Istituto Nazionale di Fisica Nucleare

PSeGe@ENSAR2

3rd Position Sensitive Germanium Detectors (PSeGe)

Novel contact in HPGe for gamma ray detectors

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ENSAR2 has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654002

OUTLINE

- Introduction
- novel n$^+$ contact on HPGe crystal:
    - ✓LTA (laser thermal annealing)
- summary

HPGe detector: p^+/n^+ contact and lateral surface passivation

Surface passivation:

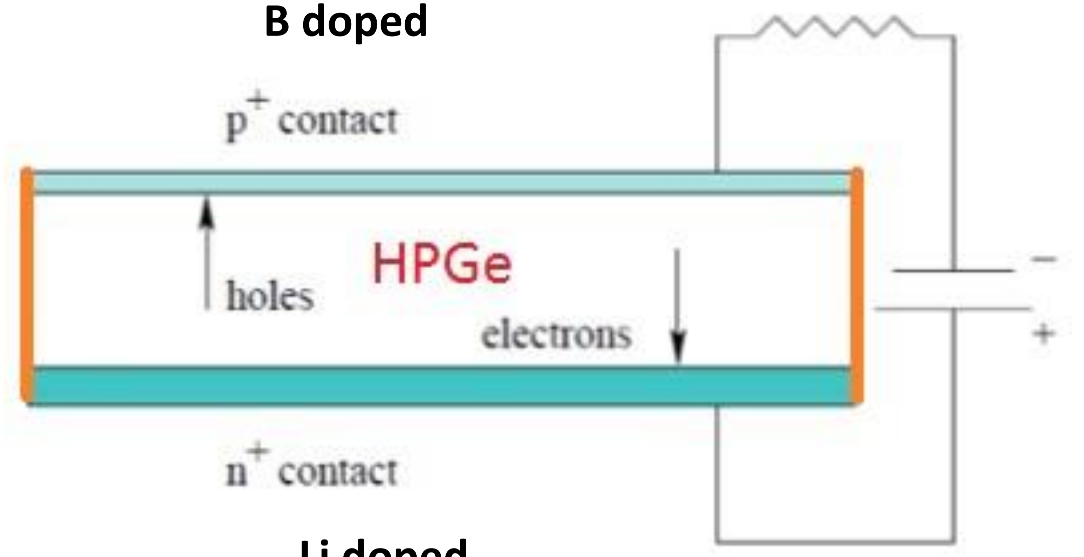
- Chemical passivation
- Eletrical passivation

- **Methanol** termination
- **Sulphide** termination
- **Low Hydride** termination (10% HF)
- **High Hidride** termination (50% HF)

G. Maggioni et al. **Eur. Phys. J. A** (2015) 51: 141

layer 0.3mm

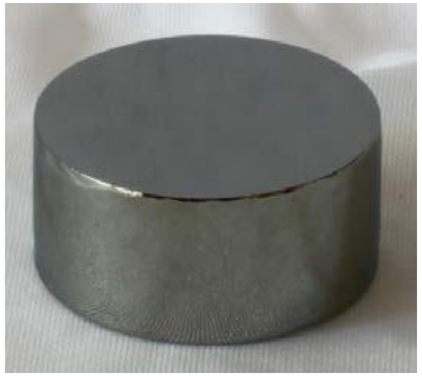
B doped



Li doped

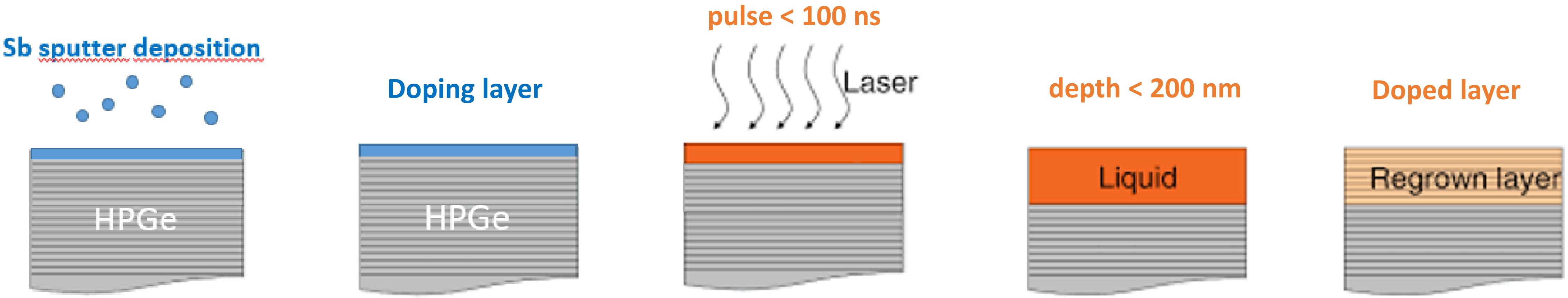
layer 0.7 - 0.9mm

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



Diameter: 40mm
Height: 20mm

n^+ contact on HPGe – LTA technology



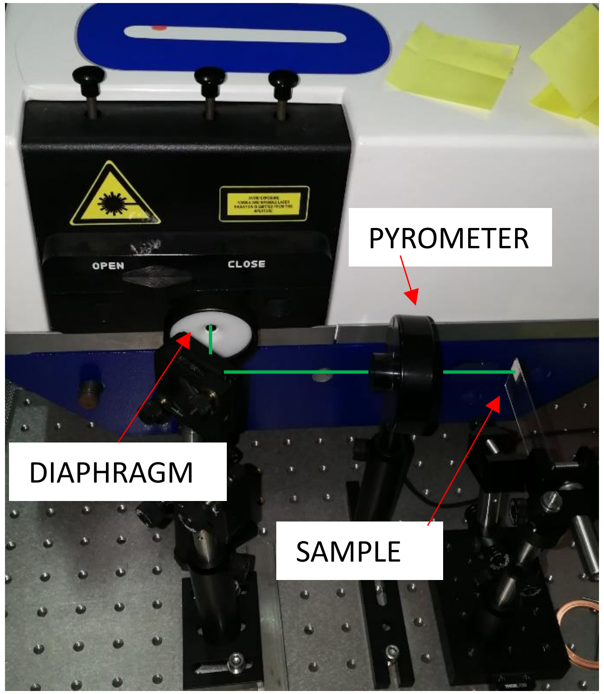
Sb sputter deposition

Doping layer

pulse < 100 ns

depth < 200 nm

Doped layer



Pulsed Laser @ LNL-INFN
Nd:YAG (Quantel YG980)
λ=355 nm (third harmonic generator)
τ=7 ns; Ø=6,5 mm; Rate = 10Hz
Radiant power ~1500 mW
Fluence ~300-400 mJ/cm^2

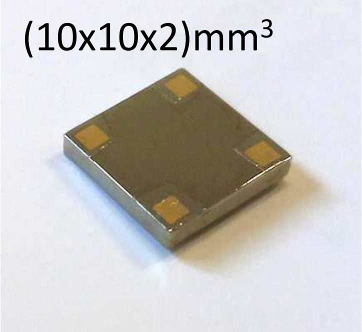
n^+ contact on HPGe – LTA (laser thermal annealing) technology

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
- Doping with heavy elements without crystal damage
- Very clean process suitable for preserving the Ge hyperpurity
- Suitable for complex contact geometries (**segmentation**)

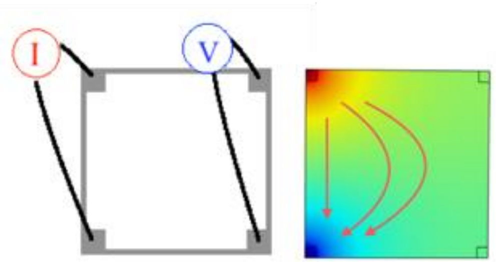
Contamination of HPGe – LTA technology

Four-wire resistance and Hall measurement



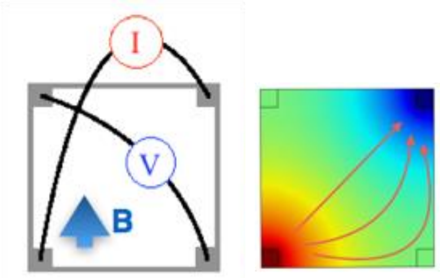
Van der Pauw method

R_{sheet}



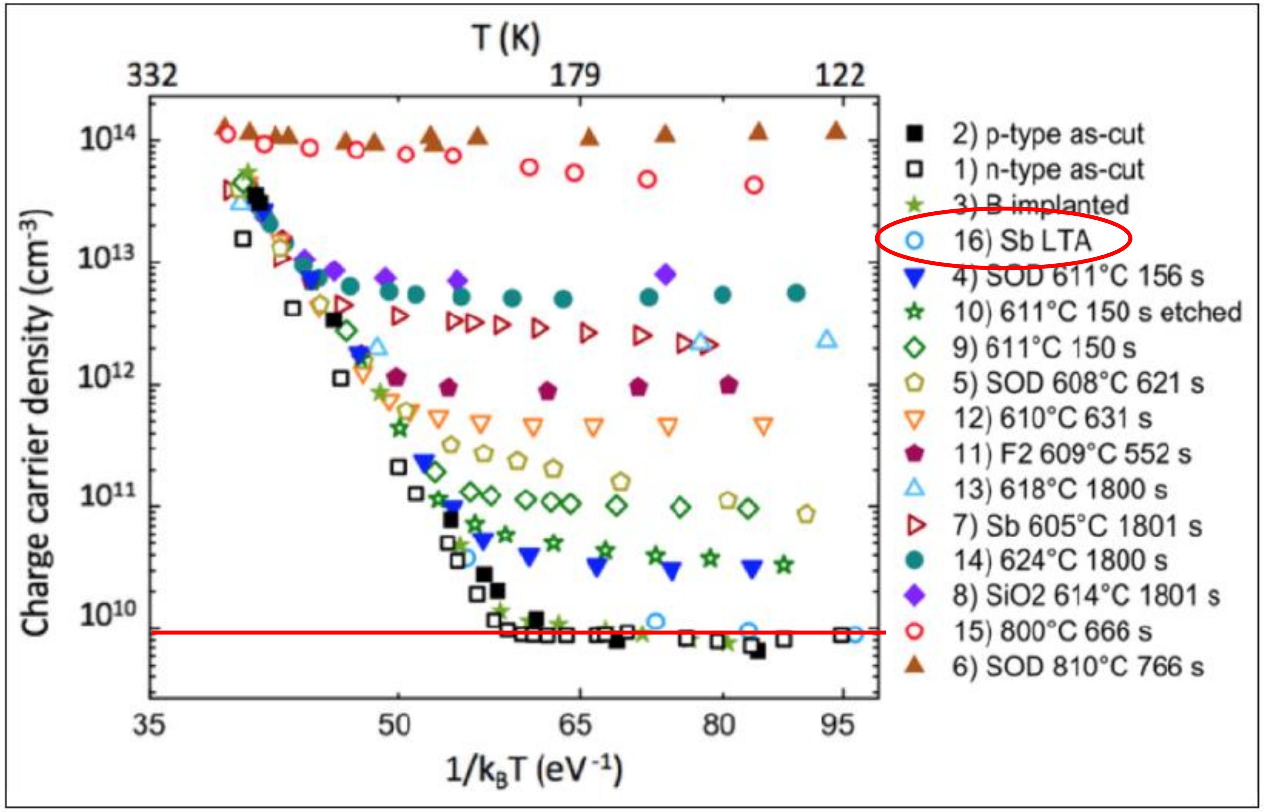
Hall-effect method

Carrier type



[From V. Boldrini et al**., Journal of Physics D: Applied Physics** (2018), *submitted*]

Contamination after laser treatment



Carrier density within the specifications (10^{10} cm^{-3})

LTA (laser thermal annealing) technology : out of equilibrium diffusion

Treatment time ↓ Treatment temperature ↑

At melting temperature, dopants diffuse orders of magnitude faster

↳ Treatment times can be drastically reduced 🙂

At melting temperature, contaminants diffuse faster too

↳ Contamination can drastically increase ☹

Melting can be limited to a thin, surface layer of HPGe

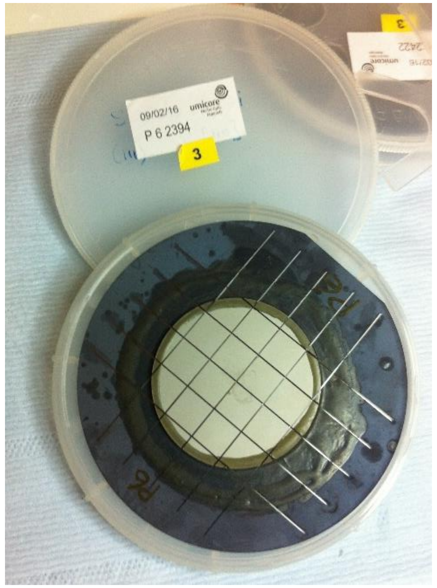
↳ Bulk contamination is prevented 🙂

} Pulsed laser annealing

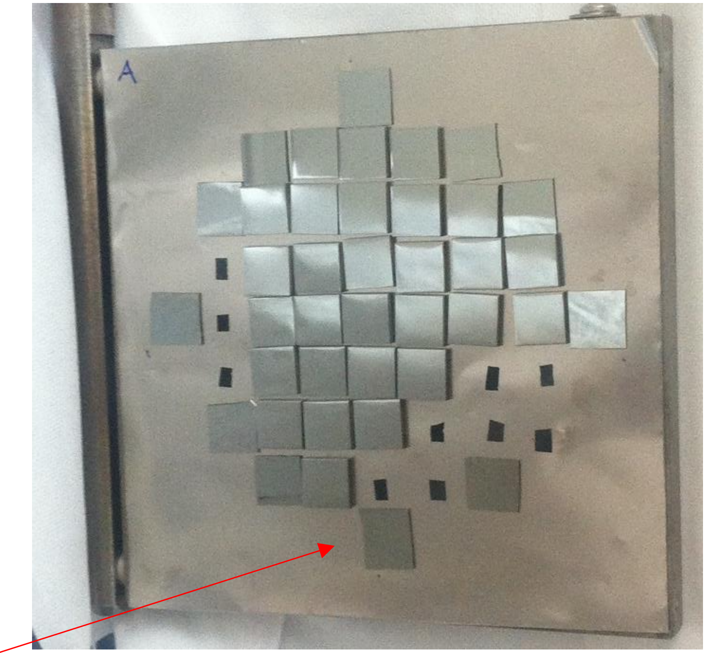
p^+ contact on HPGe

^{11}B Ionic Implantation IMM (Institute for Microelectronics and Microsystem) - Bologna

HPGe wafer cut and cleaning (isopropanol 80°C and DW 80°C)

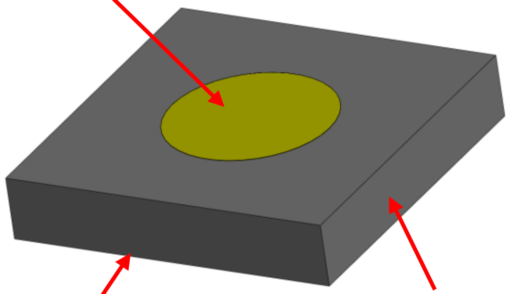


Energy = 23KeV
Dose = 1×10^{15} atoms/cm^2
(pressure = 3.8×10^{-7} torr)



HPGe
(10x10x2) mm^3

Prototype HPGe by LTA technology @LNL-INFN



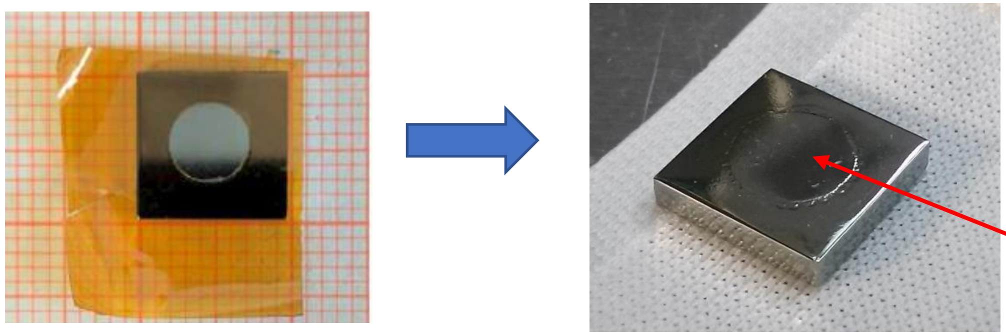
Sb deposition Ø= 5mm

HPGe p-type
(2x10x10)mm^3

B implantation
(10x10)mm^2

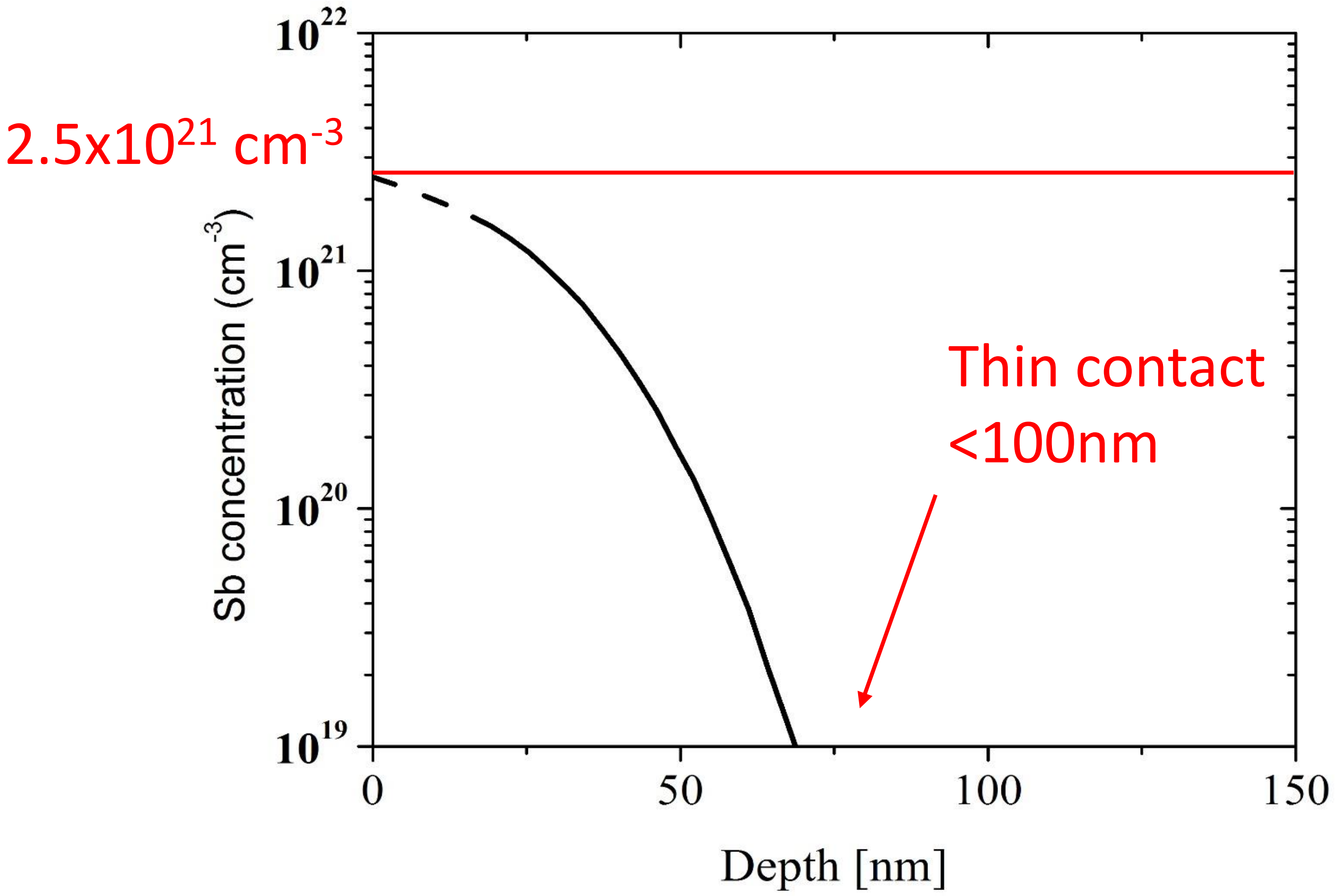
Methanol
passivation

No guard ring

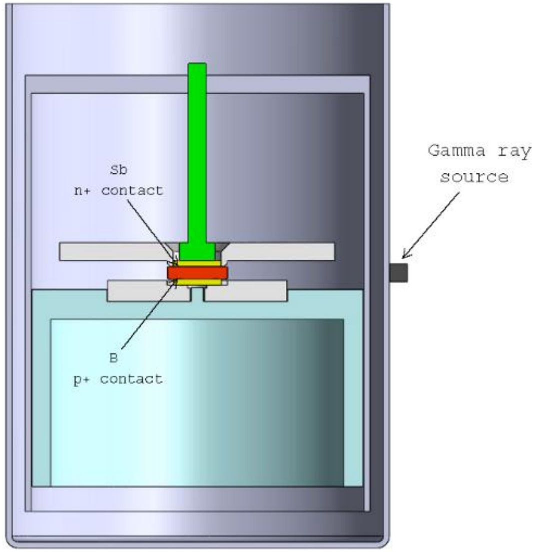


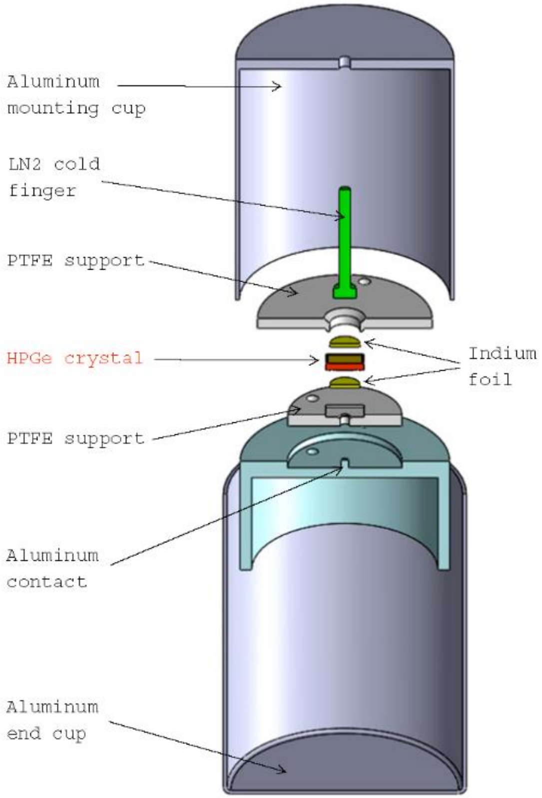
LTA laser spot
Ø= 6.5mm

SIMS profile of Sb diffusion

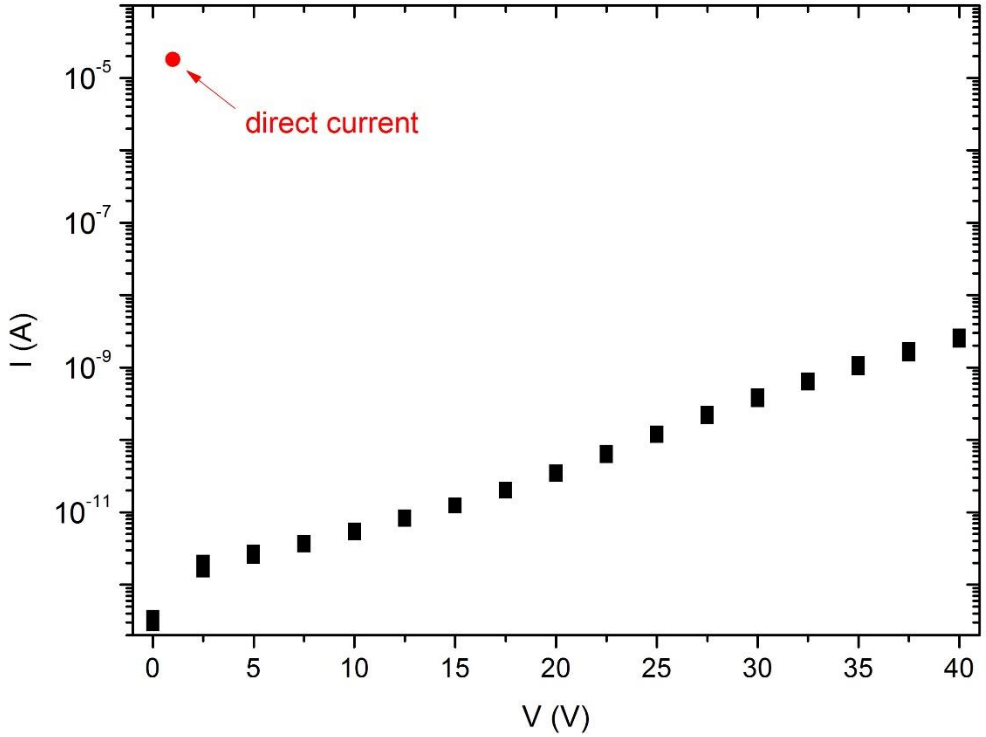


Test of small HPGe prototype: I-V diode configuration





I-V characteristic curve



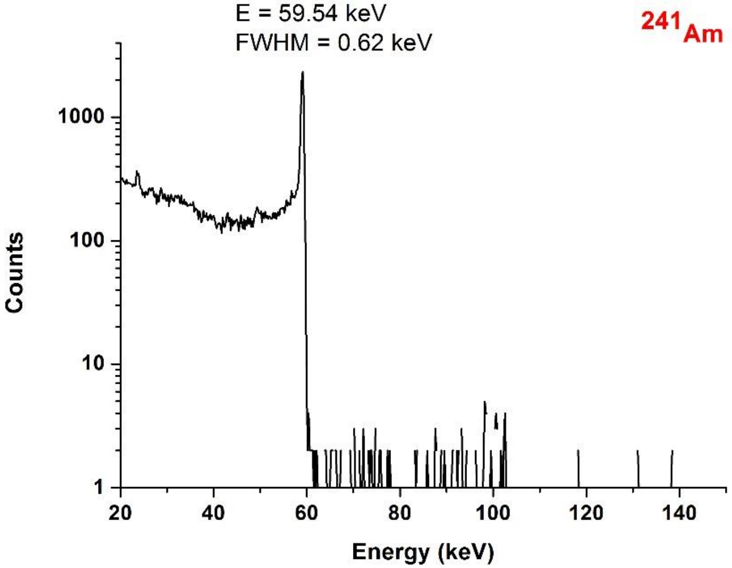
Depletion voltage: between 20 V and 35 V

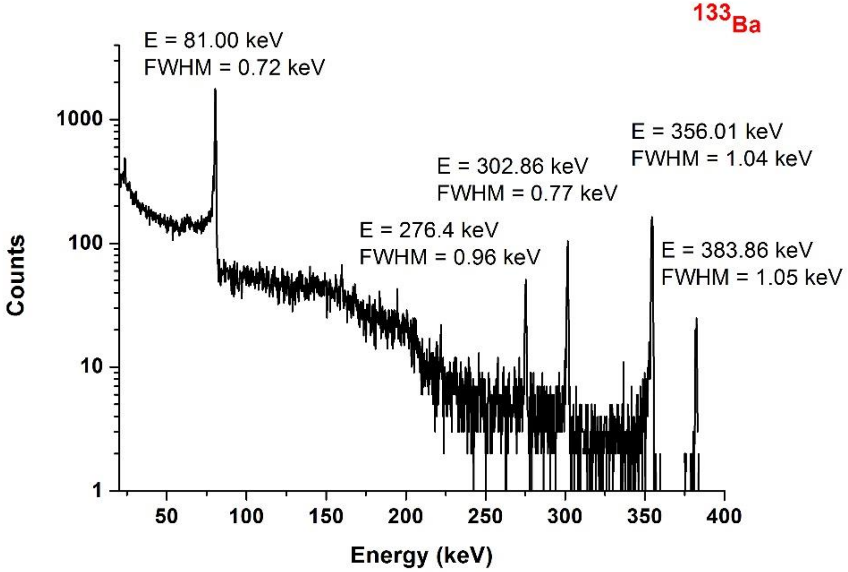
- Low leakage current
- p-n junction is obtained

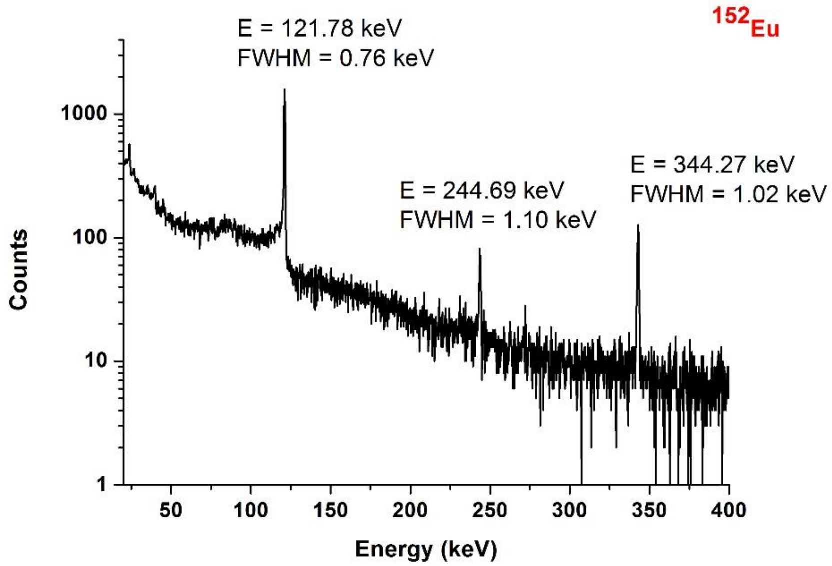
[G. Maggioni at al. Eur. Phys. J. A (2018)]

Test of small HPGe prototype: detector configuration

Sources: ^{241}Am, ^{152}Eu and ^{133}Ba



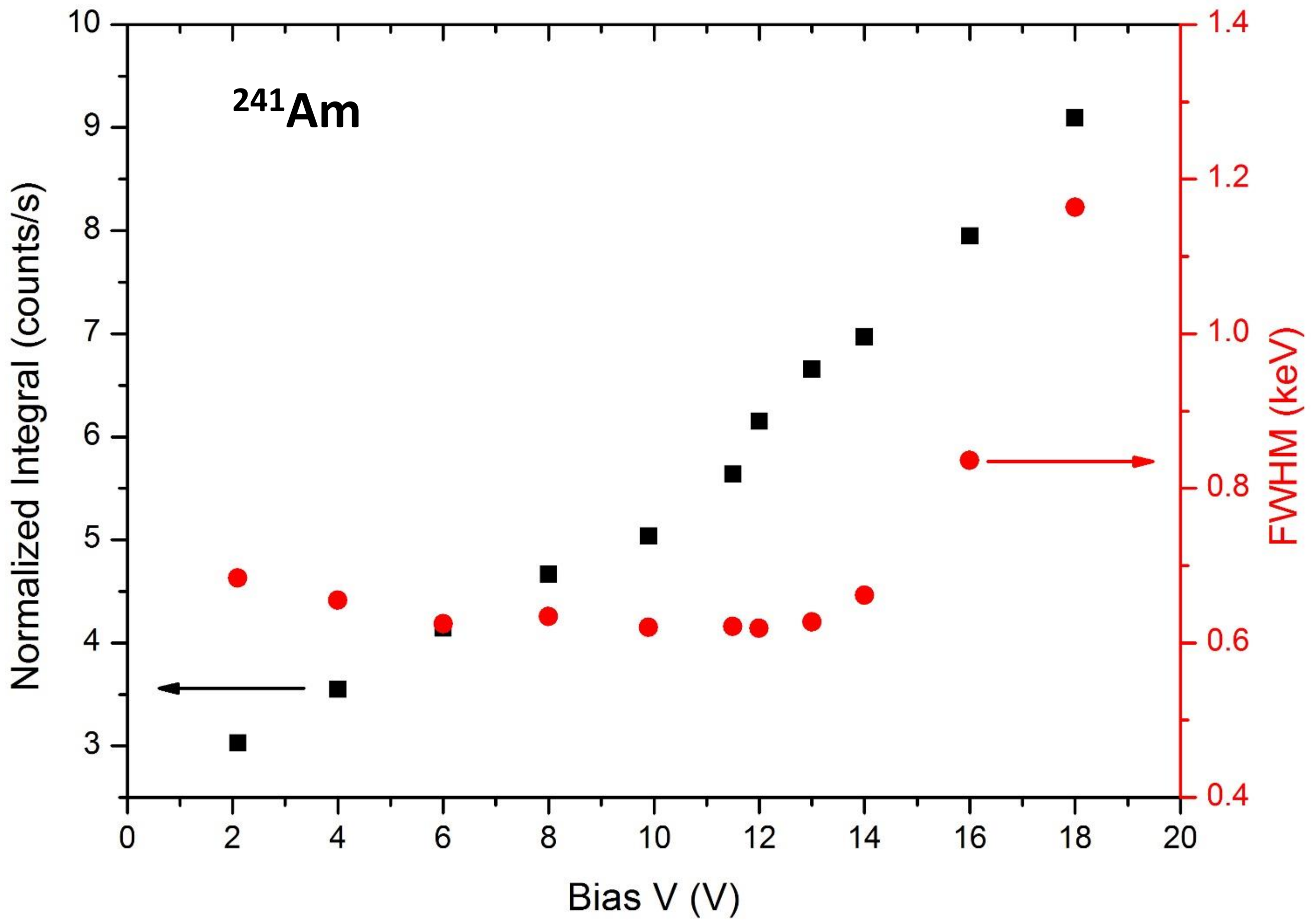




Good energy resolution all the energy range up to 400KeV

Test of small HPGe prototype: detector configuration

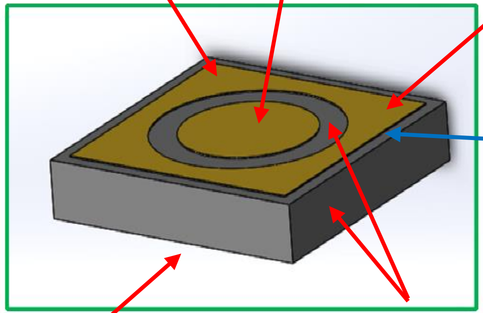
Depletion Voltage - Energy resolution



0.62 keV @ 59.54 keV (^{241}Am)

Detector not fully depleted when energy resolution worsens (contact geometry is not optimal)

Prototype HPGe by LTA technology @LNL-INFN



Deposition of gold <100nm

Central contact

Guard ring

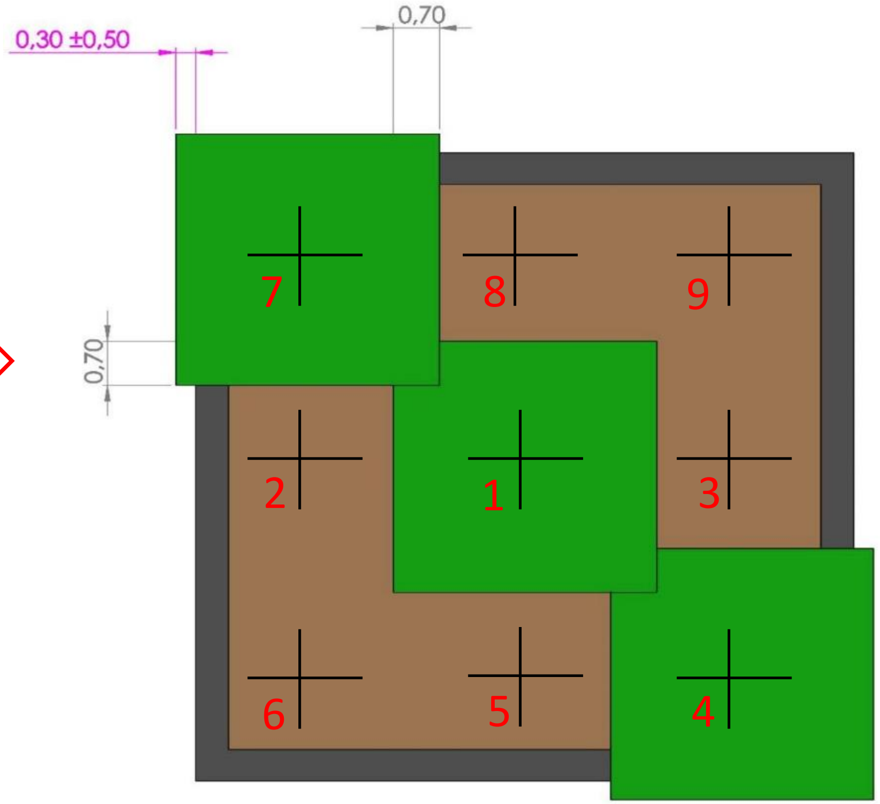
Sb deposition all the surface $(10x10)mm^2$

B implantation $(10x10)mm^2$

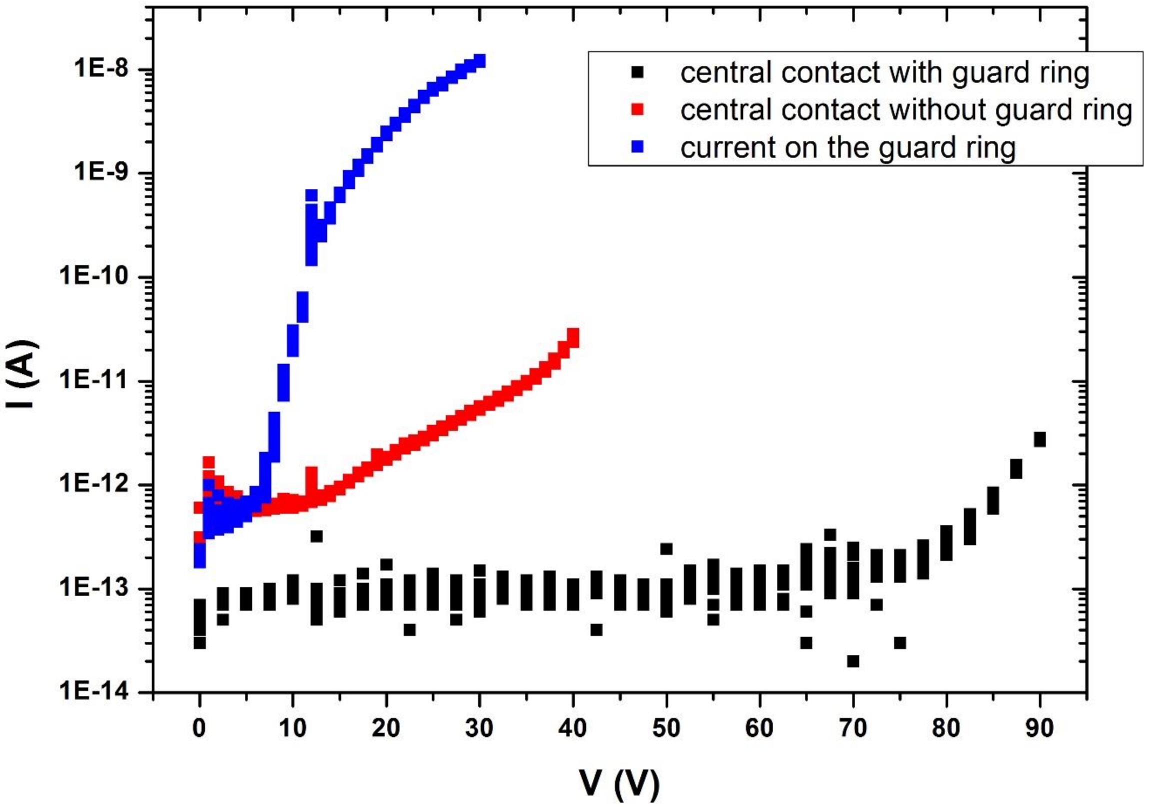
Methanol Passivation surface

Laser thermal annealing

with 9 laser spots $(4x4)mm^2$ all the Sb surface $(10x10)mm^2$ was annealed



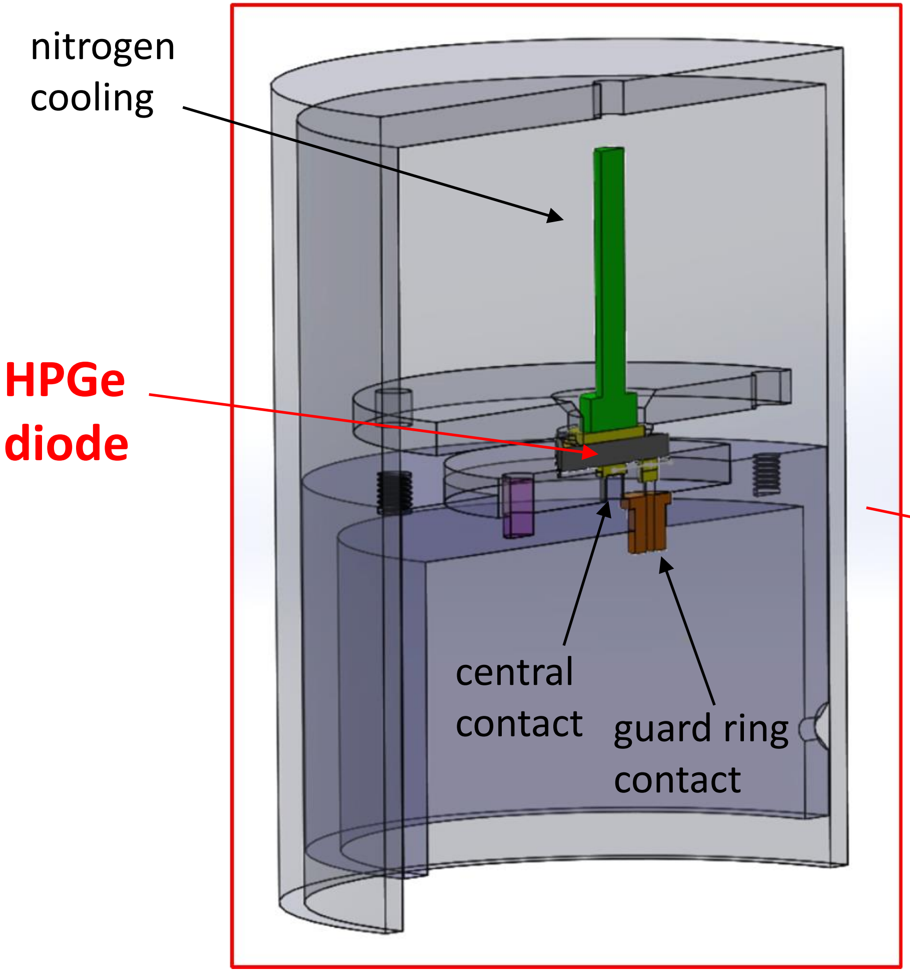
Test of small HPGe prototype: I-V diode configuration



Central contact low level of
leakeage current, 1pA @ 80V

Direct bias V=0.5 V I=0.8 μA

3D cryostat design



nitrogen
cooling

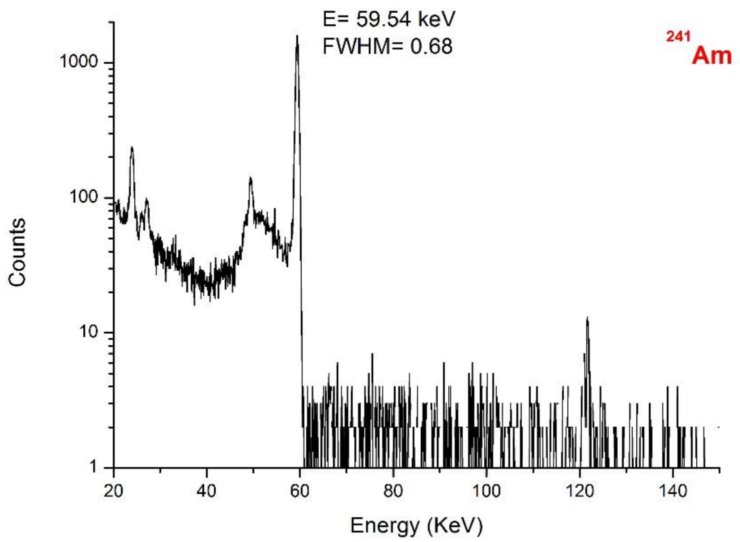
**HPGe
diode**

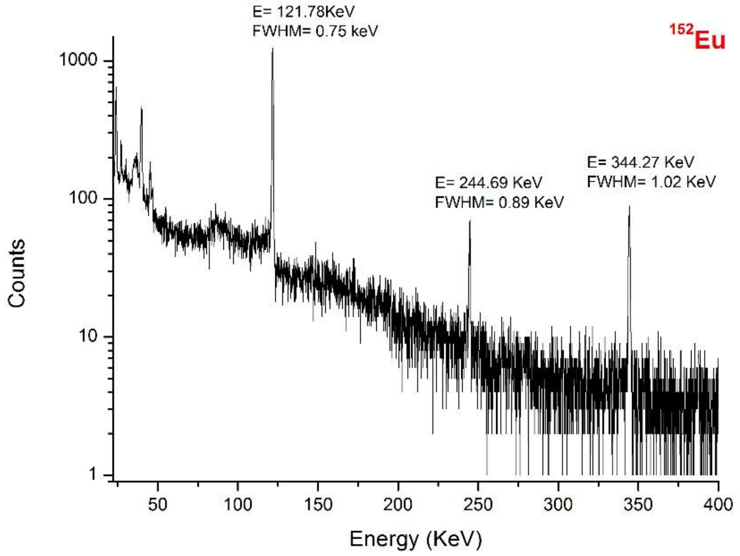
central
contact

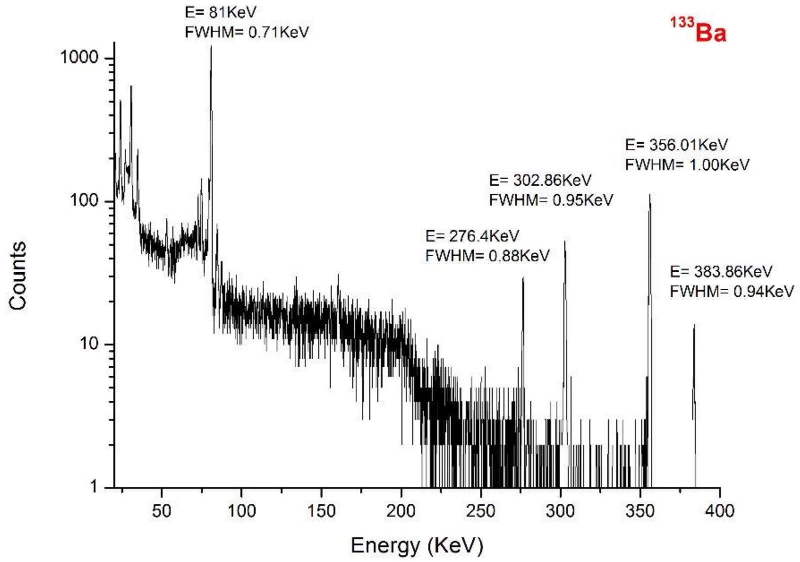
guard ring
contact

Test of small HPGe prototype: detector configuration

Sources: ^{241}Am, ^{152}Eu and ^{133}Ba



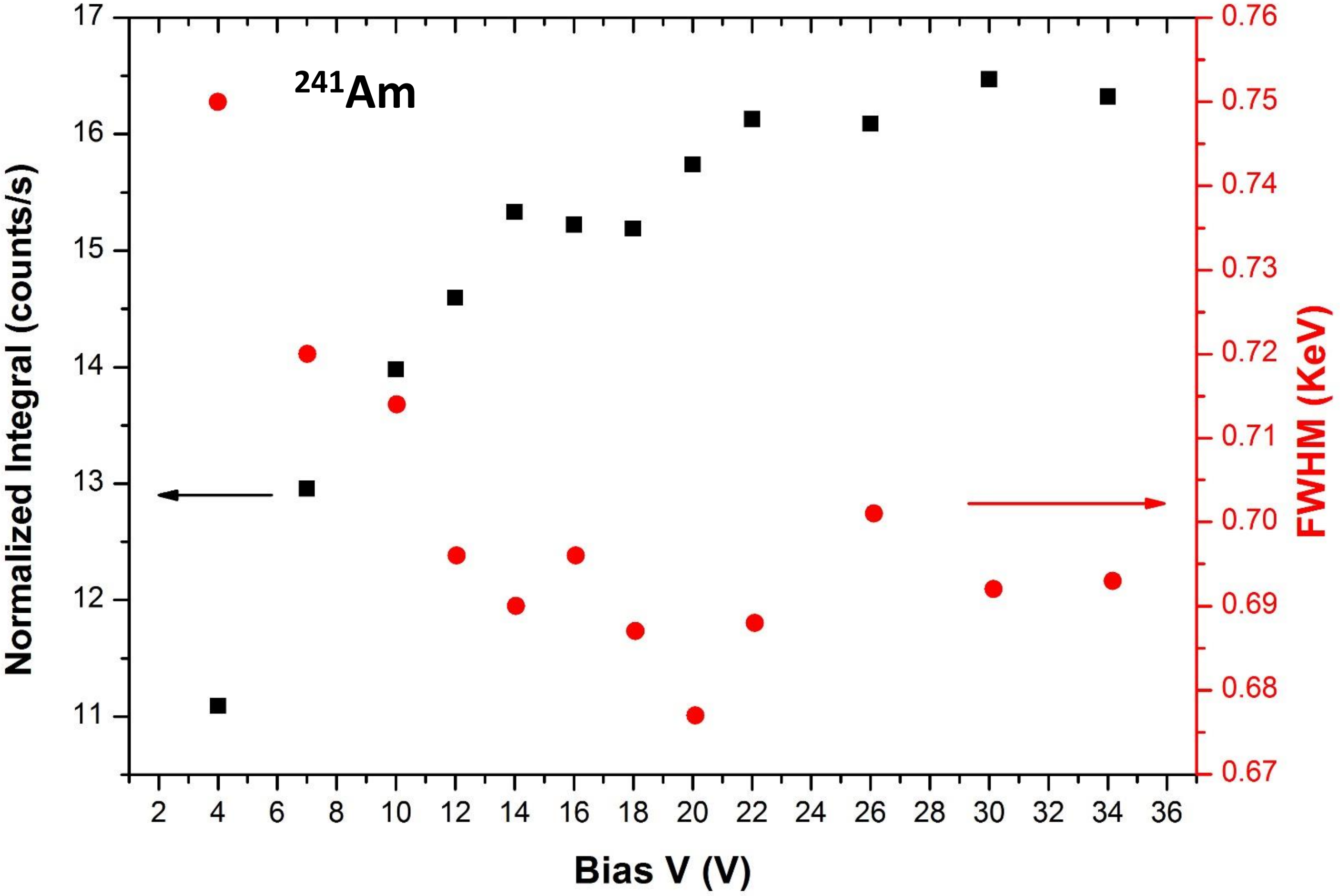


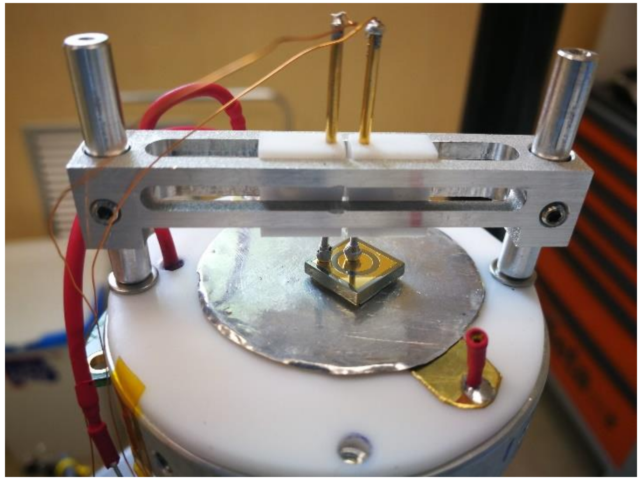


Good energy resolution all the energy range up to 400KeV

Test of small HPGe prototype: detector configuration

Depletion Voltage - Energy resolution





central contact

0.68 keV @ 59.54 keV (^{241}Am)

- detector fully depleted (plateau of normalize integral)
- very good energy resolution

Summary

- We have shown that LTA is a good technology to perform contacts in HPGe detectors.
- With this technology we have substituted Li with Sb for the n^+ contact.
- Our first detector has a good resolution 0.62KeV @ 59.5KeV, also if it is not fully depleted

- With the second prototype we have verified that the LTA technology can be scaled up to a larger surface. The detector is fully depleted and it has a good resolution 0.68KeV @ 59.5KeV

Work in progress

- Development of the bigger HPGe planar detector with laser annealed Sb contact

- Development of p^+ and n^+ contacts on HPGe with other materials by LTA

Multidisciplinary Team

INFN-LNL	D.R. Napoli, W. Raniero
INFN-LNL and University of Padua:	D. De Salvador, G. Maggioni, S. Carturan E. Napolitani, V. Boldrini, F. Sgarbossa
INFN-LNL and University of Verona	G. Mariotto
INFN-LNL and University of Trento	G. Della Mea
INFN-PG and University of Camerino	N. Pinto
INFN-PG and University of Perugia	S. Riccetto
CSIC-IFIC of Valencia	A. Gadea, S. Bertoldo
IKP Cologne	J. Eberth
CNR-IMM Bologna	R. Nipoti, F. Mancarella, M. Bellettato

Thanks for the attention !!

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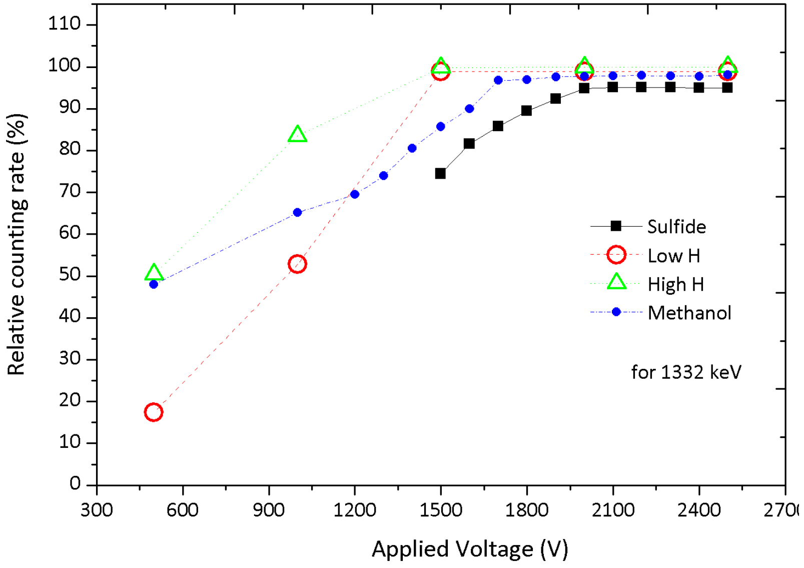
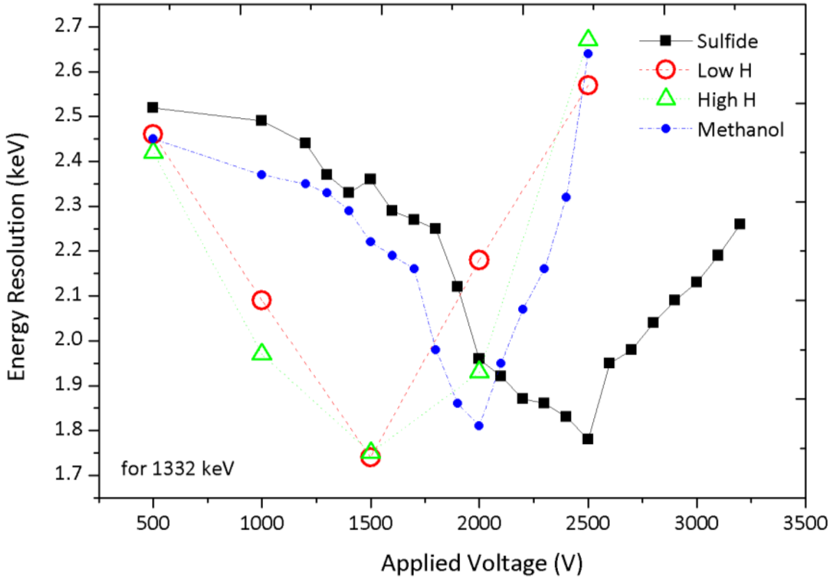
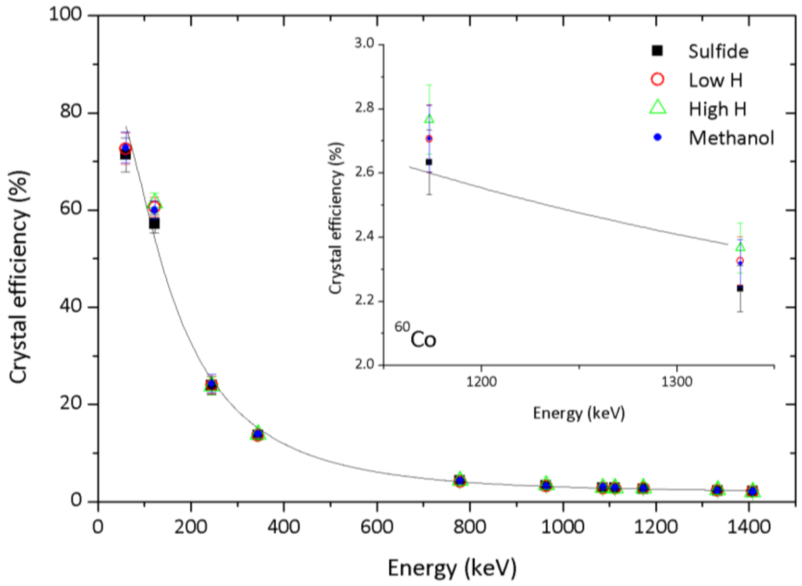
HPGe Passivation: lateral scan ^{241}Am on passivated surface







Depletion Voltage: from 1500 to 2000 V

Energy Resolution (@1.33 MeV, ^{60}Co): from 1.74 to 1.79 keV

Intrinsic Efficiency: a difference of just some %

G. Maggioni et al. Eur. Phys. J.
A (2015) 51: 141

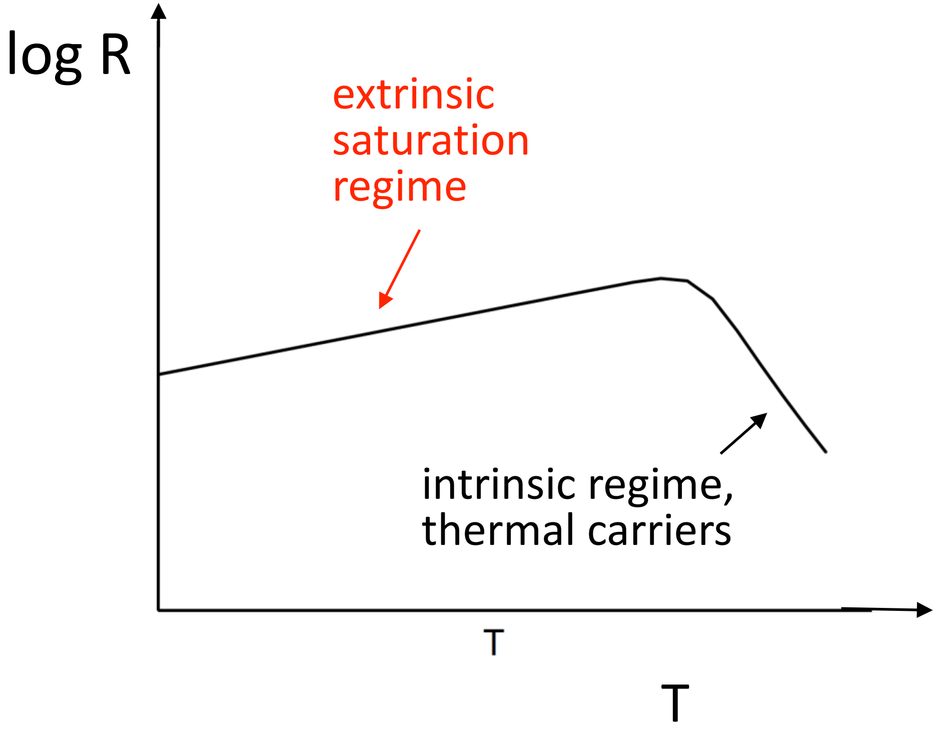
… theory…

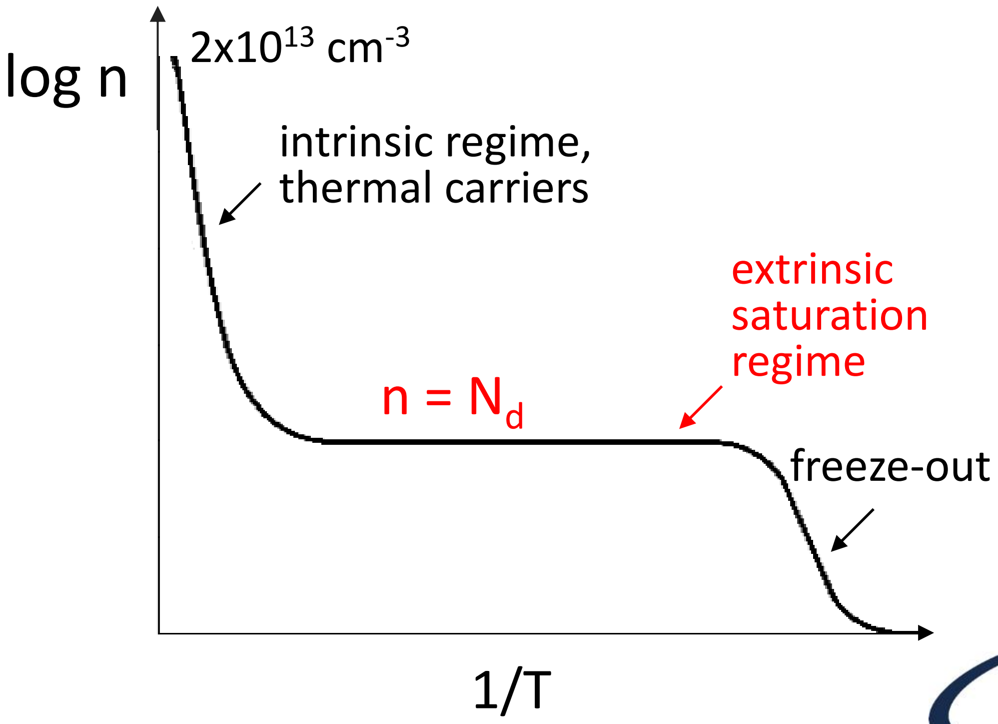
$$R_{sheet} = \frac{1}{e\, d\, n(T)\, \mu(T)}$$

d = sample thickness

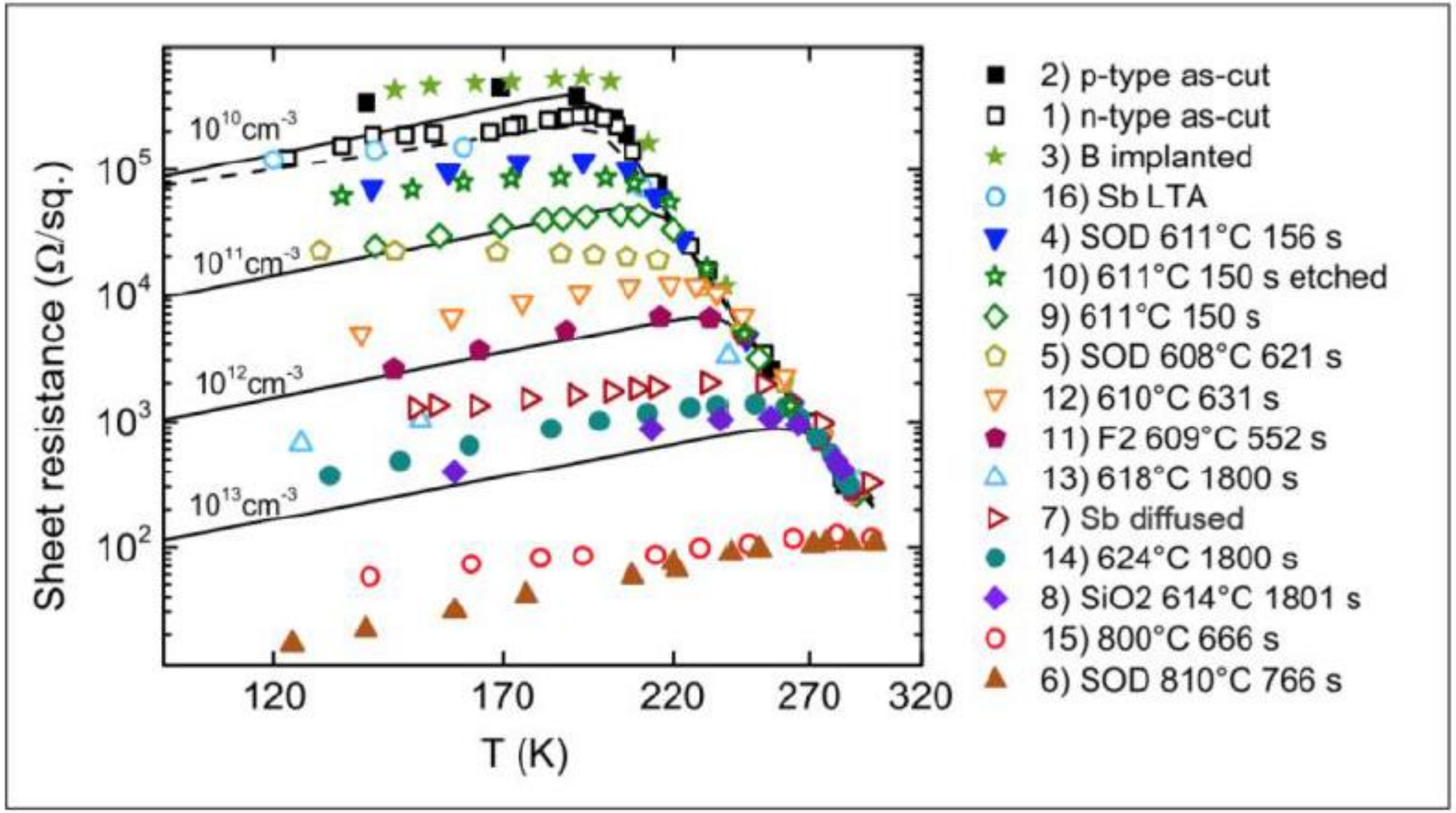
µ(T) = carrier mobility

n(T) = carrier density

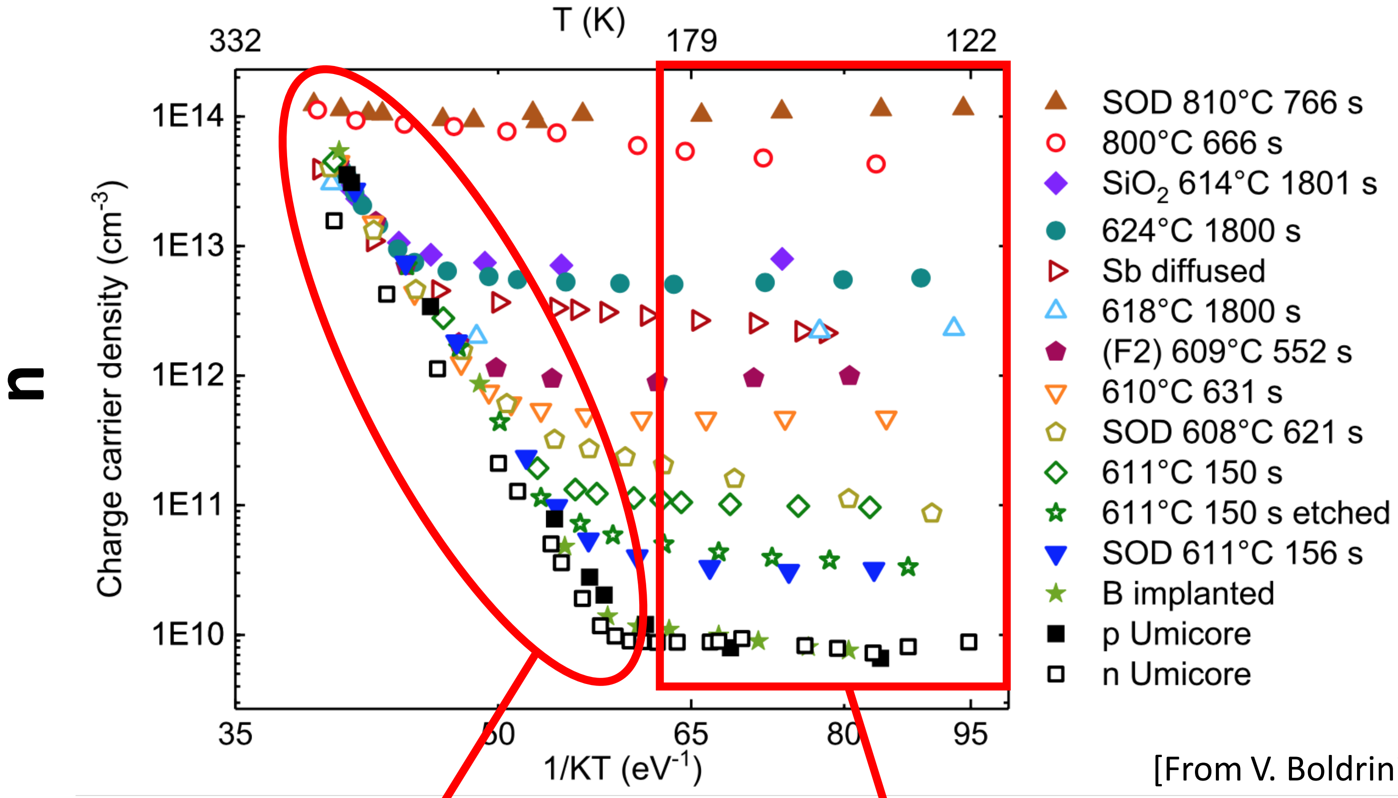




Sheet resistance: experimental results



Charge carrier density: experimental results



[From V. Boldrini et al., **Mater. Sci. Semicond. Proc.** (2018), *submitted*]

Intrinsic regime
thermal carriers

Extrinsic saturation regime

Impurity concentration

Theoretical model: contaminant density and thermal budget

An Arrhenius relation exists between contaminant density and temperature, with further dependence on time

For very long treatment times (hours or days)

$$n_{eq} = n_0 exp\left(-\frac{E_{act}}{k_B T}\right) \qquad (1)$$

$$\frac{dn}{dt} = r(n_{eq} - n) \qquad (2)$$

[From V. Boldrini et al.**, Journal of Physics D: Applied Physics** (2018), *submitted*]

For short treatments (≤ 30 min)

$$(n_{eq} >> n)$$

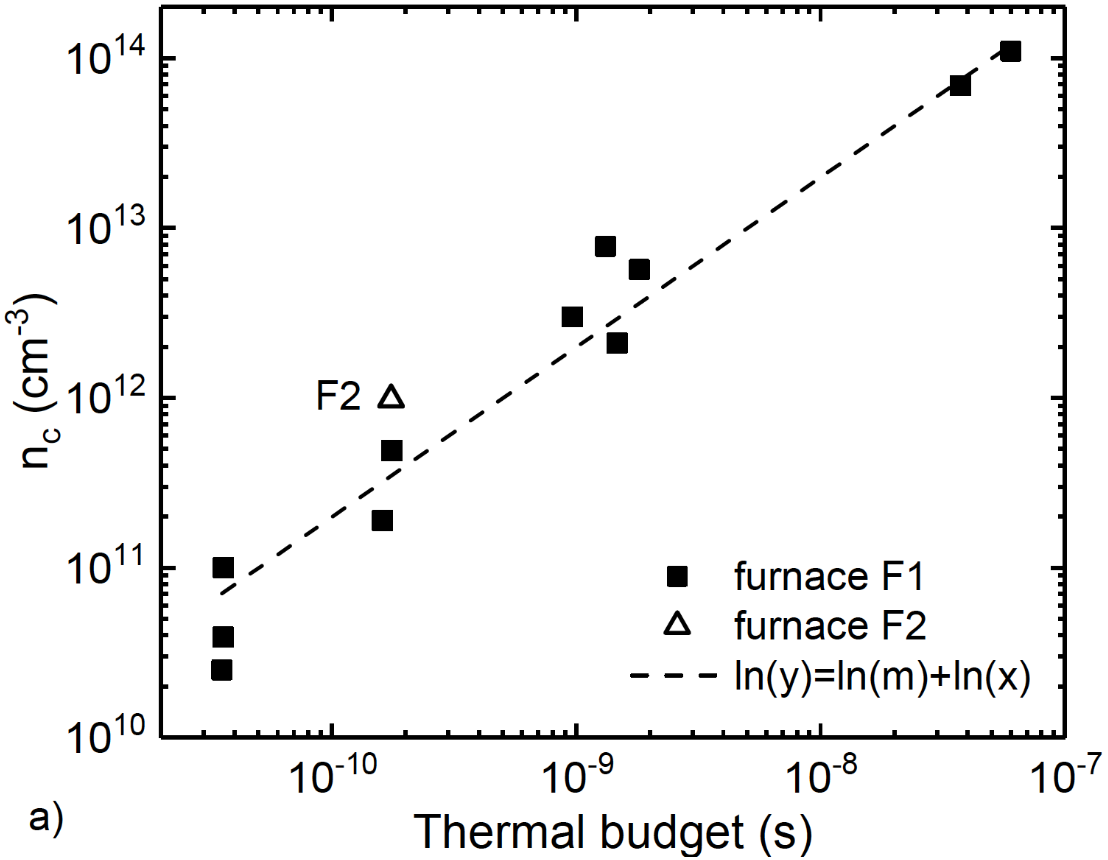
$$\frac{dn}{dt} = r\, n_0\, exp\left(-\frac{E_{act}}{k_B T(t)}\right) \qquad (3)$$

$$n = r\, n_0 \overbrace{\int exp\left(-\frac{E_{act}}{k_B T(t)}\right) dt}^{TB} \qquad (4)$$

$$ln(n) = ln(r n_0) + ln(TB)$$

Fit results

Best linear fit between *ln(n)* and *ln(TB)* is found through the minimization of the reduced chi squared.



[From V. Boldrini et al., **Mater. Sci. Semicond. Proc.** (2018), *submitted*]

Best fit results:

E_{act} = 2.1±0.1 eV

r n_0 = 2×10^{21} cm^{-3}s^{-1}

- p-type contamination
- fast diffusion
- literature (E.E. Haller et al. (1980),…)

Cu

$$E_{act}^{Cu} \sim 1.6\ eV$$

(H. Bracht, MSSP (2004))

Thermal process window for standard annealing?

Contamination threshold (constant T):

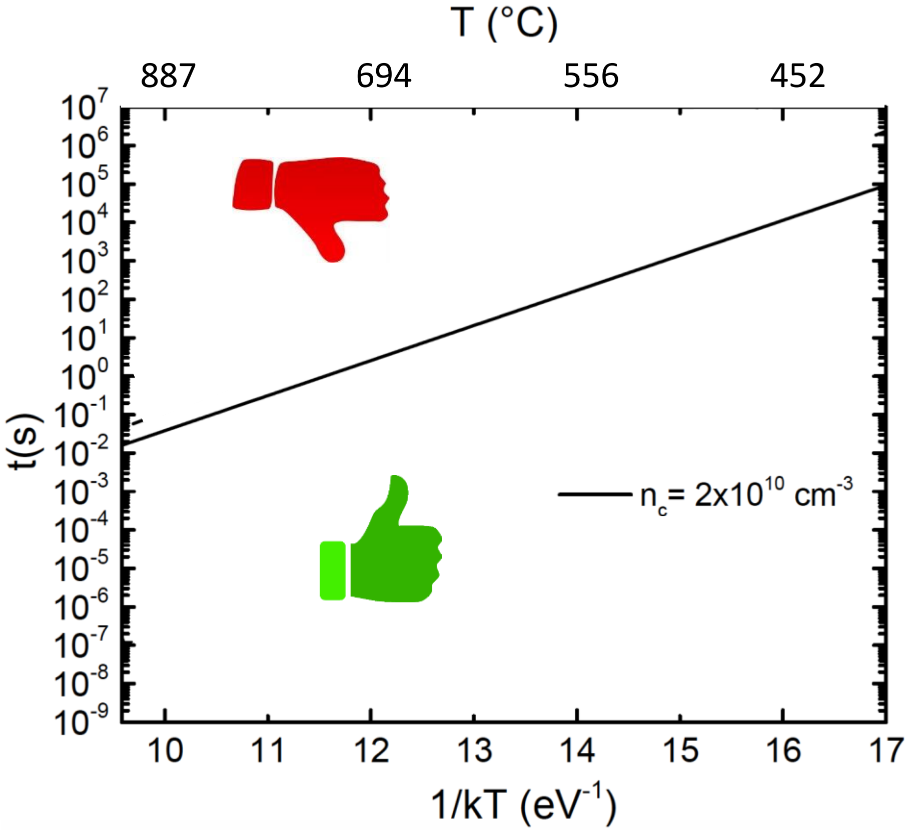
$$n_c = N_0 \; t \; exp(-E_{act}/(k_B T)) \leq Nc_{thr}$$

$$ln(t) \leq \left(\frac{Nc_{thr}}{N_0}\right) + \frac{E_{act}}{k_B T}$$

If:

$Nc_{thr} = 2 \times \; 10^{10} cm^{-3}$

$E_{act} = 2.1$ eV



Thermal process window

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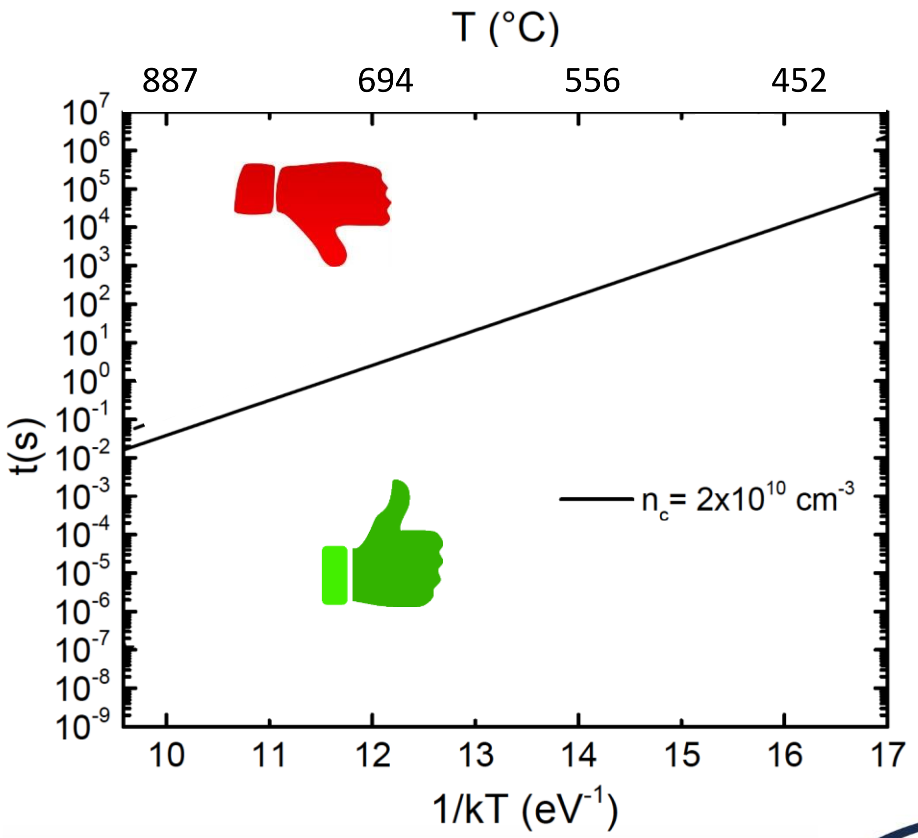

Dopant diffusion threshold (P and Sb):

L = dopant diffusion length

L_{thr} = 200 nm

$$L^2 = L_0 \; \boxed{t} \; exp(-E_{act}/(k_B T)) \leq L^2_{thr}$$

$$ln(t) \leq \left(\frac{L^2_{thr}}{L_0}\right) + \frac{E_{act}}{k_B T}$$

Thermal process window

Contamination threshold (constant T):

$$n_c = N_0\ t\ exp(-E_{act}/(k_B T)) \leq Nc_{thr}$$

$$ln(t) \leq \left(\frac{Nc_{thr}}{N_0}\right) + \frac{E_{act}}{k_B T}$$

If:

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E_{act} = 2.1 eV

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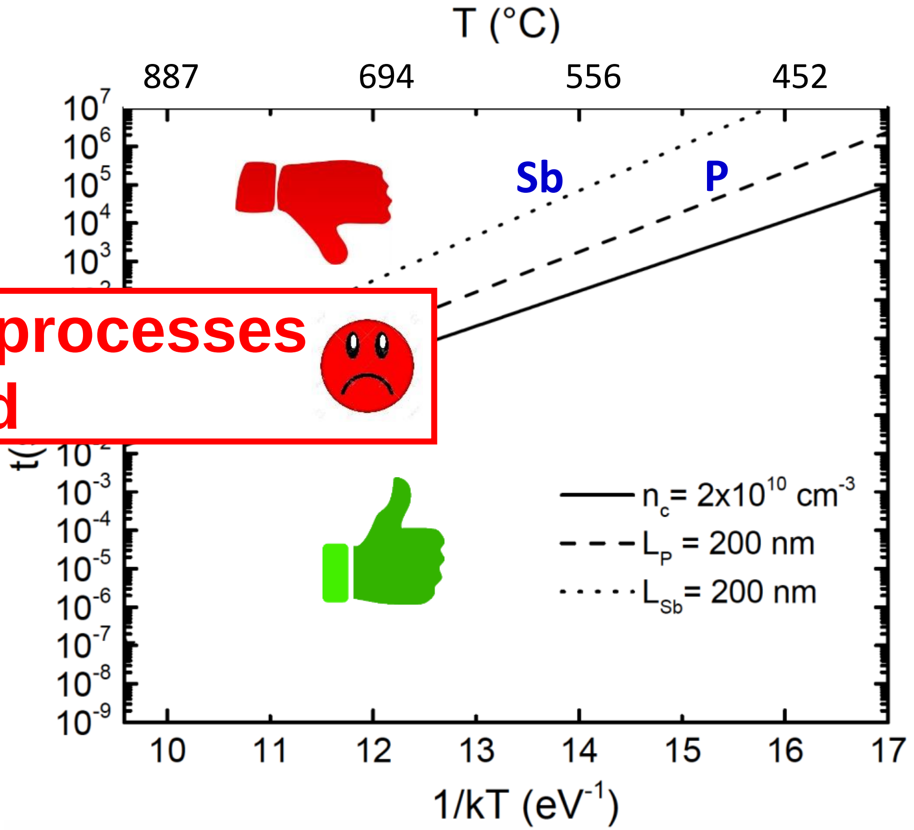

In-equilibrium processes cannot be used