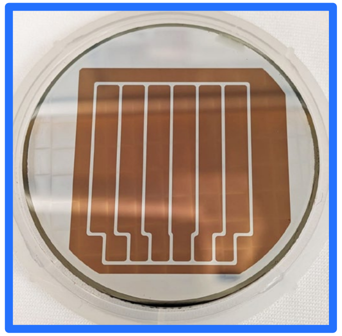
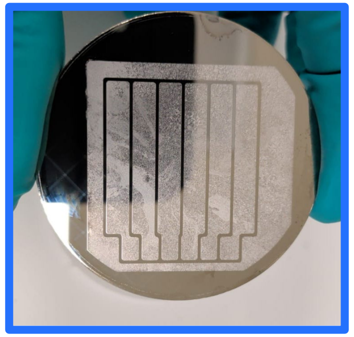
Surface roughness RMS nm

TMAH

H_3PO_4 HNO_3 CH_3COOH

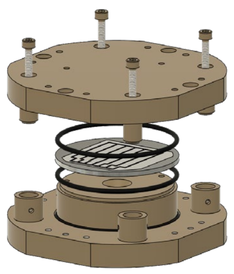
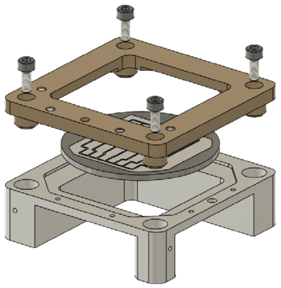
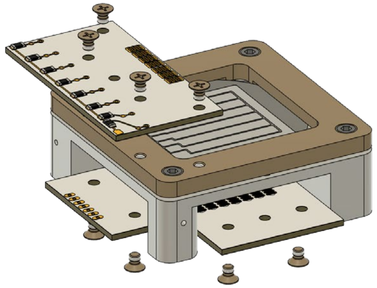
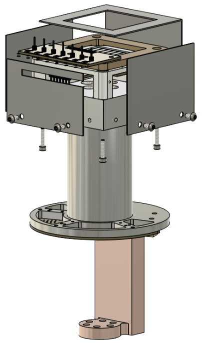
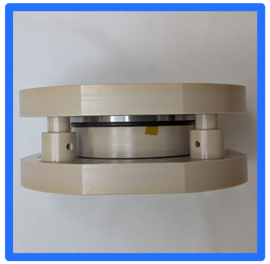
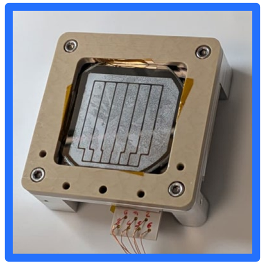
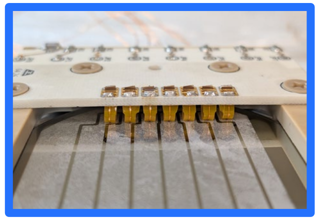
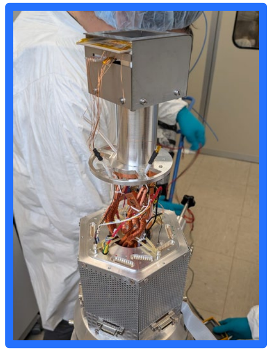
NMP

In-house CMP polishing of raw HPGe wafers
SiO_2 slurry, pH 14 + 1% H_2O_2

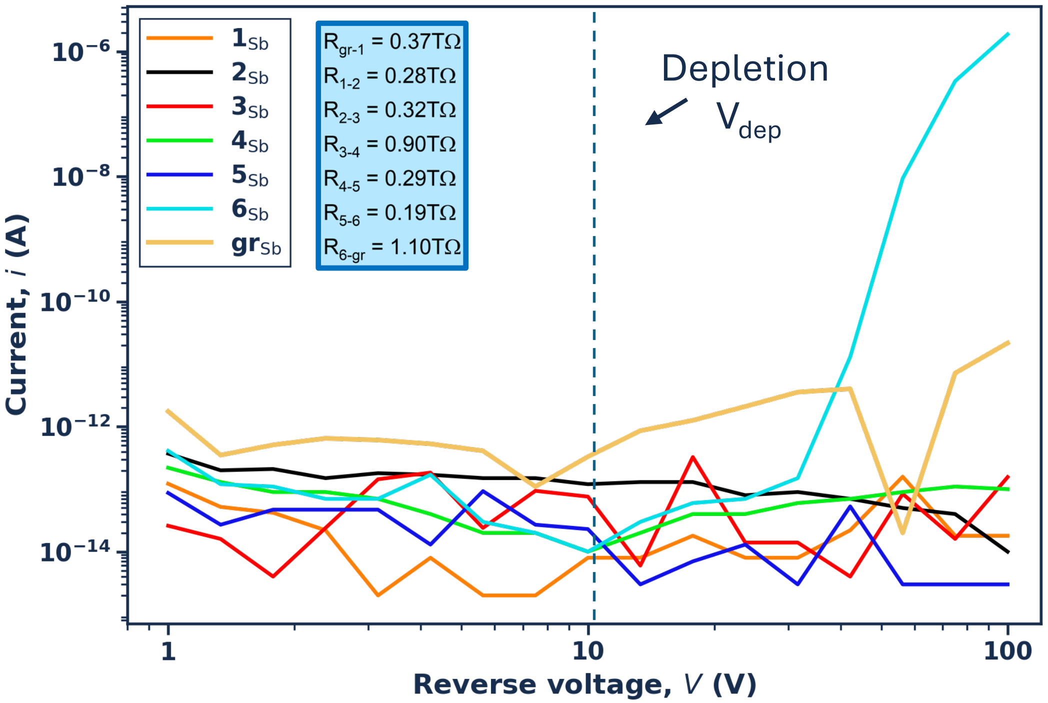
Design and Assembly DSSD HPGe detector

Scan me to see assembly animation

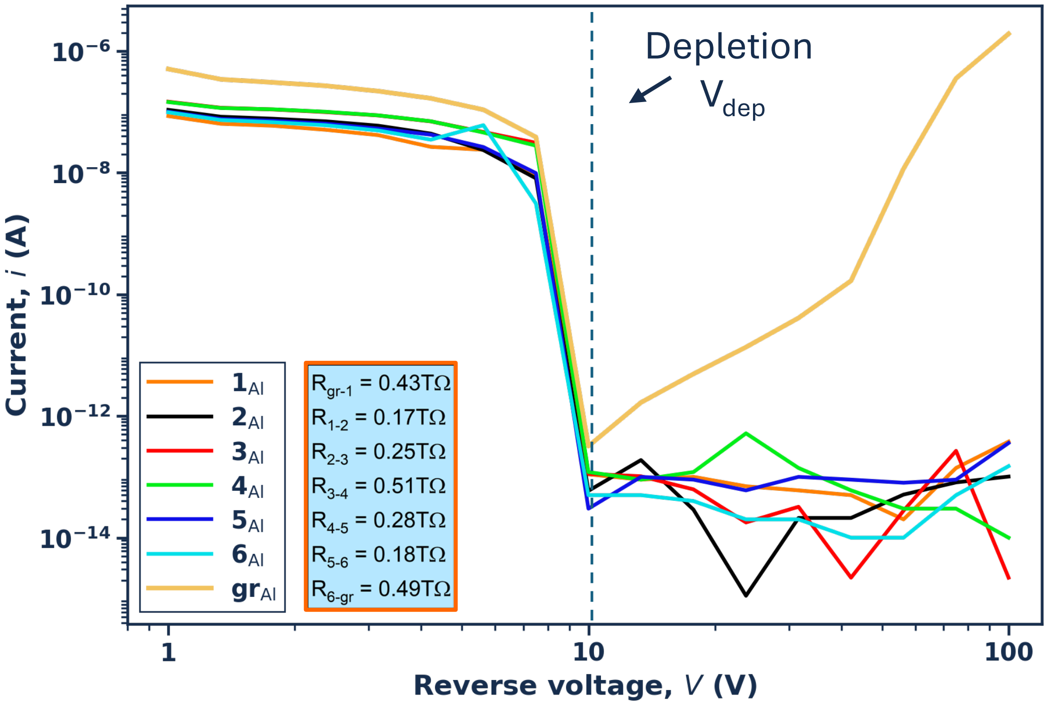
lateral passivation	holder assembly	PCB assembly	cryostat integration and wiring
			
		 	
HNO₺•HF‰‰¥‰₀₀ *₺‰₀ḏ ▪‰ά‰₀₸‰₀* *Qṡḅḷ ăễḏ ẹ‰ḅOH•*	*Aĭ Aĭ⁼Oₐ ‰aọẹ‰ά‰ễḅάk aĭ‰₀₀* *ăľ ṡȍĭḏ ẹ* *PEEK‰ȍ!!ễľ ĭạḅά‰ά‰V!!ọḏḅ‰₀₀* *ḅĭḅăıάḏăaĭ‰ṡĭaıḏ ḷ*	Rogers PCB Drop-shaped flex-PCB for soft electrical contacts	10^{-6}-10^{-7} mbar vacuum LN_2 cooling 77K

DSSD HPGe PLM detector: I-V characterization

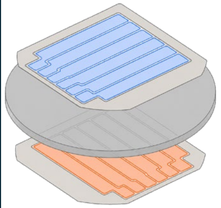
Sb contacts I-V



Al contacts I-V



6 Sb-PLM
n+ contacts

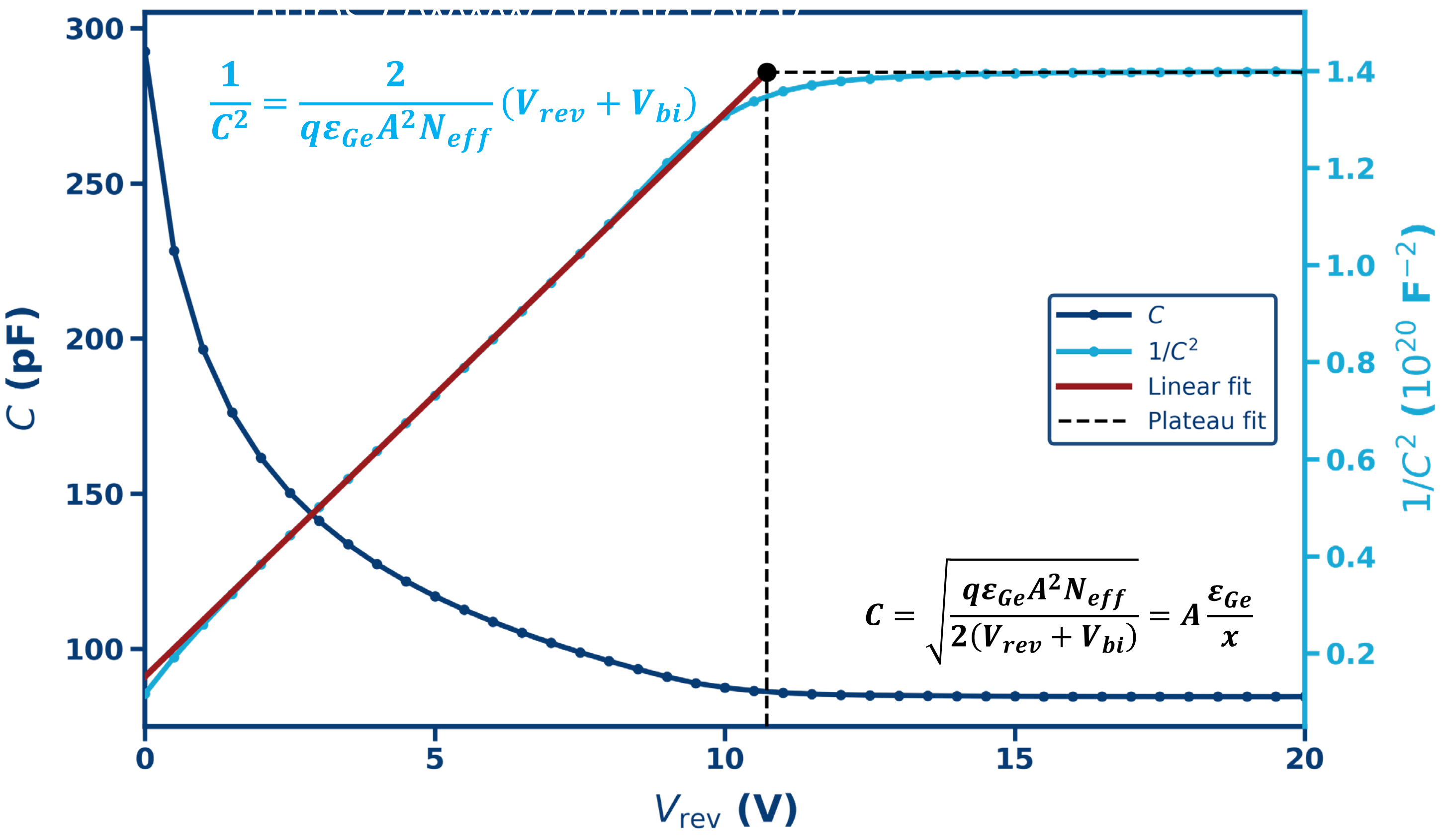


6 Al-PLM
p+ contacts

- $V_{break} > V_{dep}$ for all contacts
- Sb6 $V_{break} \approx$ 30–40 V $\approx 3V_{dep}$
- Excellent $R_{intergap}$,
- Low leakage currents

DSSD HPGe detector: C-V characterization

All contacts C-V



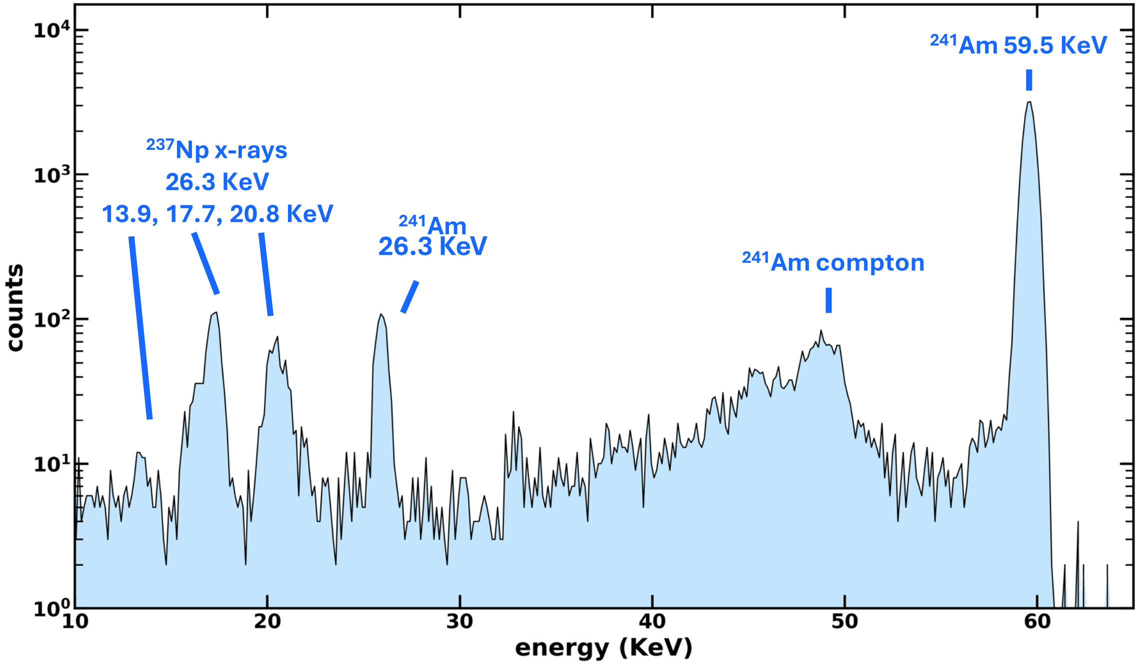
Ideal Full depleted detector

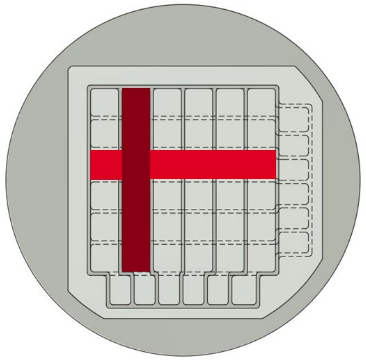
- C [illegible]
- N [illegible] $= 0.6 \cdot 10^{10}$ cm^{-3}

Real Full depleted detector

- $C_{sat} \rightarrow V_{dep}$
- C_{sat} (85.4 pF)
- $N_{eff} = 0.52 \cdot 10^{10}$ cm^{-3}
- $V_{dep} = 10.5$V

DSSD HPGe detector: γ spectroscopy performance





FWHM Digital acquisition Caen DT5730

^{241}Am: 59.54 keV | ^{137}Cs: 661.66 keV

Channel	^{241}Am FWHM [keV]	^{137}Cs FWHM [keV]
1_{Sb}	0.854 ± 0.002	1.65 ± 0.03*
2_{Sb}	0.881 ± 0.002	1.58 ± 0.03
3_{Sb}	0.879 ± 0.002	1.63 ± 0.02
4_{Sb}	N.D.	N.D.
5_{Sb}	0.874 ± 0.002	1.64 ± 0.04
6_{Sb}	0.879 ± 0.002	1.70 ± 0.03
1_{Al}	0.883 ± 0.002	1.957 ± 0.008
2_{Al}	N.D.	N.D.
3_{Al}	0.878 ± 0.002	1.944 ± 0.009
4_{Al}	0.897 ± 0.002	1.983 ± 0.009
5_{Al}	0.919 ± 0.002	1.998 ± 0.007
6_{Al}	0.907 ± 0.002	1.953 ± 0.007

Summary

- PLM technology is fully compatible with HPGe crystals, preserving their high purity and spectroscopic performance.
- PLM enables the fabrication of thin, finely segmentable junctions.
- Following neutron damage, PLM-segmented detectors can be effectively restored through annealing while retaining excellent energy resolution.
- The PLM-based HPGe DSSD has demonstrated promising FWHM performance.
- Ongoing work focuses on increasing the detector thickness to 15 mm (V_{depl} 2000/2500V)

R&D Gamma ray detector Team

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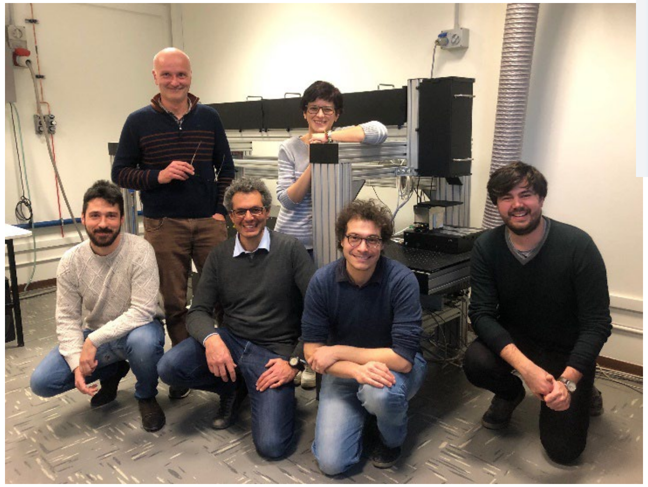
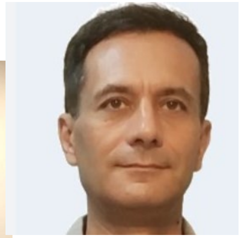
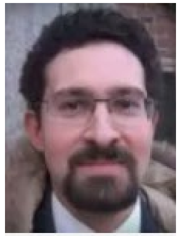

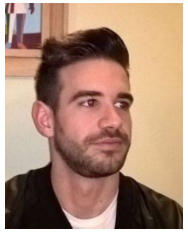



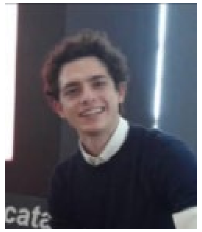
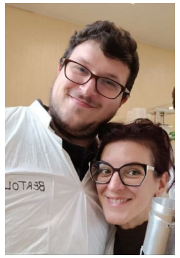


Development of Thin, Thermally Stable n-type Junctions for Segmented HPGe Detectors via Pulsed Laser Melting

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https://web.infn.it/gamma
https://www.agata.org