Passivation and segmentation developments at LNL

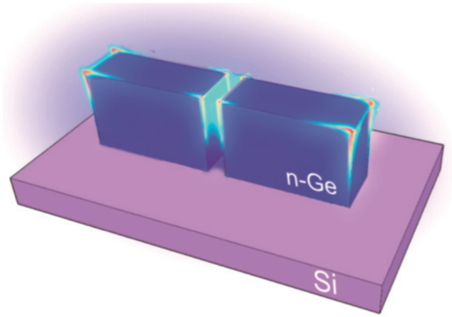
Daniel R. Napoli *(INFN LNL, Italy)*

S. Bertoldo *(IFIC, Spain and INFN-LNL)*

W. Raniero *(INFN LNL)*, C. Carraro *(Univ. of Padova and INFN)*

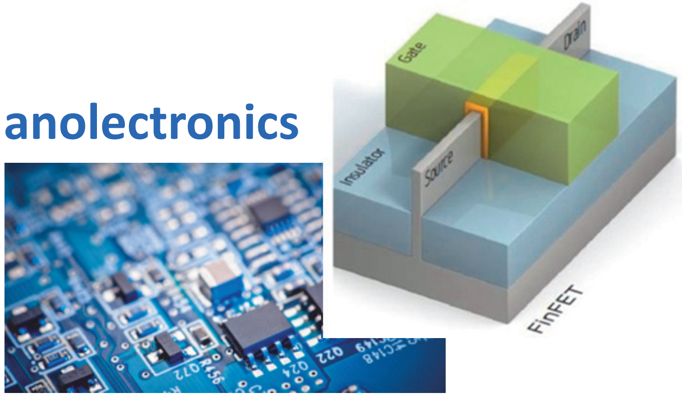
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 654002

Ge-based devices

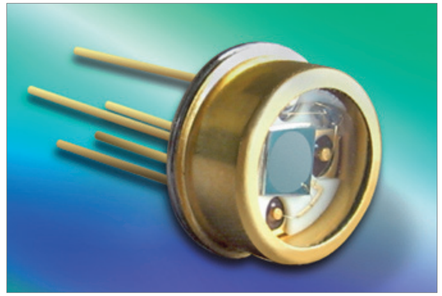


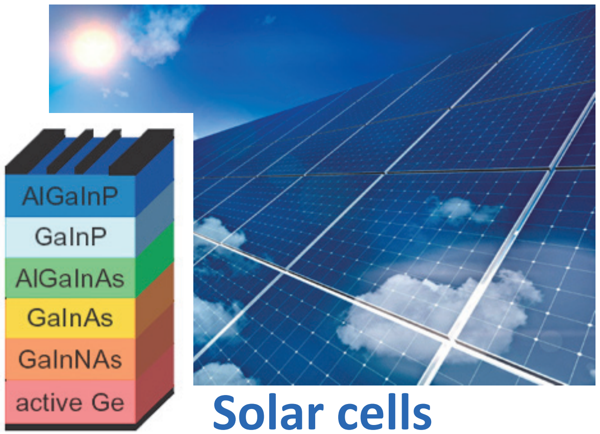
Plasmonic molecular sensors

Nanolectronics

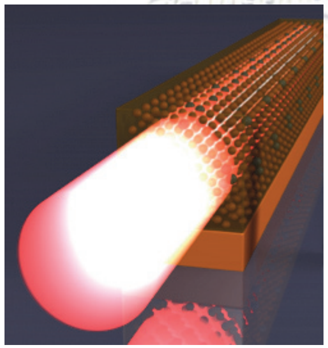


Photodetectors



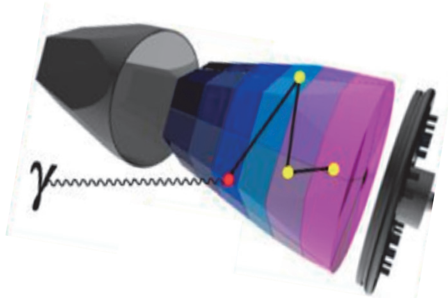


Solar cells



Lasers

γ-Ray detectors

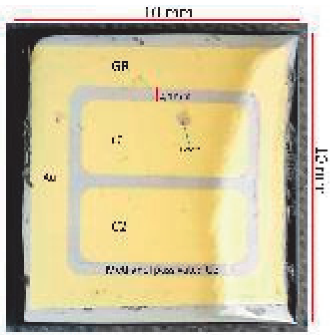


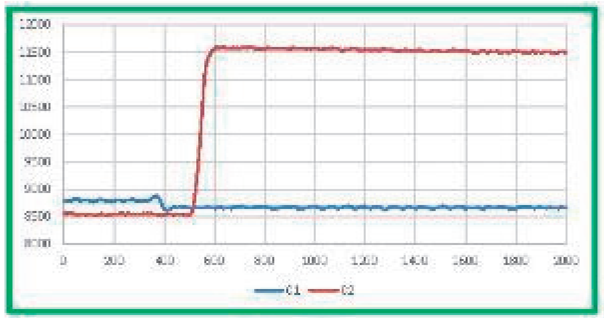
Detector Developments

New Encapsulation, R&D on Ge detector

ENSAR2 JRA2 – PSeGe R&D on Position-Sensitive Germanium Detectors for Nuclear Structure and Applications

- Task 1: New technologies on passivation and segmentation (INFN, IKP-Cologne)
- Task 3: R&D on segmented p-type coaxial detectors (IFIC, INFN, Univ. Padova)





2mm thick p-type HP-Ge prototype. Gap 0.4mm next 0.2 mm

INFN-LNL, Univ. Padova, IFIC, IKP-Köln

slide from A.Gadea "Status of AGATA", this meeting

Main topics of our current activity at LNL and Unipd

- To develop new passivation/protection techniques

- To develop new thinner contacts, which could replace the present ones (especially Li)

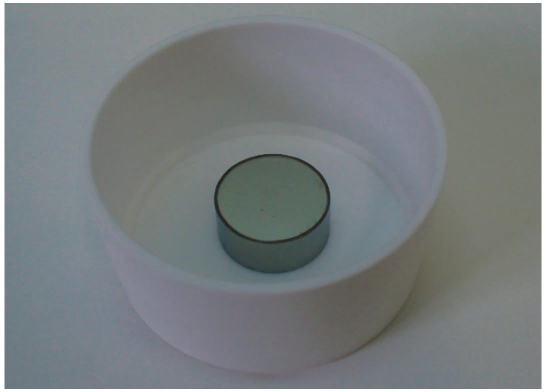
- To improve the method of construction and the robustness of the surfaces for costs reduction in both fabrication and maintenance (needed also for applications).

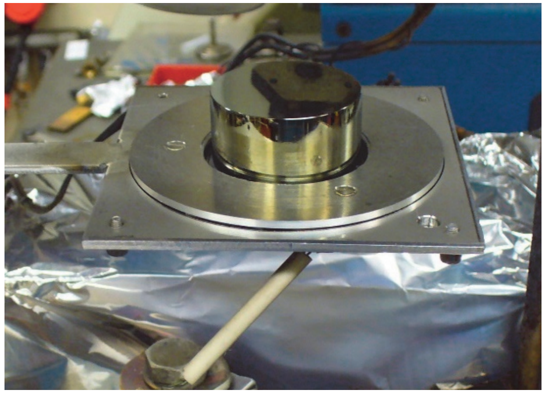
First step: our first High Purity Ge detector

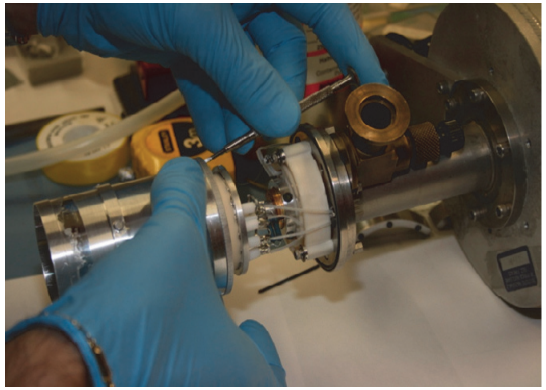
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

R&D on HPGe production technologies

First step:
we acquired the basic know-how for the **in-house** production of commercial-like planar HPGe detectors.



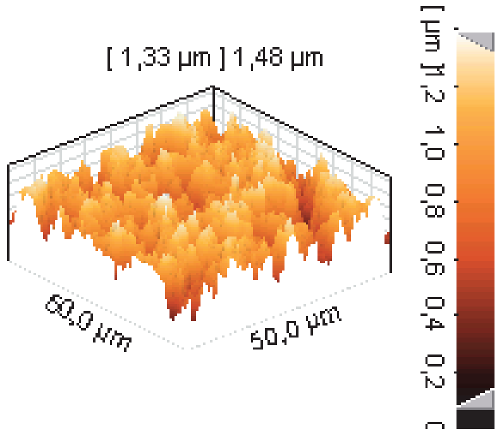


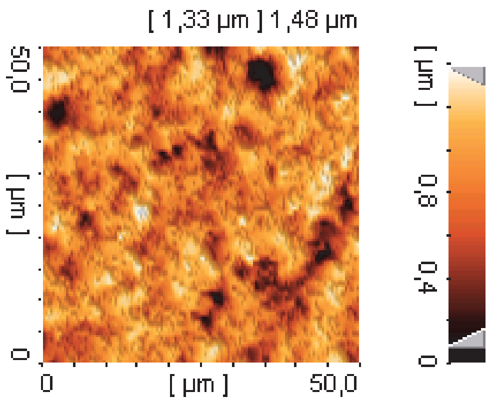


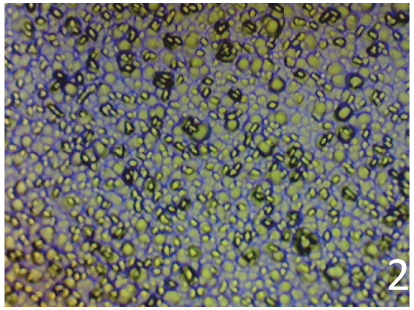
- Mechanical treatment and chemical preparation of the surfaces
- n^+ -contact made with Li diffusion doped method (600 - 900 µm thick)
- p^+ -contact with B implantation (about 0.3 µ thick) + Au film deposition...
- Surface passivation & mounting

Mechanical treatment of the HPGe surfaces (lapping)

AFM



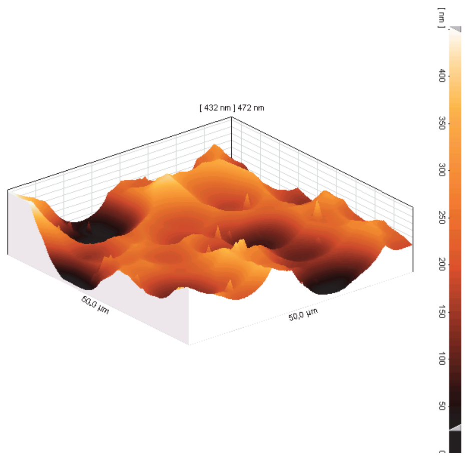


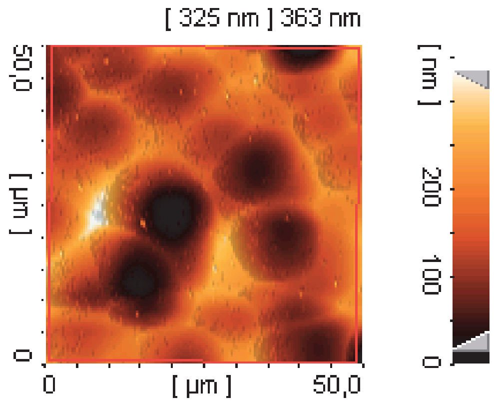


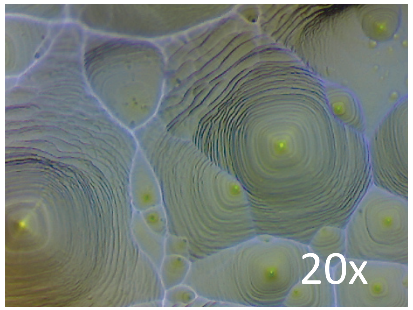
Count of the crystal dislocations

Roughness after lapping: 150 - 250 nm

Chemical preparation of the HPGe surfaces (etching)

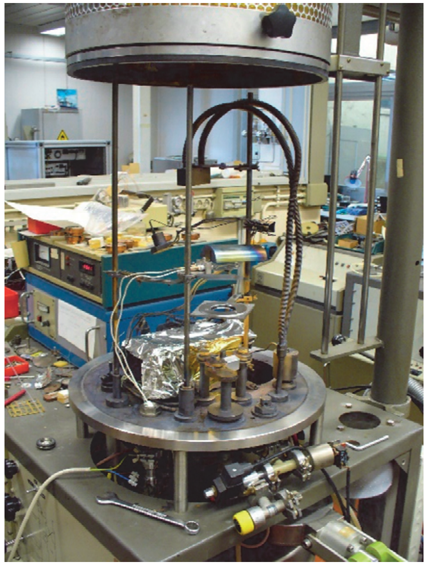




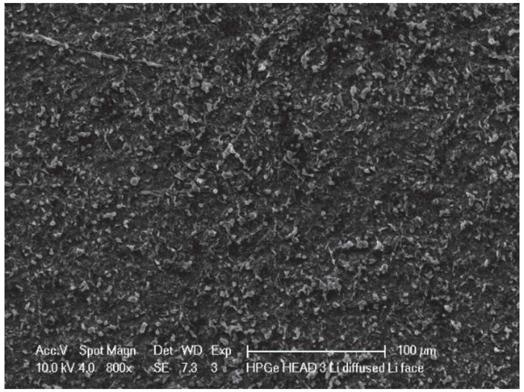


Roughness after etching: 50 - 100 nm

n+ -contact made with Li diffusion method



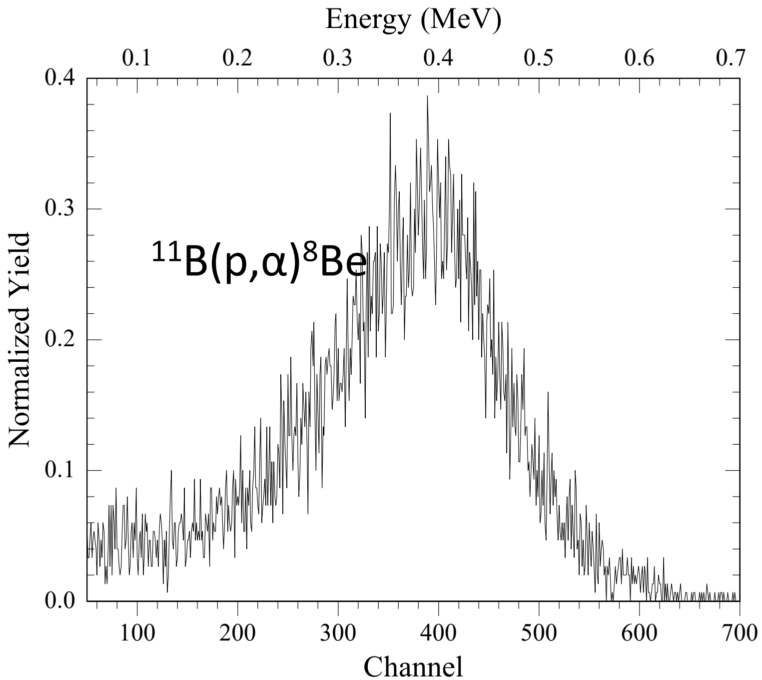
Evaporation apparatus



Li-coated surface

p+ -contact made with B implantation

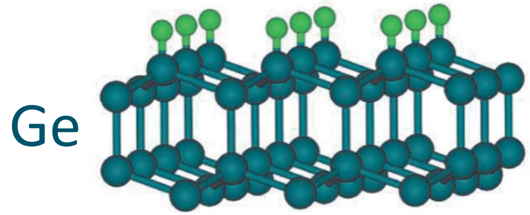
NRA technique

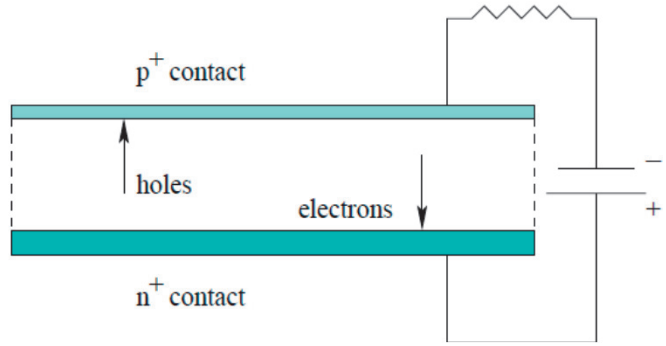


Ion implantation apparatus

PASSIVATION

Passivation of the intrinsic surface





Ideal Passivation

<u>electrical</u>: low leakage current

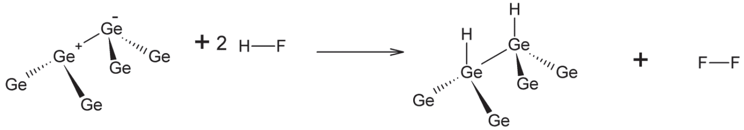
<u>chemical</u>: prevents the surface from reacting with the atmosphere

Ge is not like Si and natural Ge oxides are not stable

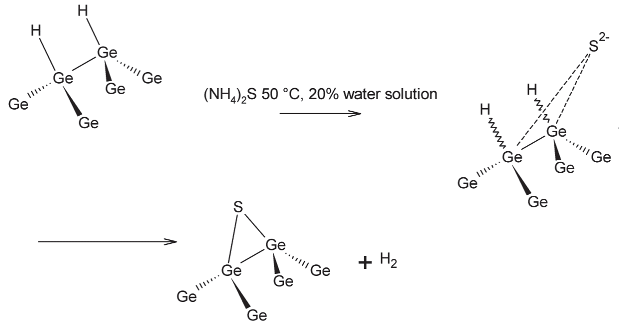
Some known passivations: SiO_2 or amorphous Ge(H)

Passivation techniques

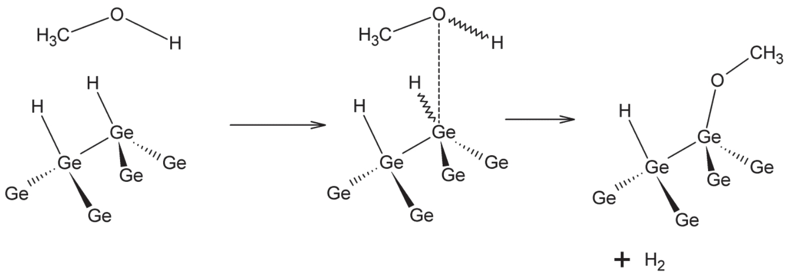
- **Hydride termination - three types:**
  - **Low hydride** (low concentration HF)
  - **High hydride** (high concentration HF)
  - **Hyper hydride** (same like High hydride but with after a different surface preparation)



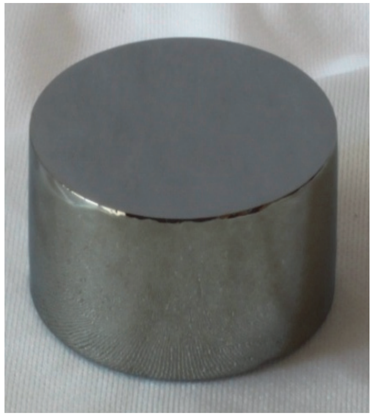
- **Sulfide termination** ($(NH_4)_2S$)



- **Methanol Passivation** (3:1 etching followed by methanol quenching)



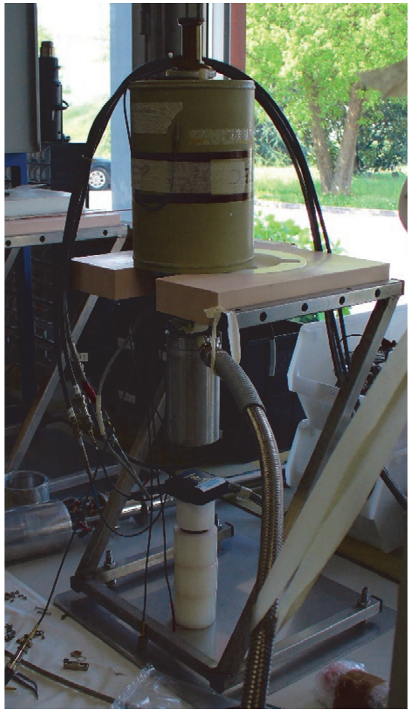
O-H bond dissociation

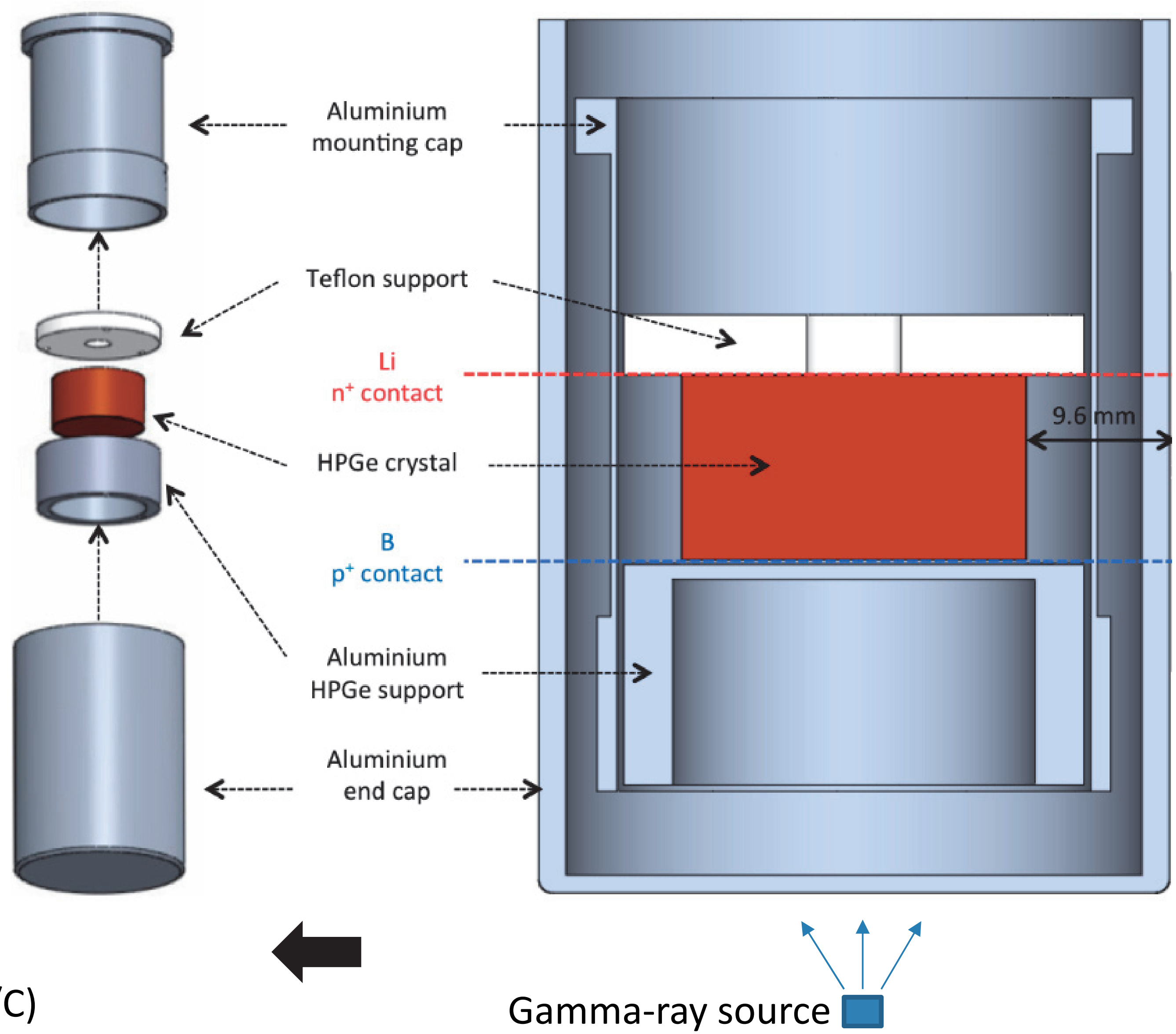


n-type HPGe crystal
planar detector with
B and Li contacts
NO Guard Ring
ϕ 40 mm, h 20 mm

The **same detector** was used for **all** the different passivation treatments to avoid bulk effects of the crystal and highlight surface effects.

Measurement setup for determining the detector bulk properties

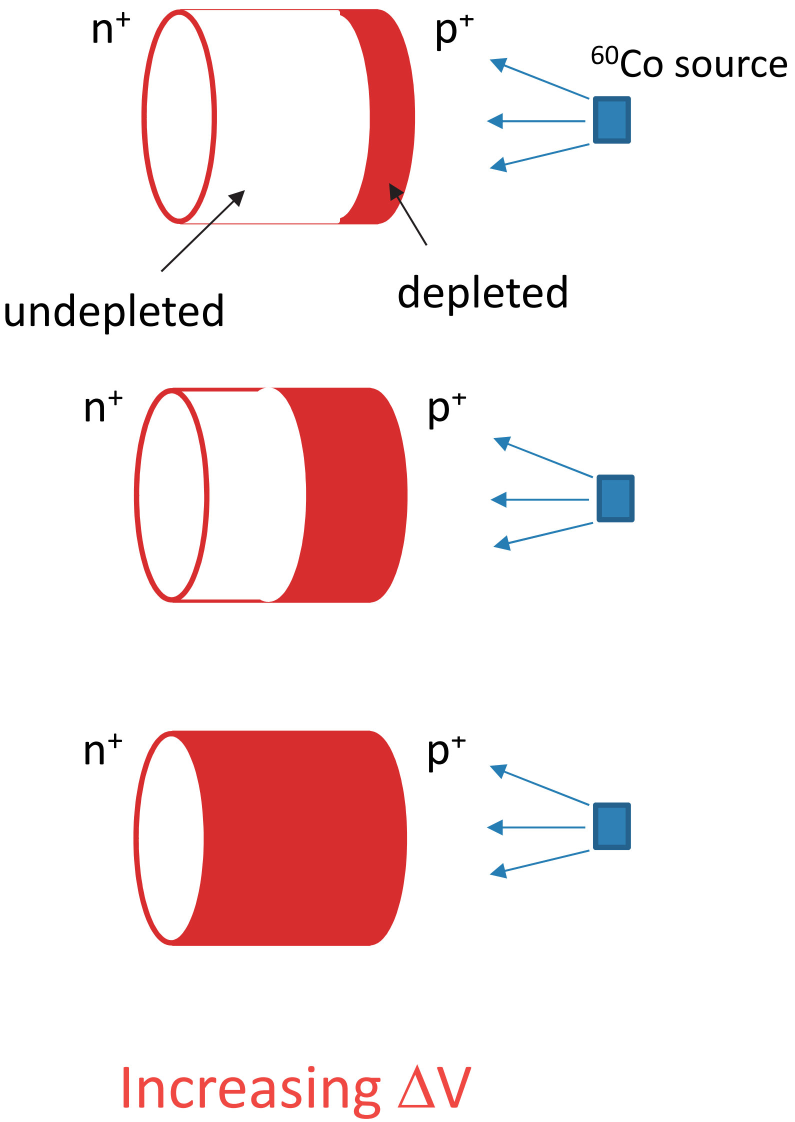




"Bulk" properties:

- Depletion voltage
- Efficiency
- Resolution
- Peak-to-Compton ratio (P/C)

Depletion voltage

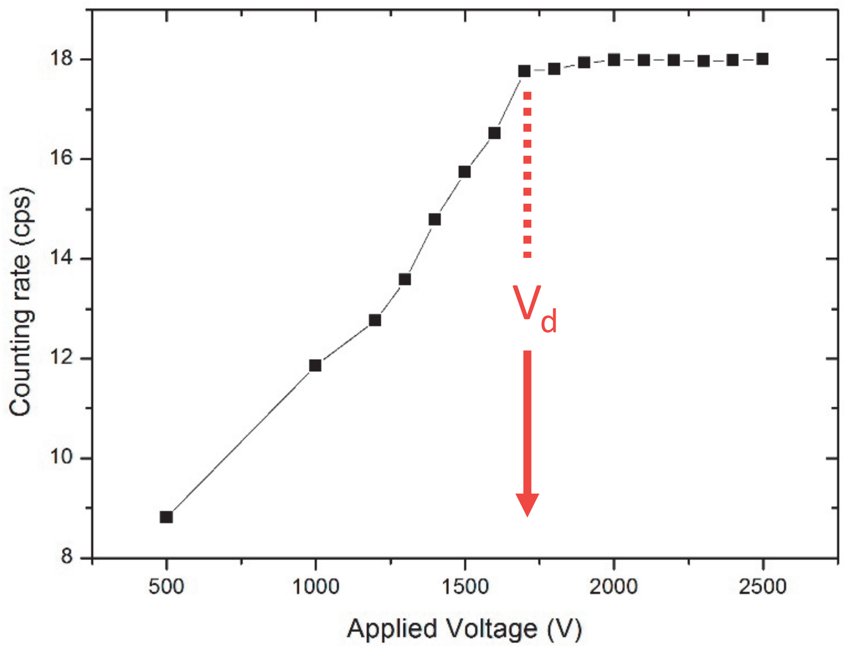


Depletion voltage: the voltage at which the depletion depth is equal to the detector thickness

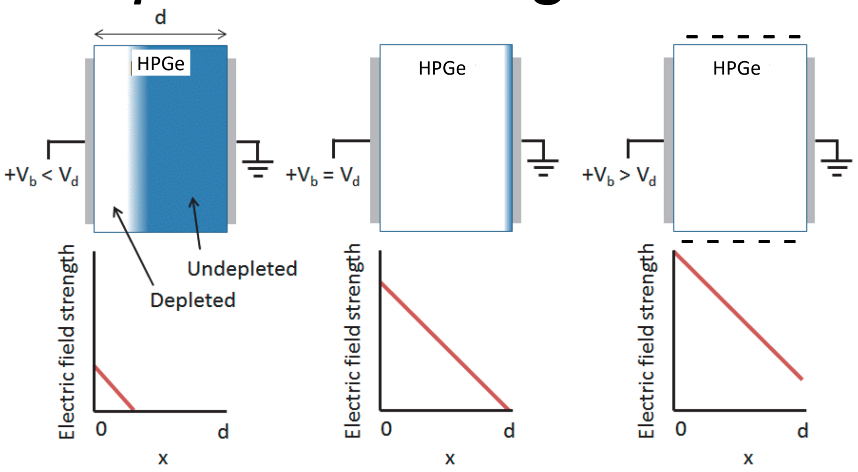
If surface effects can be neglected

$$V_d = N\, q\, d^{\,2} / 2\, \varepsilon$$

N = impurity density in the bulk
q = electronic charge
d = detector thickness
ε = dielectric constant of germanium



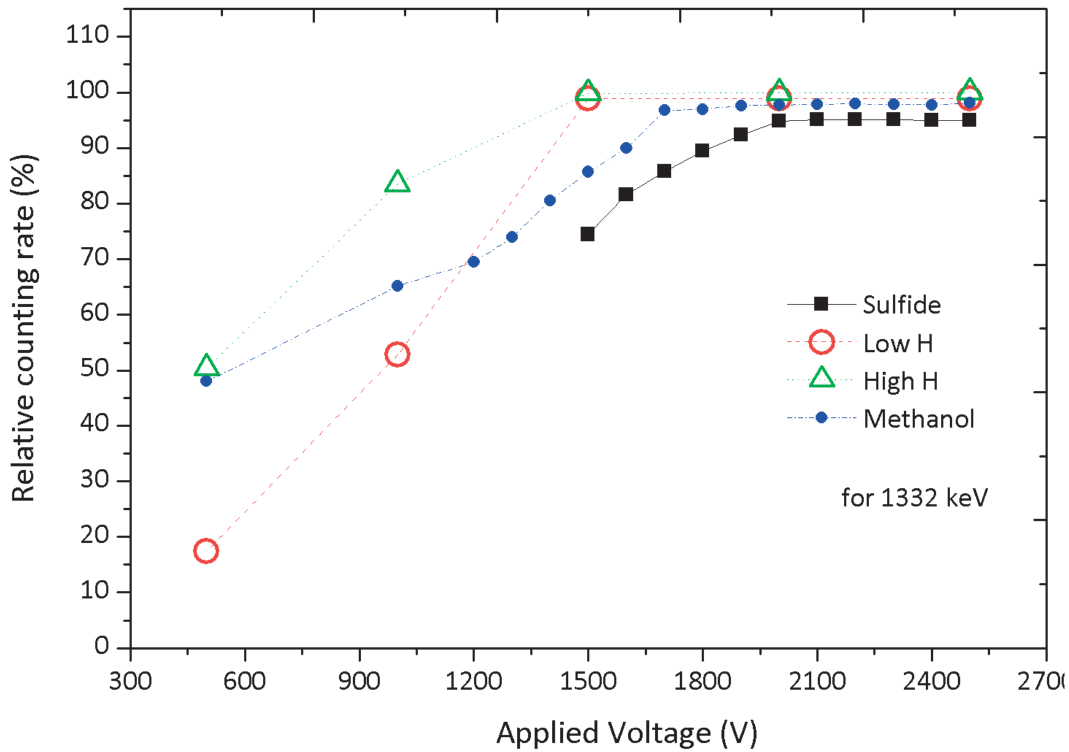
Depletion voltage



	Depletion Voltage (V)
Low H	≤ 1500
High H	≤ 1500
Methanol	1700
Sulfide	2000
Hyper H	≤ 1500

Experimental results

(from G. Maggioni et al., EPJA 2015)



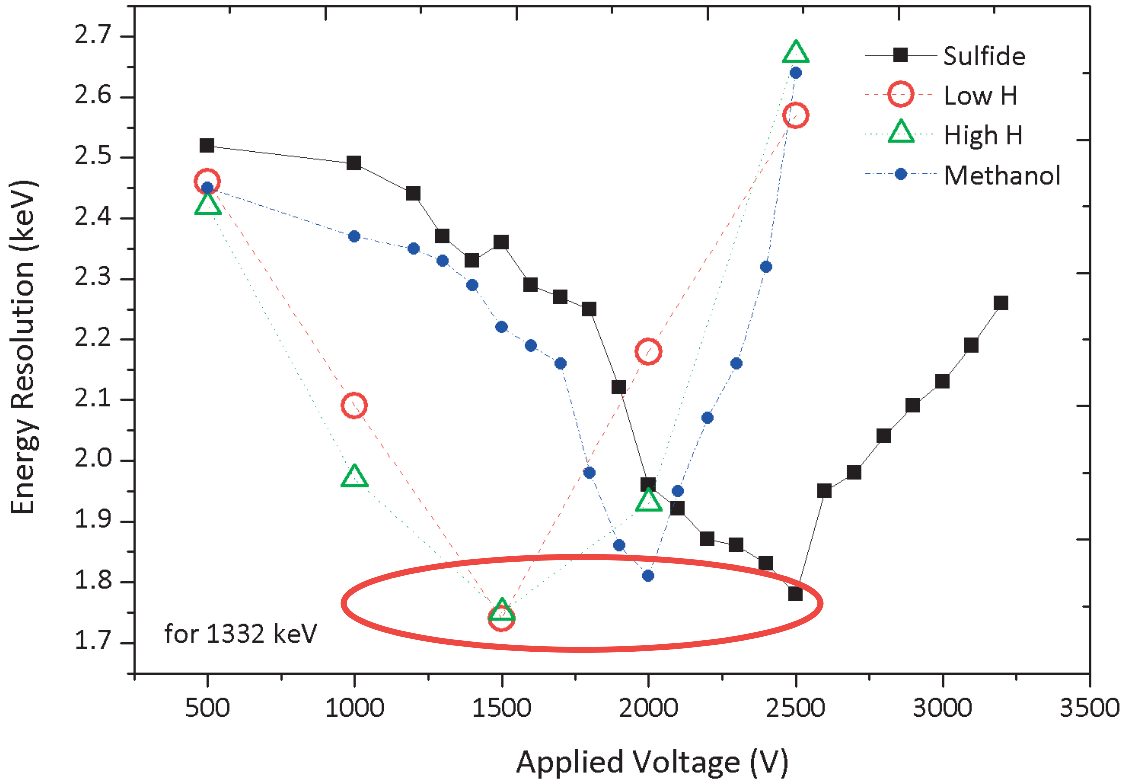
Surface effects are important → Passivation can give rise to a charge accumulation, which distorts the local field

Plateau value of counting rate for sulfide is lower → lower active volume (90-95%)

Detector resolution (FWHM) vs Bias voltage

Best resolution
≈ 1.7 keV at 1332 keV
for all passivations

	Voltage for best resolution (V)
Low H	1500
High H	1500
Methanol	2000
Sulfide	2500
Hyper H	1500



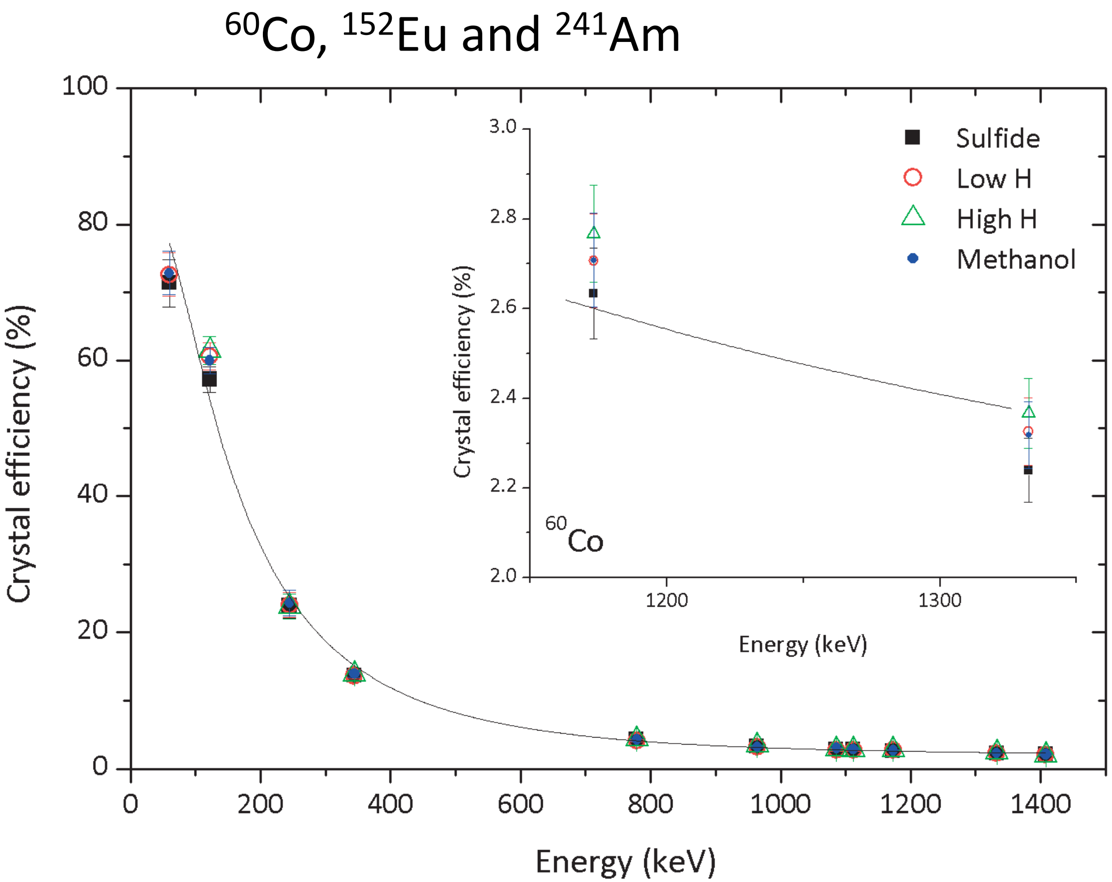
(from G. Maggioni et al., EPJA 2015)

Detector efficiency

$$\epsilon_{exp} = \frac{R}{A \times I \times \exp(\sum_{i=1}^{3} -(\mu_i \times d_i) \times (\Omega/4\pi)}$$

R = counting rate
A = source activity
I = emission probability of the line of interest
d_i and μ_i = thickness and total absorption coefficient of the absorbing layers, respectively
Ω = solid angle subtended by the detector

(from A. Elanique et al., Appl. Rad. Isot. 2012)



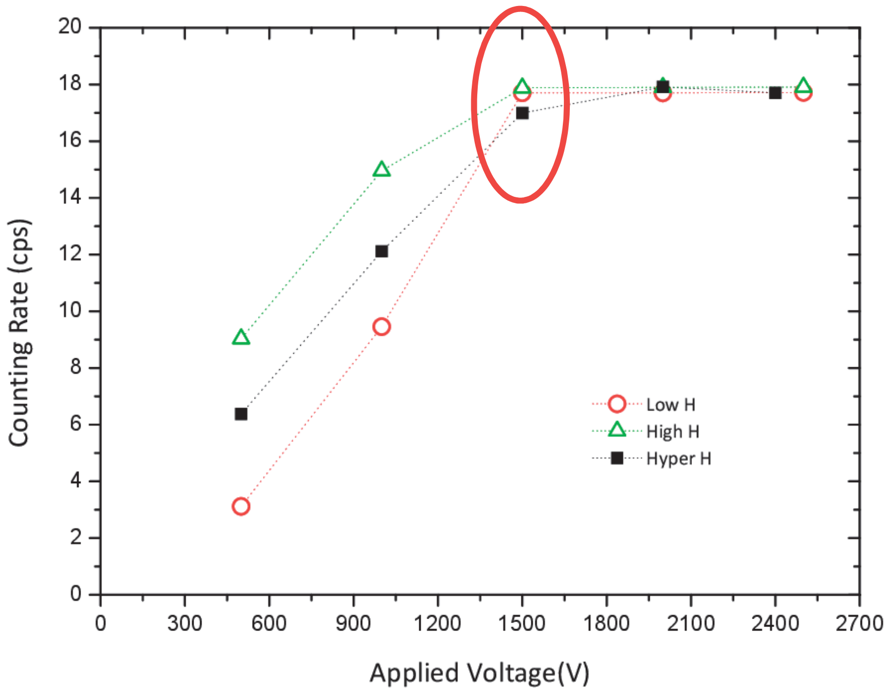
Surface passivation slightly affects the detector efficiency

(from G. Maggioni et al., EPJA 2015)

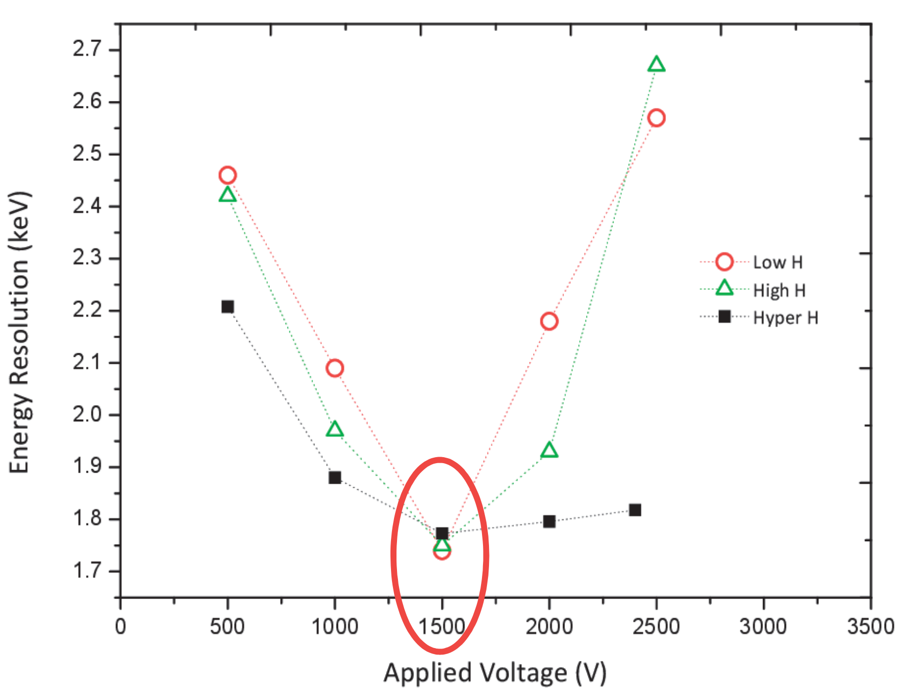
Detector properties and surface passivation: current results

Passivations: Low H, High H and Hyper H

Depletion Voltage



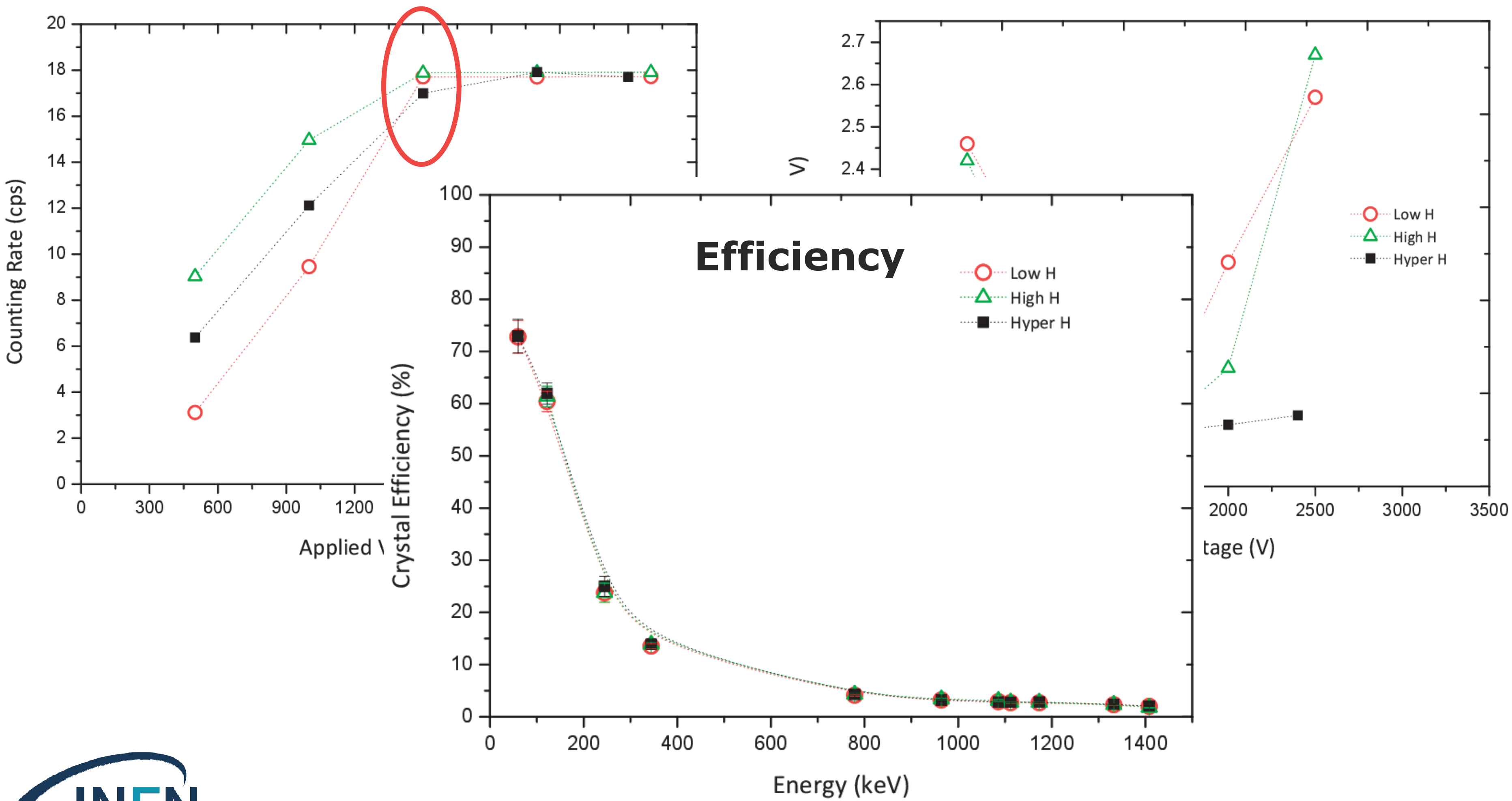
Energy Resolution



(from S. Riccetto et al., to be submitted to ***EPJA****)*

Passivations: Low H, High H and Hyper H

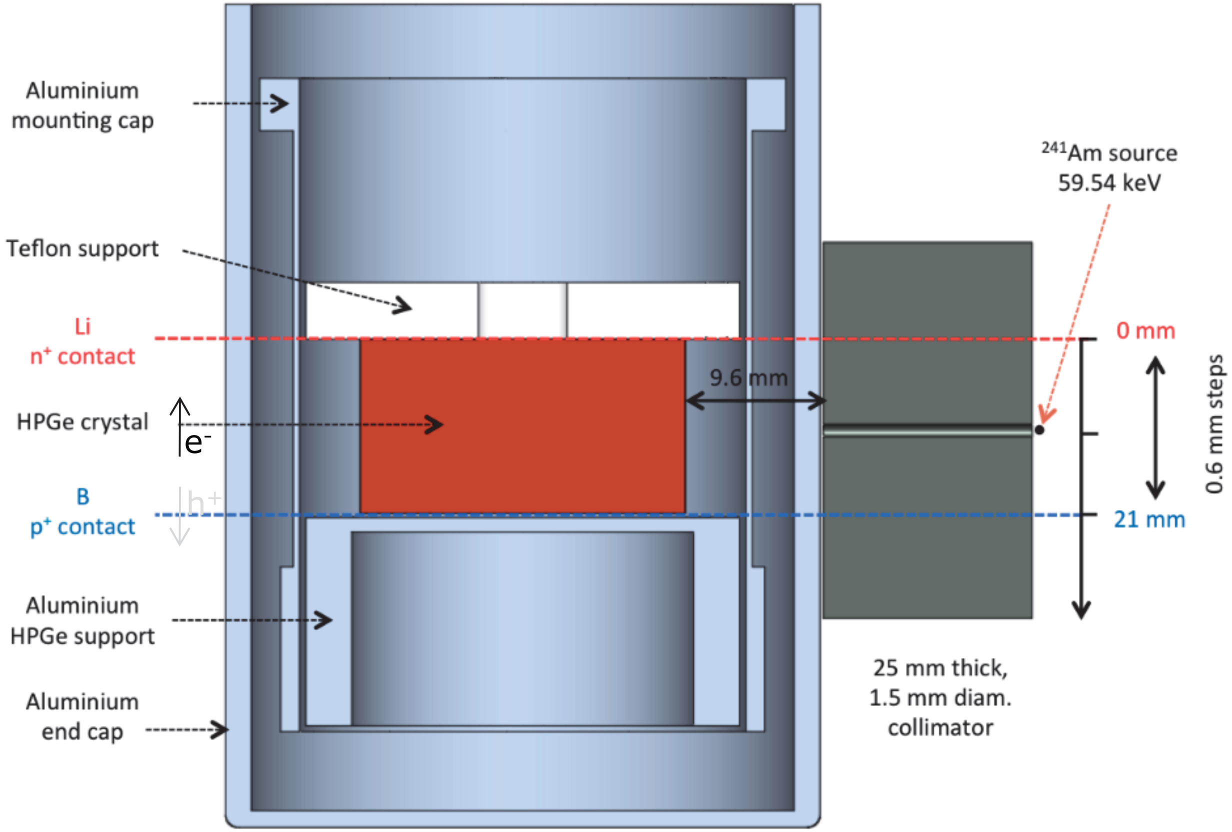
Depletion Voltage **Energy Resolution**

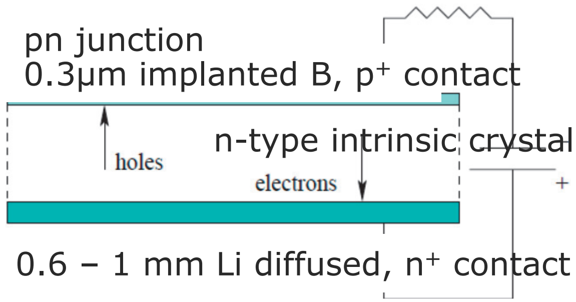


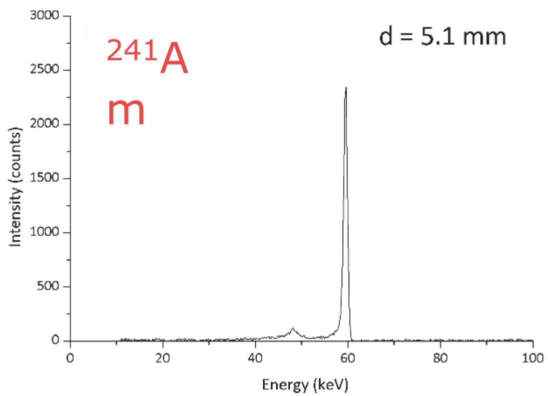
(from S. Riccetto et al., to be submitted to ***EPJA****)*

Lateral scan with 60eV ϒ-rays

Lateral scans with a Collimated ^{241}Am Source to study the passivated surface.

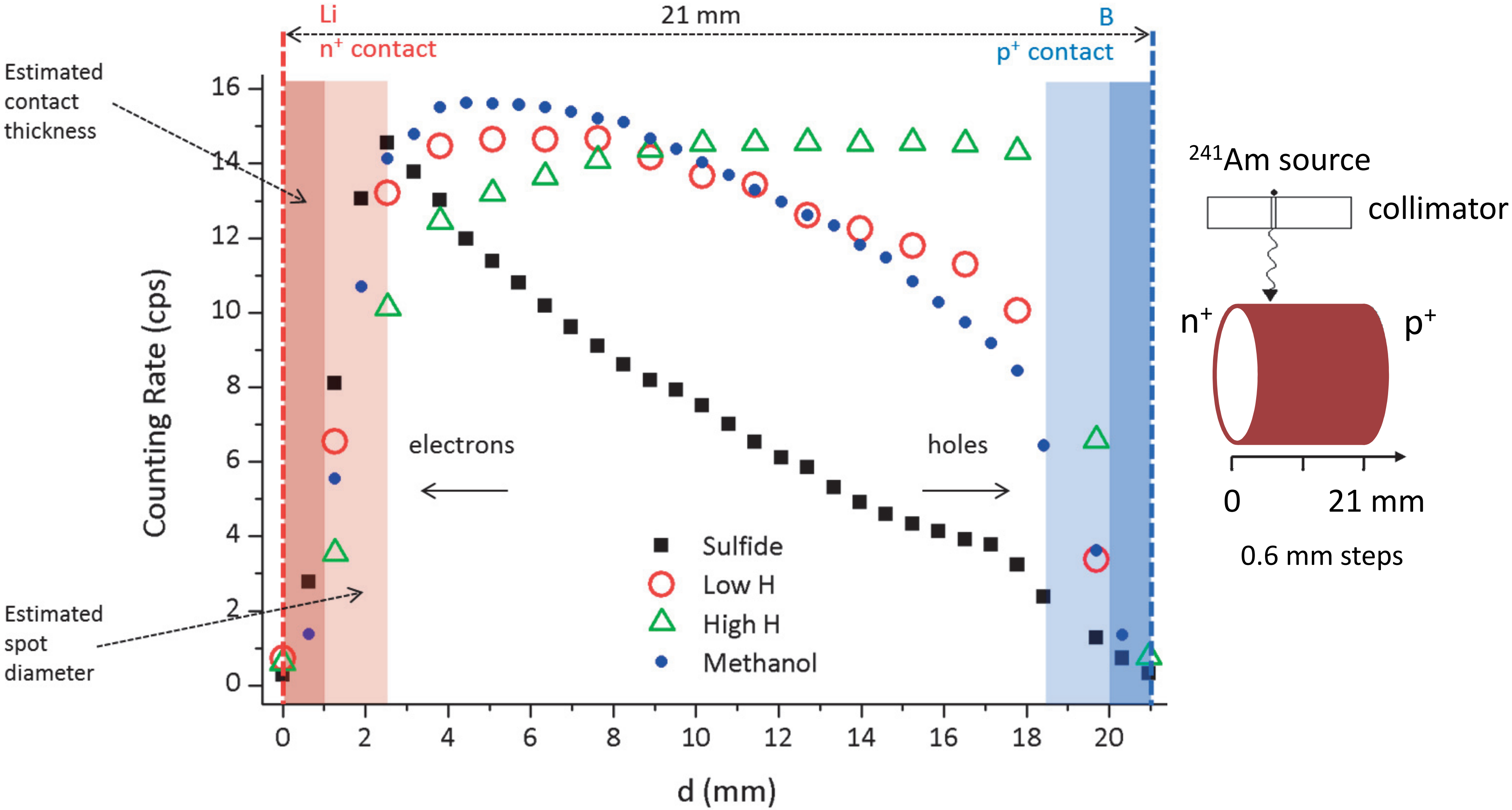






Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

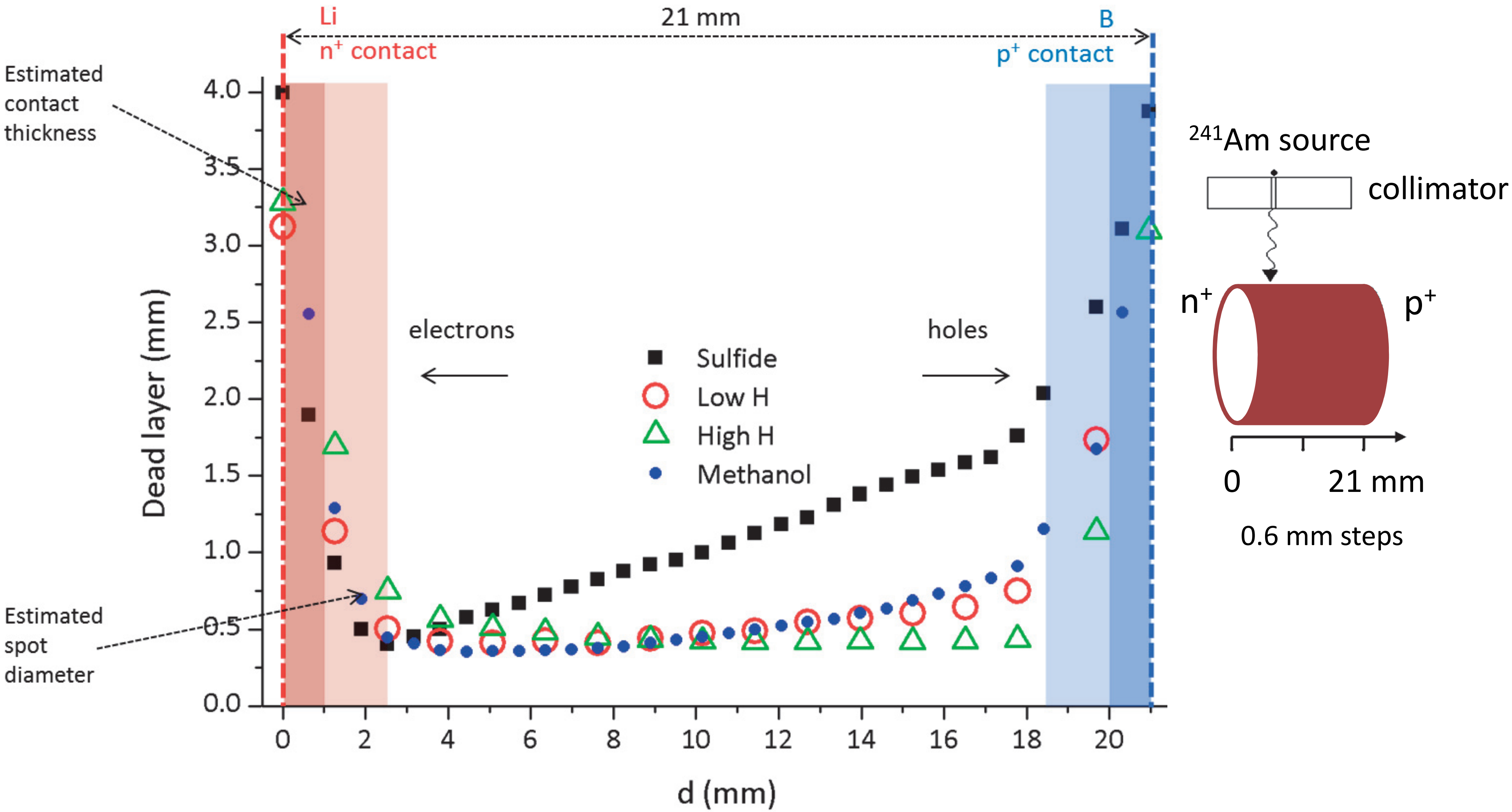
Scan of the passivated surface: counting rate vs distance



- Strong decrease of counting rate close to the electrodes
- S-terminated detector: n-type surface behavior, which can be related to a negative charge accumulation
- For the other passivations the n-type/p-type behavior is less pronounced

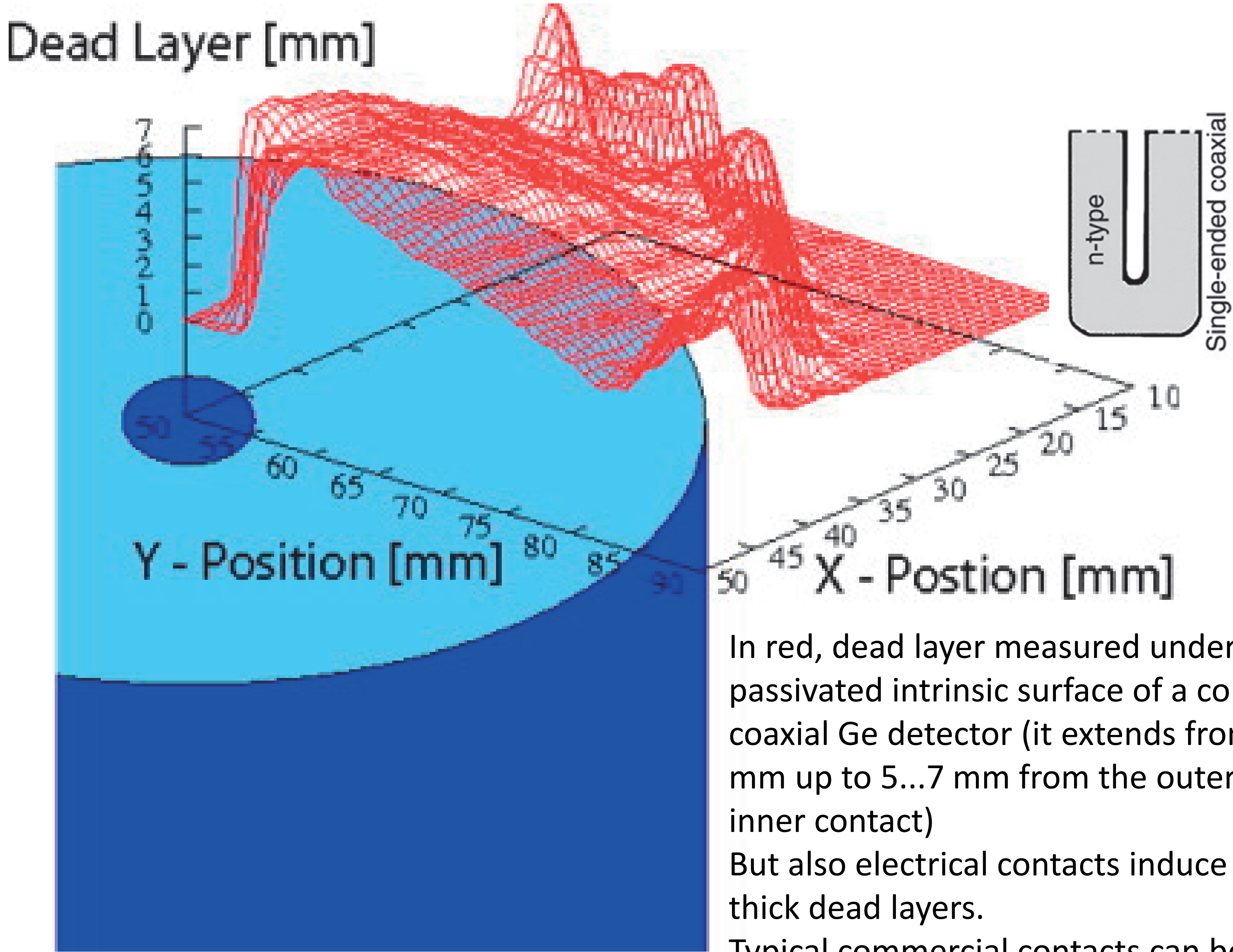
(from G. Maggioni et al., EPJA 2015)

Scan of the passivated surface: dead layer vs passivation



- The average dead layer is below 1 mm, except for S-terminated detector
- The difference in dead layer thickness involves a difference in the active volume, which can reach 10% in the case of the S-terminated detector

(from G. Maggioni et al., EPJA 2015)



In red, dead layer measured under the passivated intrinsic surface of a commercial coaxial Ge detector (it extends from 1...2 mm up to 5...7 mm from the outer to the inner contact)

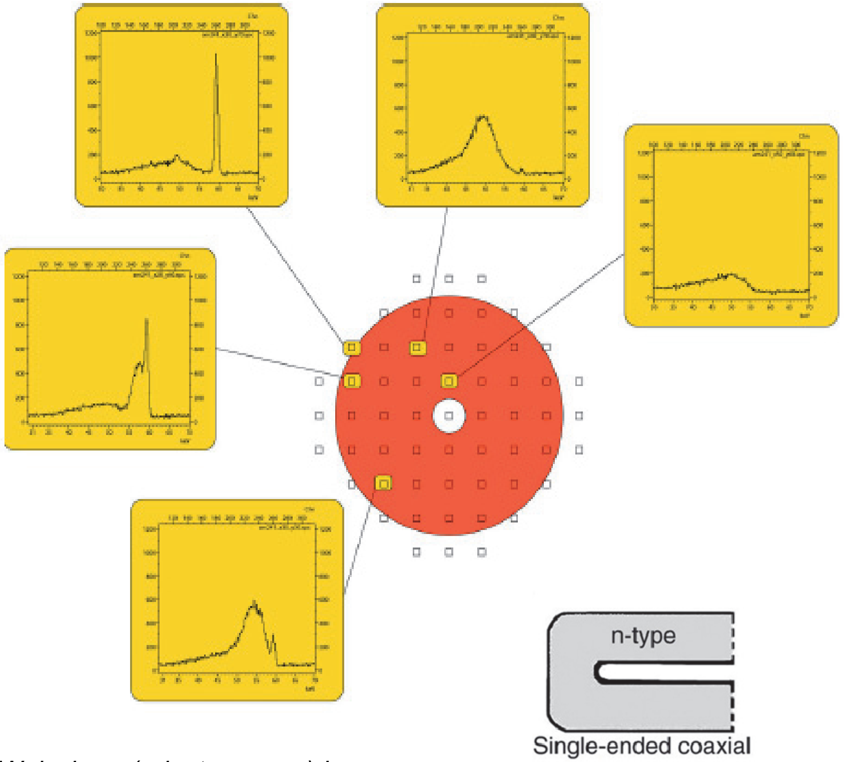
But also electrical contacts induce relatevily thick dead layers.

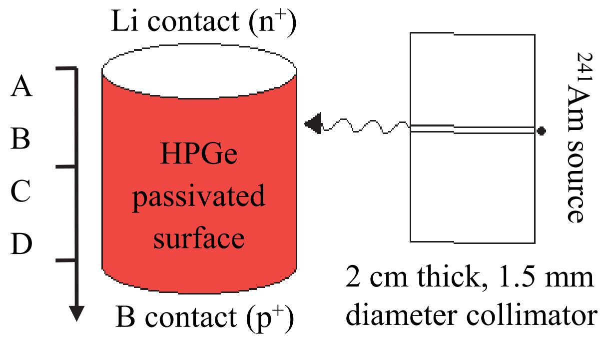
Typical commercial contacts can be: Li, B, a-Ge(H), a-Si(H), Y, etc.

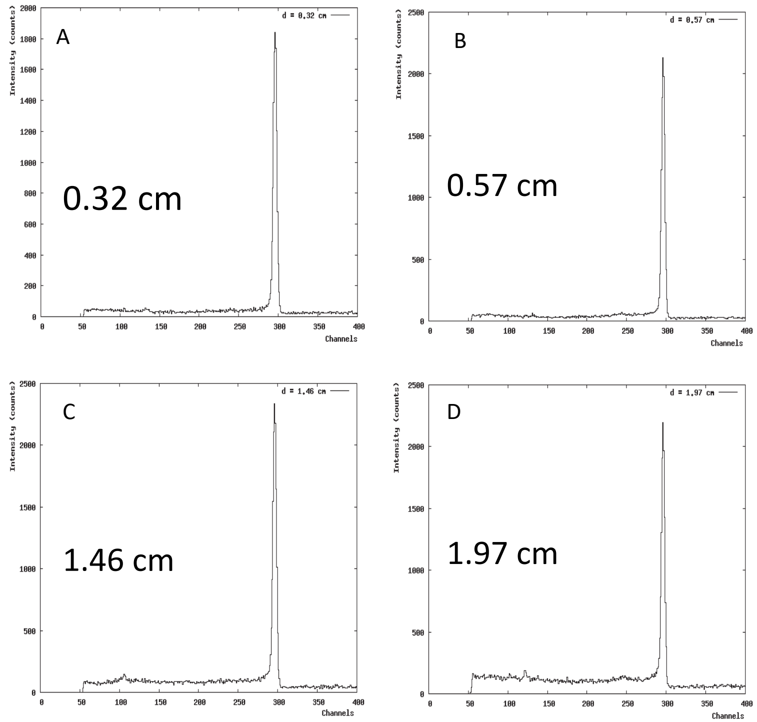
from D.Weisshaar (private comm.) in Eberth & Simpson, Progr.Part.Nucl.Phys.2008

Incomplete charge collection near the passivated surface

Comparison between an LNL prototype and a commercial detector

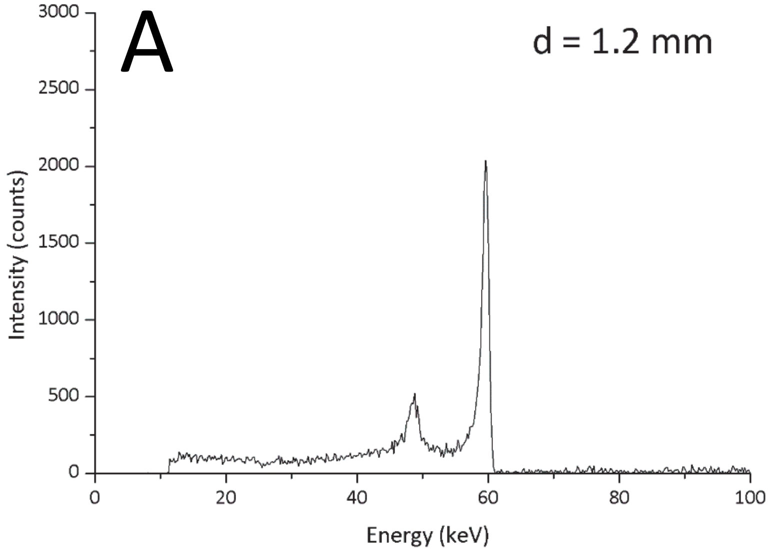


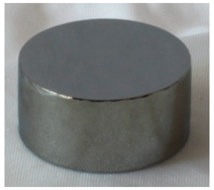


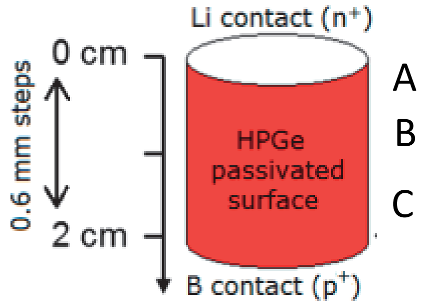


from D. Weisshaar (private comm.) in J. Eberth and J. Simpson, Progress in Particle and Nuclear Physics 60(2008)283

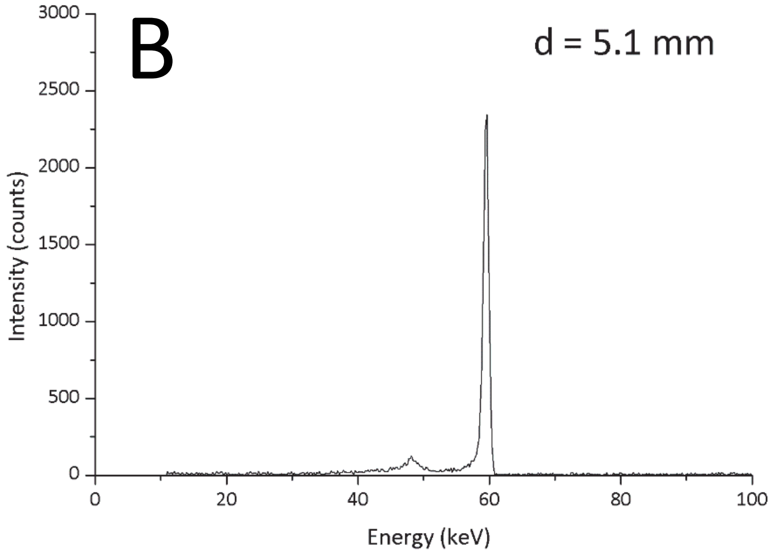
High H-passivated detector: ^{241}Am spectra

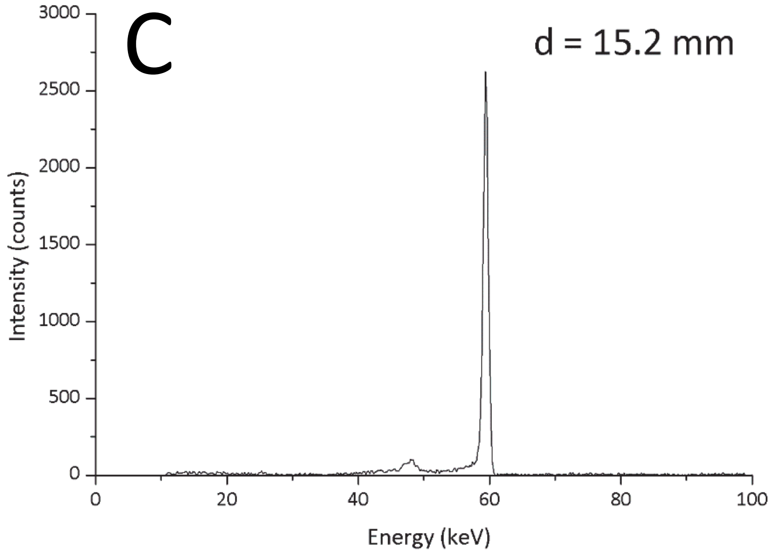






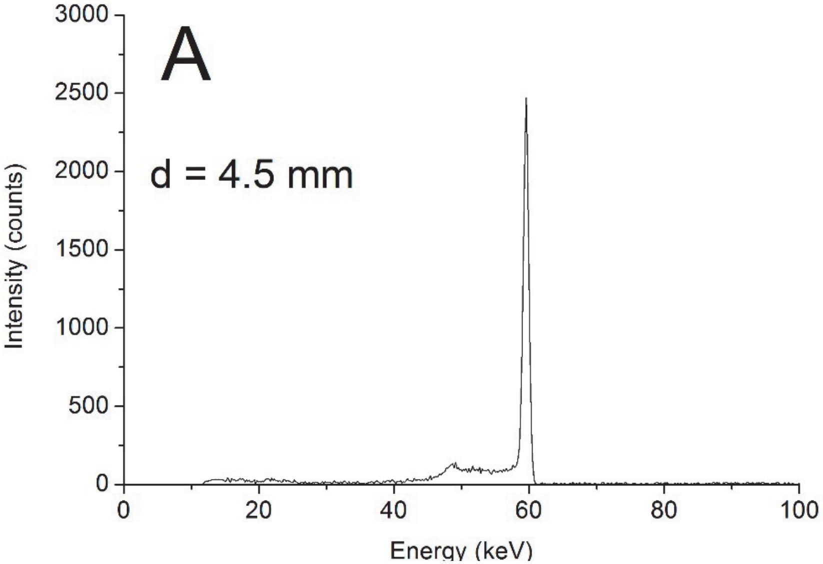
Constant photopeak area normalization

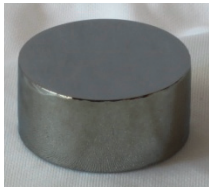


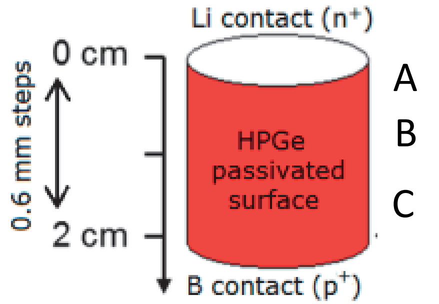


(from G. Maggioni et al., EPJA 2015)

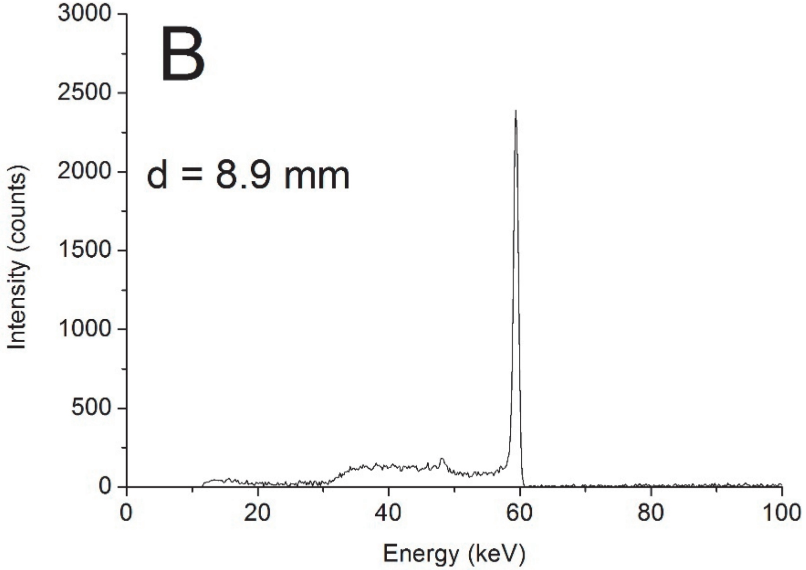
Sulfide passivated detector: ^{241}Am spectra

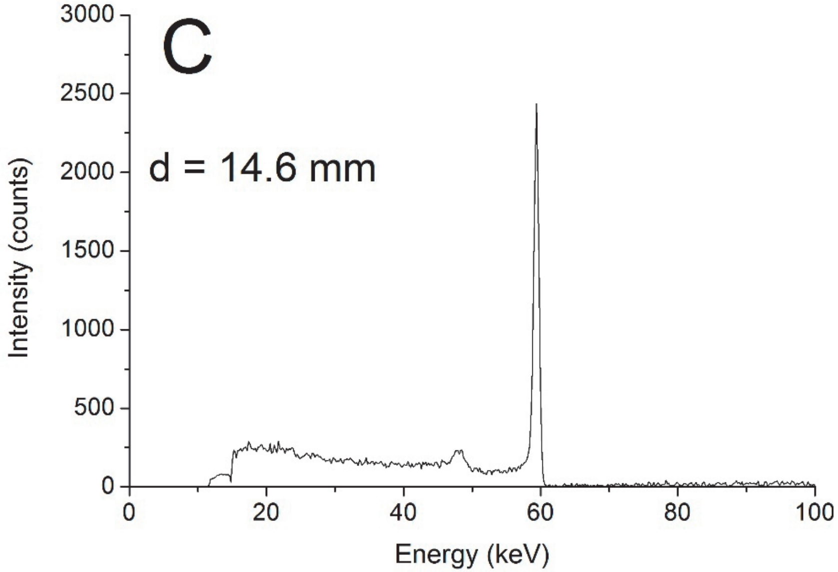






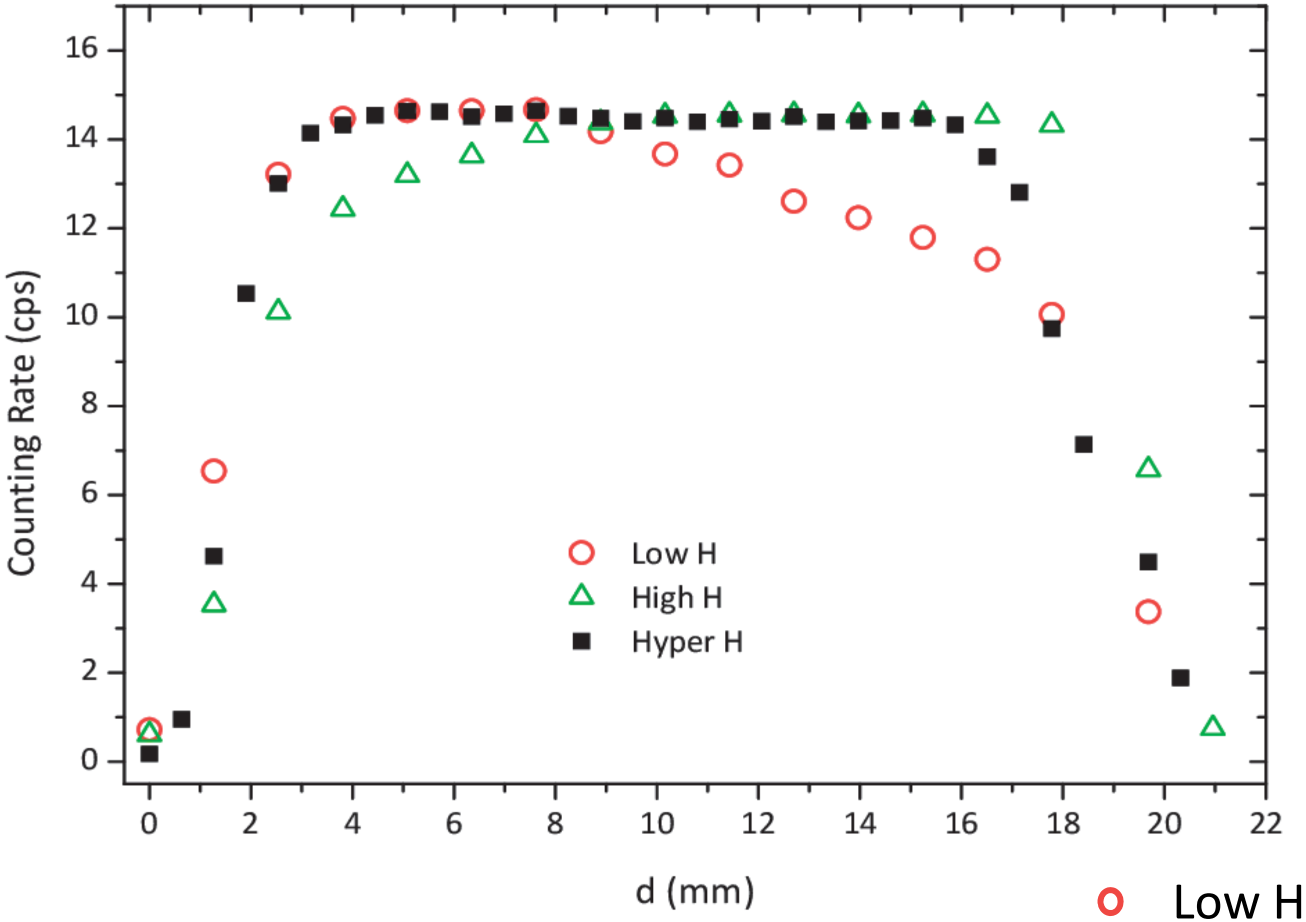
Constant photopeak area normalization

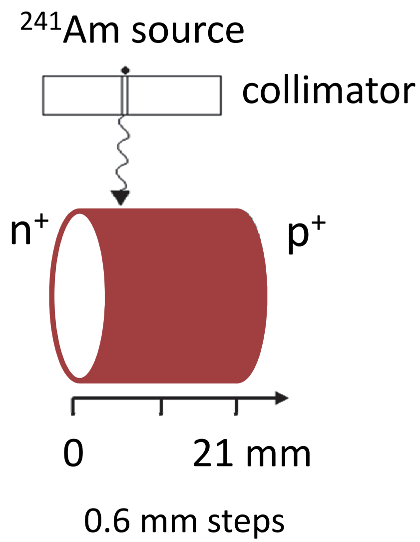




(from G. Maggioni et al., EPJA 2015)

Scan of the passivated surface: counting rate

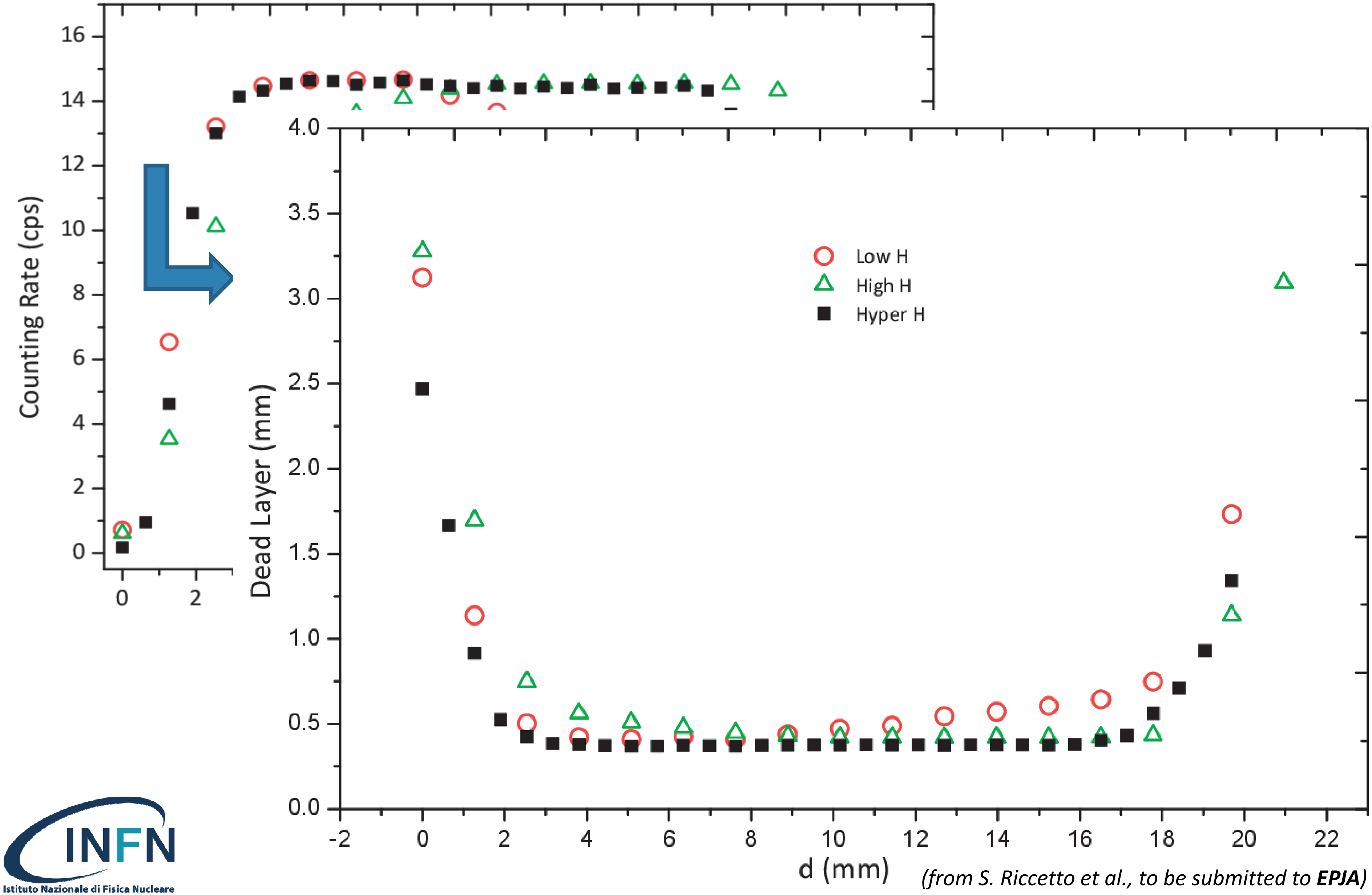




- Low H: slightly n-type surface
- High H: slightly p-type surface
- Hyper H: essentially "neutral"

(from S. Riccetto et al., to be submitted to ***EPJA****)*

Hyper H: the smallest dead volume

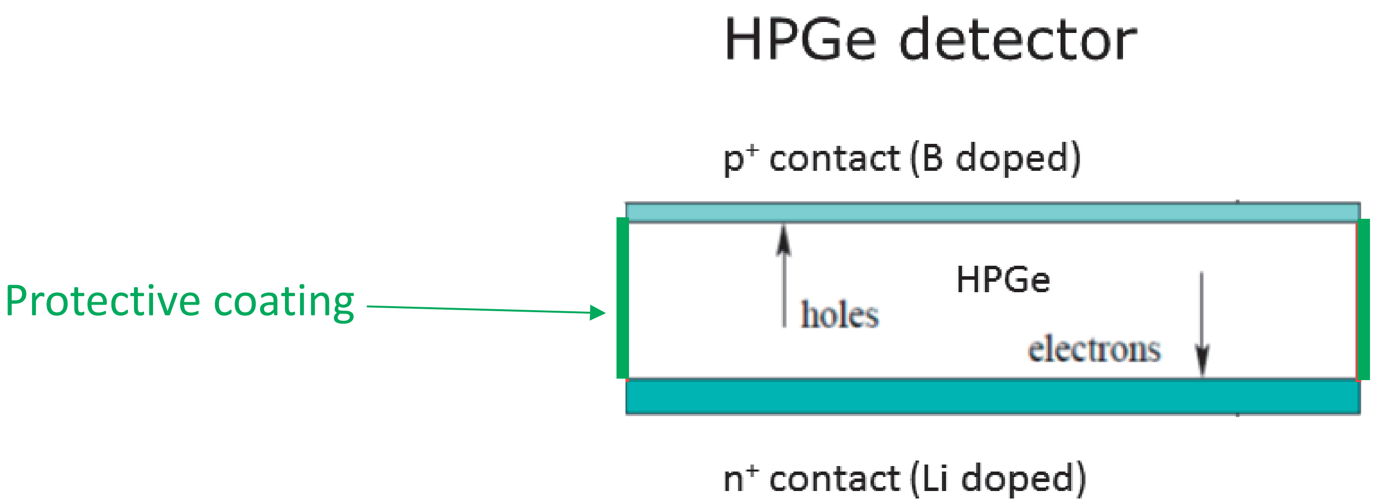


(from S. Riccetto et al., to be submitted to ***EPJA****)*

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Problem: all these passivations are not stable

Solution: New protective coating

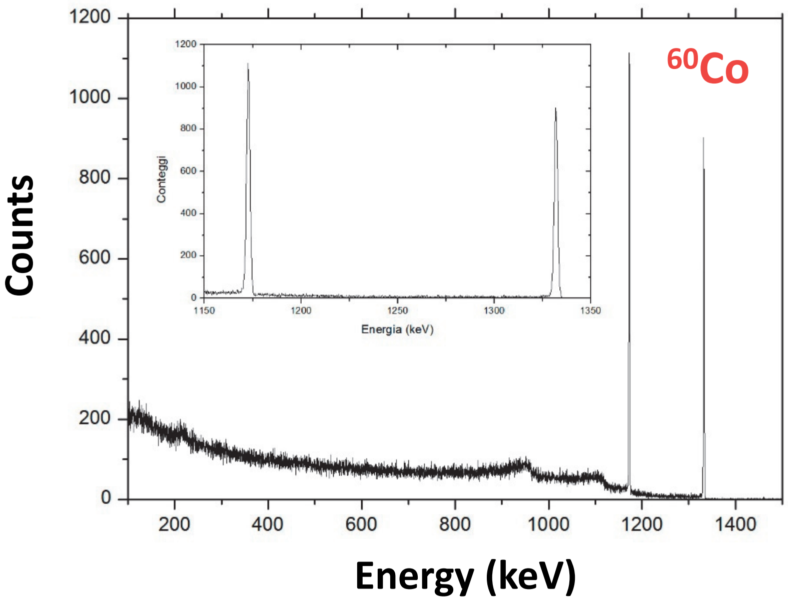


Preliminary tests of coated detectors

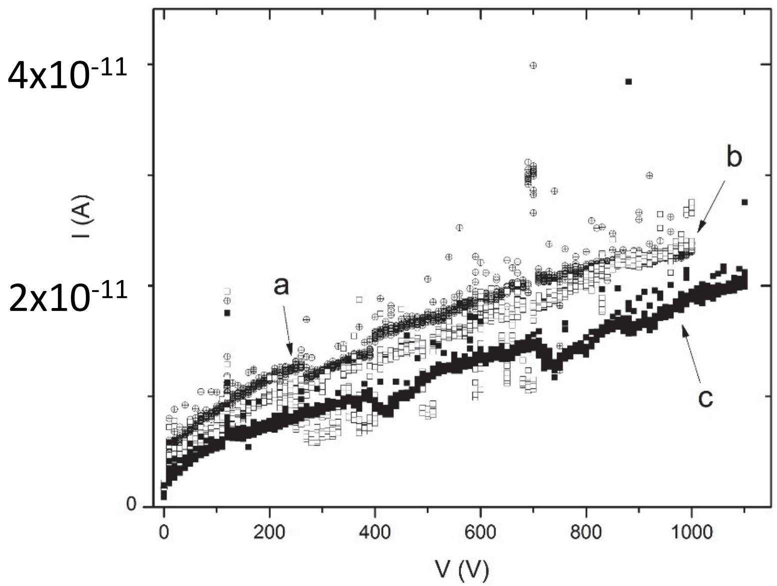
✓ Methanol passivation followed by the protective coating application

- 19 months at room temperature under static vacuum
- 10 minutes at room temperature on the desk
- 40 hours at 103°C under vacuum

The properties of the coated detector do not change after these tests



Leakage current



Summary

- Several passivation routes have been applied to a planar HPGe detector and their effects on the detector characteristics have been investigated.
- Lateral scan measurements highlighted the electrical nature of the passivated surface (either n-type or p-type) and its influence with bulk propertis of Ge dets.
- Hydride-based passivations are the bests to reduce dead layers in HPGe dets.
- A detector coating has been developed to substitute the mechanical incapsulation for protecting and stabilizing the passivated surfaces (also in between segments!)

NOVEL CONTACTS

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Development of novel contacts

Thermally-induced dopant diffusion

Thermally-induced contamination

(Impurity diffusion inside semiconductors is a thermally activated process)

Which one of them is predominating?

''Thermal process window''?

List of studied processes

- P diffusion by Spin-On-Doping **[V. Boldrini et al., Appl. Surf. Sci. 392 (2017)]**
- Sb diffusion from a remote sputtered source **[G. Maggioni et al., MSSP (2018)]**
- High-T annealing treatments on as cut samples

> - Temperature range: from 600 to 810°C
> - Time range: from 2 to 30 minutes

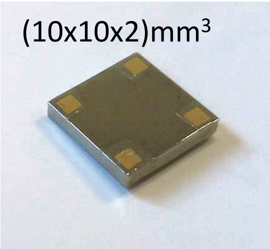
- Reference samples:
  - n-type HPGe
  - p-type HPGe

  } Supplied by Umicore

  - B ion implanted (23 keV, 1e15 cm^{-2})

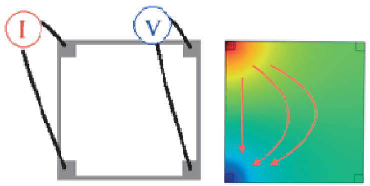
Contamination of HPGe in thermal processes

Four-wire resistance and Hall measurement



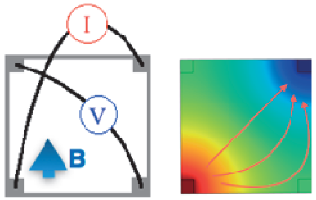
Van der Pauw method

R_{sheet}



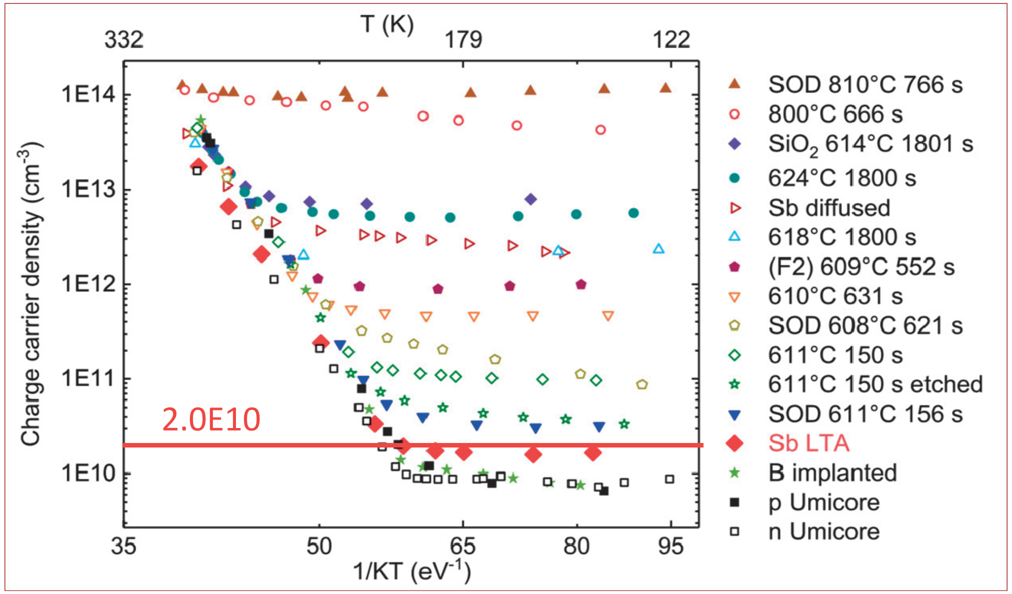
Hall-effect method

Carrier type



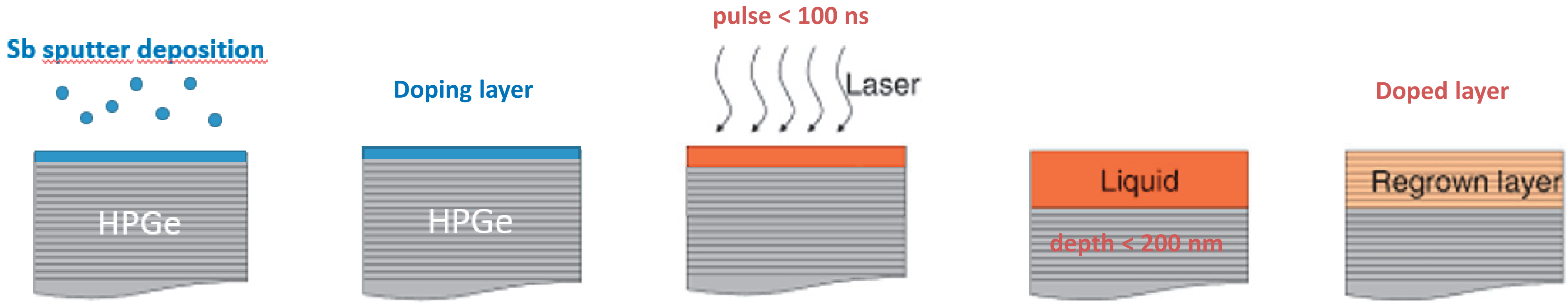
[From V. Boldrini et al., **Mater. Sci. Semicond. Proc.** (2018), *submitted*]

Contamination after laser treatment



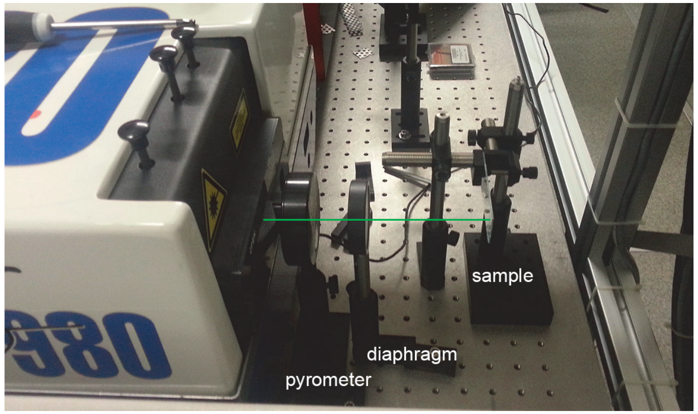
Carrier density within the specifications (0.4-2.0E10 cm^{-3})

n^+ contact on HPGe – LTA technology



Advantages:

- Melting temperature is reached and maintained for a short time (<100 ns)
- Only the surface (< 200 nm) is melted, the bulk is at room temperature
- High dopant concentrations → → near-ideal p-n- junctions
- Doping with heavy elements without crystal damage
- Very clean process suitable for preserving the Ge hyperpurity
- Suitable for complex contact geometries (segmentation)



Pulsed Laser @ LNL-INFN

Nd:YAG

λ=355 nm (third harmonic generator)

τ=7 ns; Ø=6,5 mm; Rate = 10Hz

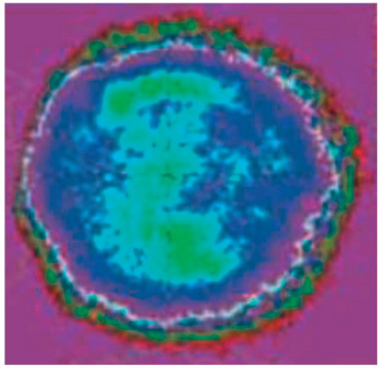
Radiant power ~1500 mW

Fluence ~300-400 mJ/cm^2

The small detector prototype

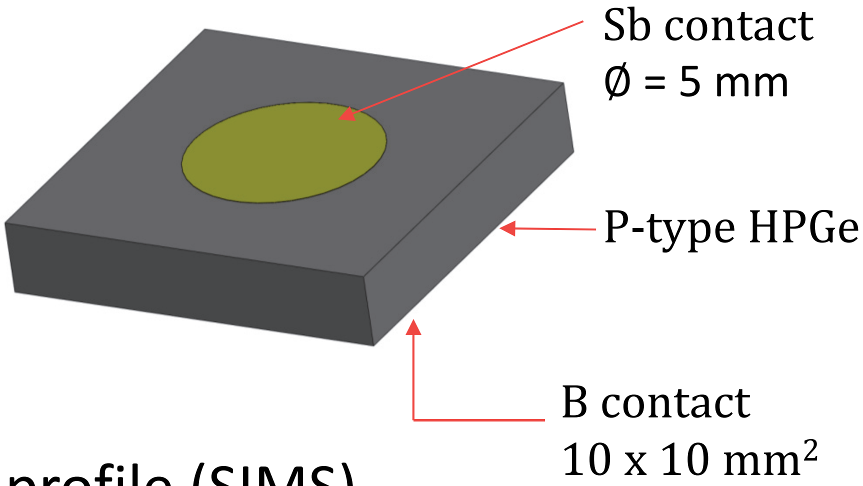
Laser geometry was favoured at the expense of detector performance

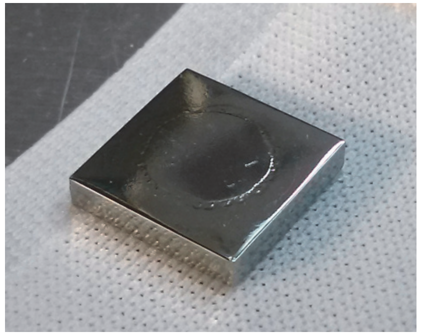
Laser spot



Ø = 7 mm

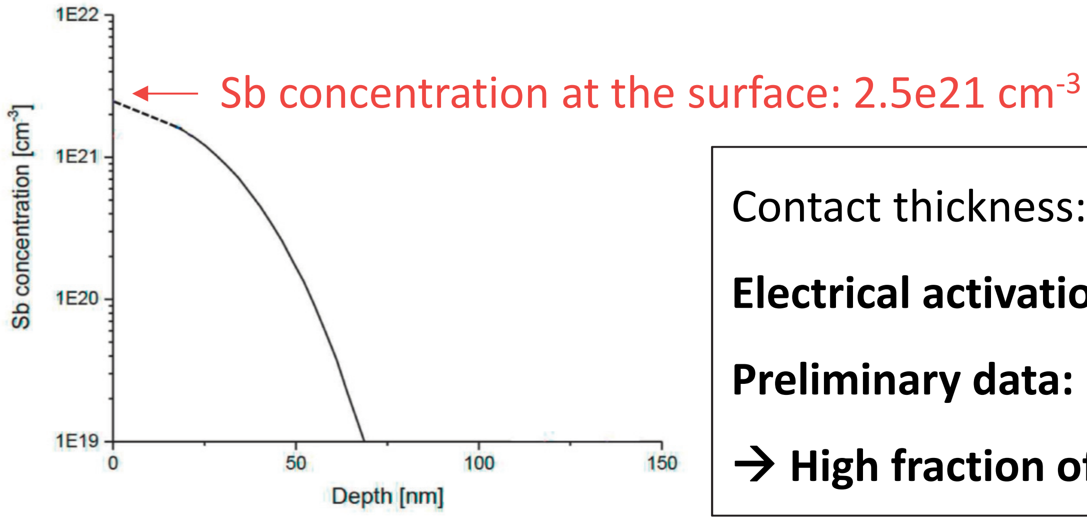
Detector sample
(10 x 10 x 1.9 mm^3)





No guard ring

Sb diffusion profile (SIMS)



Contact thickness: ≤ 100 nm

Electrical activation of dopant

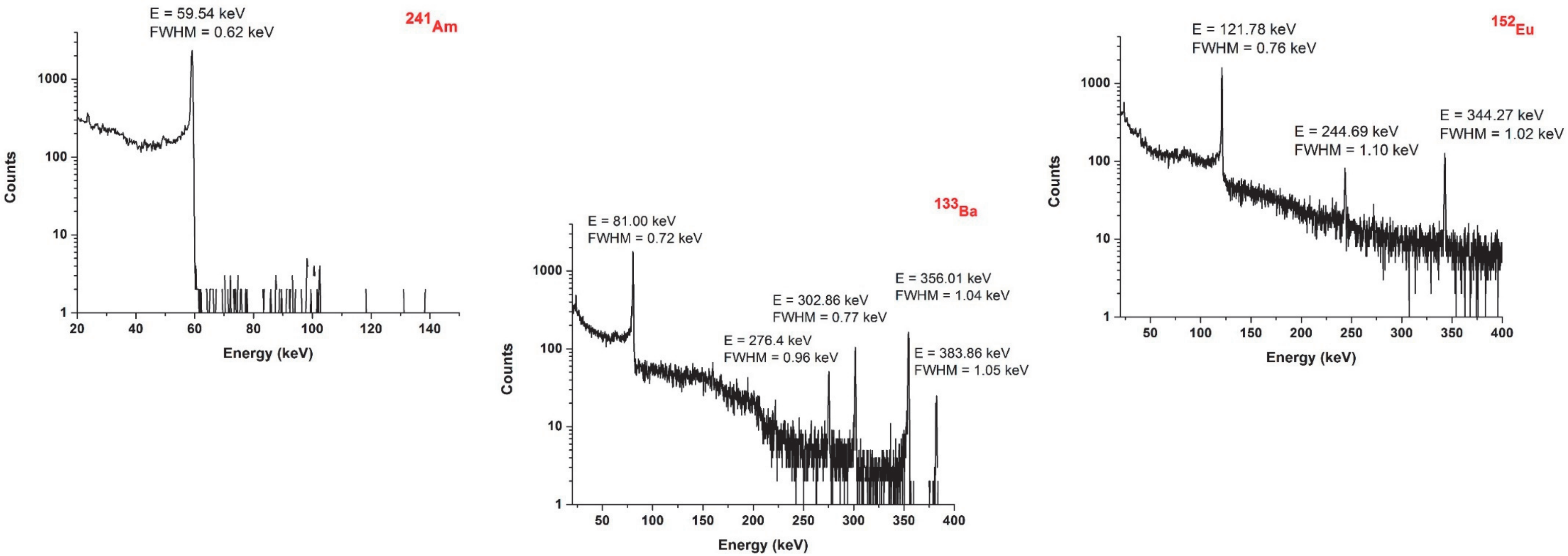
Preliminary data: > 50%

→ High fraction of substitutional Sb

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Test of small HPGe prototype: detector configuration

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

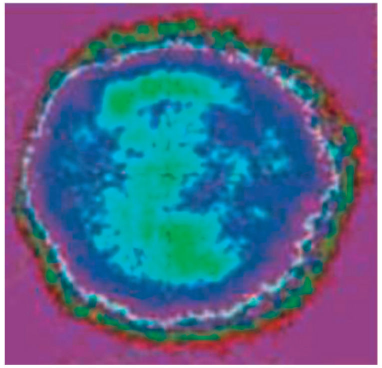


Good energy resolution all the energy range up to 400KeV

The small detector prototype

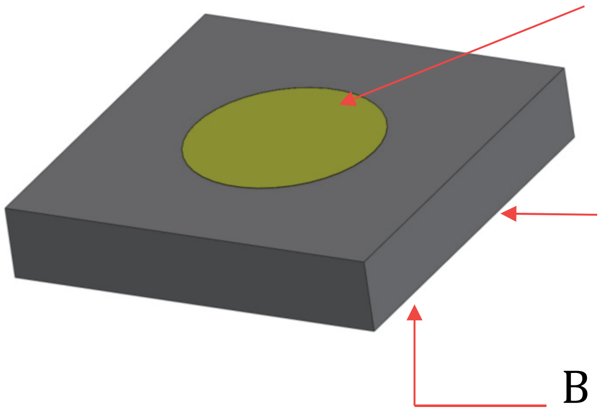
Laser geometry was favoured at the expense of detector performance

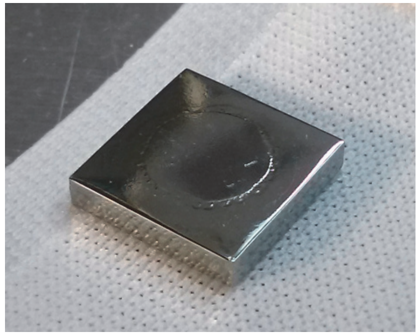
Laser spot



Ø = 7 mm

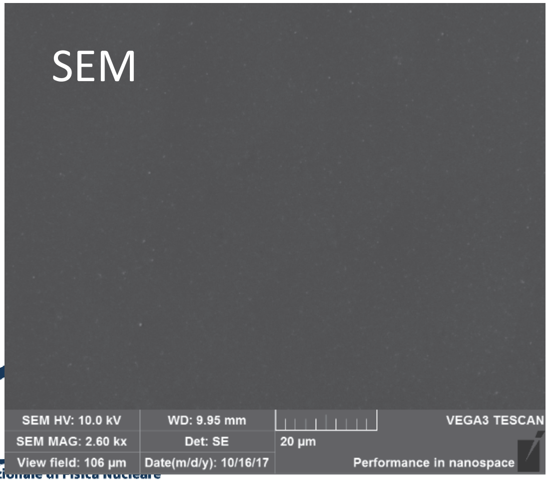
Detector sample
(10 x 10 x 1.9 mm^3)



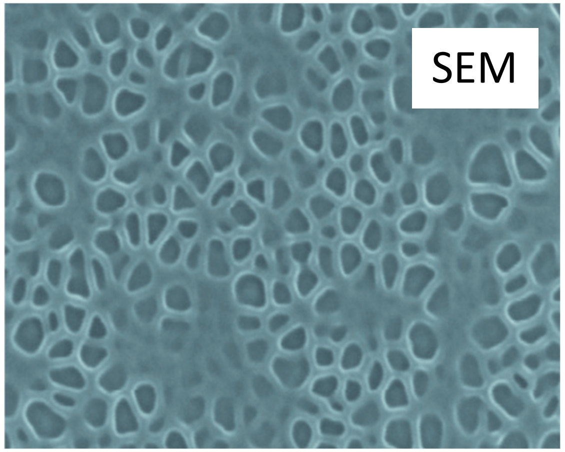


No guard ring

Surface morphology:
No laser-induced defects

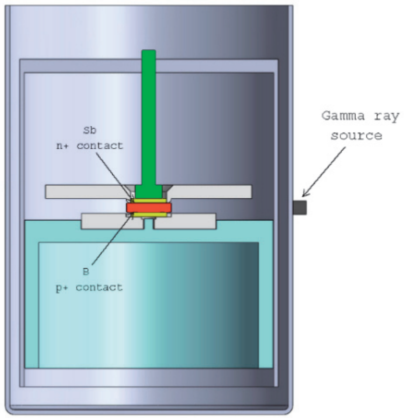


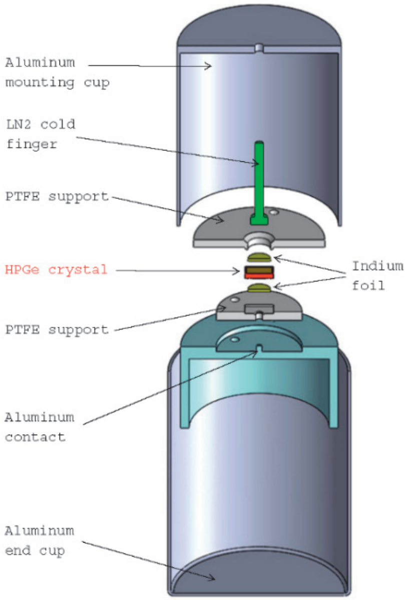
Sb
Ion Implantation
(6×10^{15} Sb cm^{-2} , 50 KeV, at LN_2)



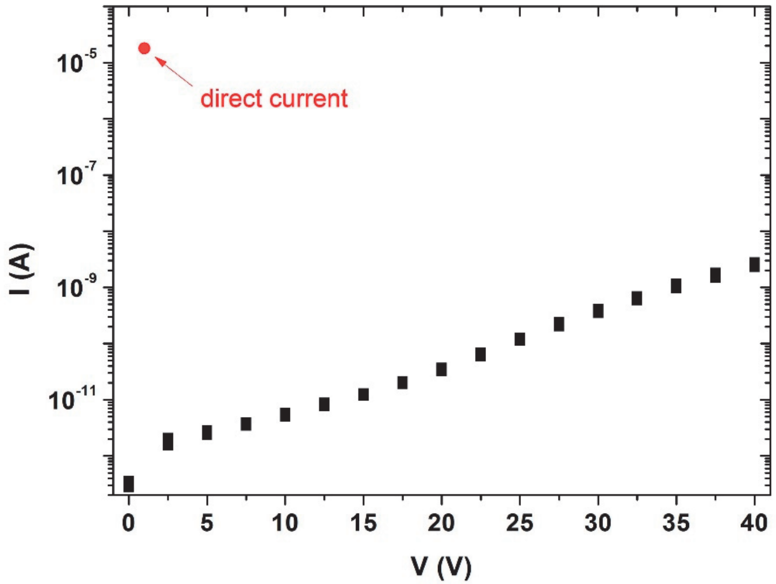
(from E. Bruno et al., **JAP** (2010))

Test of small HPGe prototype: I-V diode configuration





I-V characteristic curve



- Low leakeage current
- p-n junction is obtained

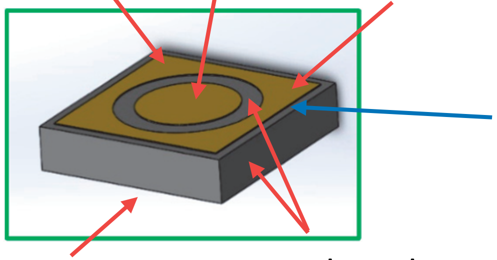
from G. Maggioni at al. Eur. Phys. J. A (2018)

Prototype HPGe by LTA technology @LNL-INFN

Deposition of gold
<100nm

Central contact

Guard ring



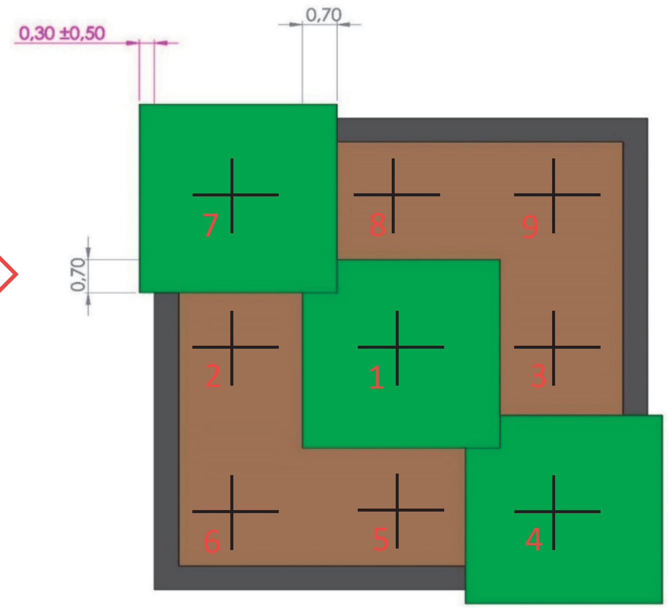
Sb deposition all the surface $(10x10)mm^2$

B implantation
$(10x10)mm^2$

Methanol
Passivation surface

Laser thermal annealing

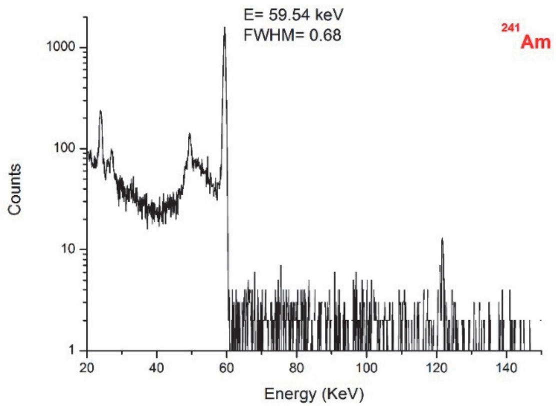
with 9 laser spots $(4x4)mm^2$ all the Sb surface $(10x10)mm^2$ was annealed

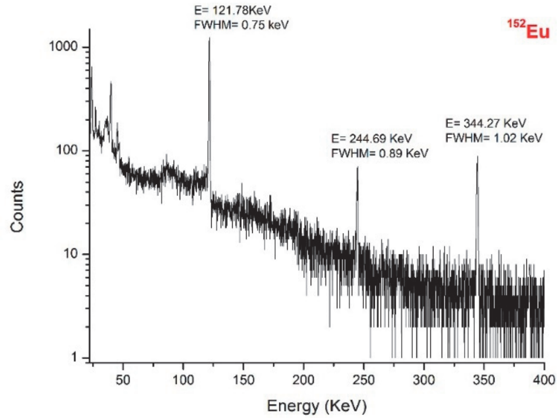


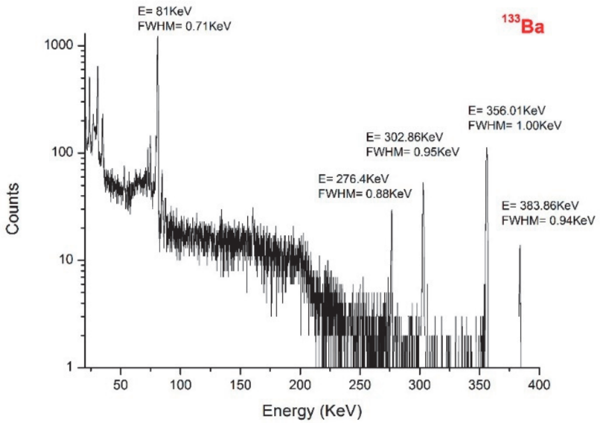
from W. Raniero (LNL - INFN) - PSeGe 2019

Test of small HPGe prototype: detector configuration

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





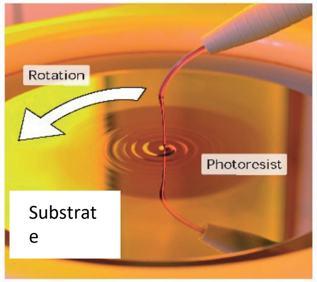


Good energy resolution all the energy range up to 400KeV

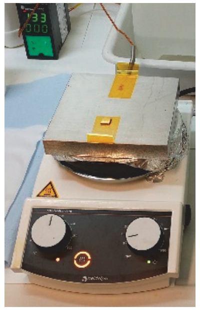
from W. Raniero (LNL - INFN) PSeGe 2019

Photolithography segmentation detector (LNL-INFN)

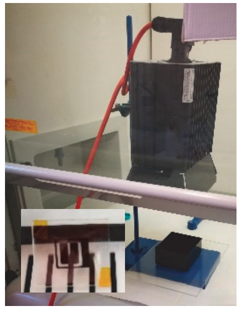
Spin coating positive photoresist on gold coating surface



Short Soft bake photoresist (1 min)



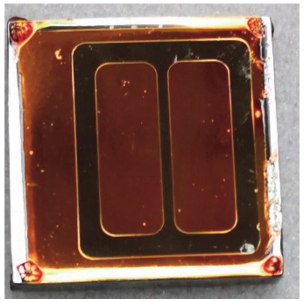
UV exposure (mask)



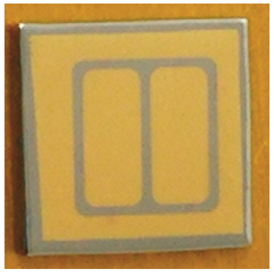
Dissolve the exposed photoresist

long soft bake photoresist (15min)

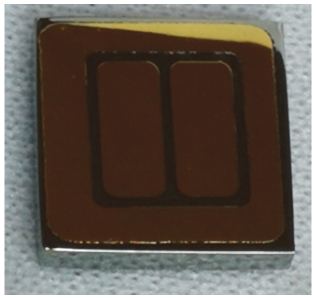
Gold etchant



Photoresist removal (aceton)



HPGe etching and passivation

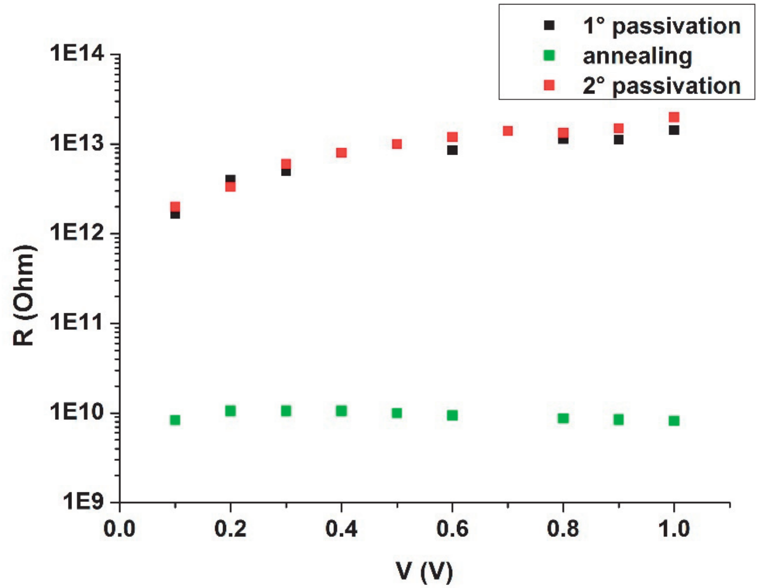


from W. Raniero (LNL - INFN) PSeGe 2019

Test of small HPGe prototype: diode configuration

gap 0.4mm

Second methanol passivation



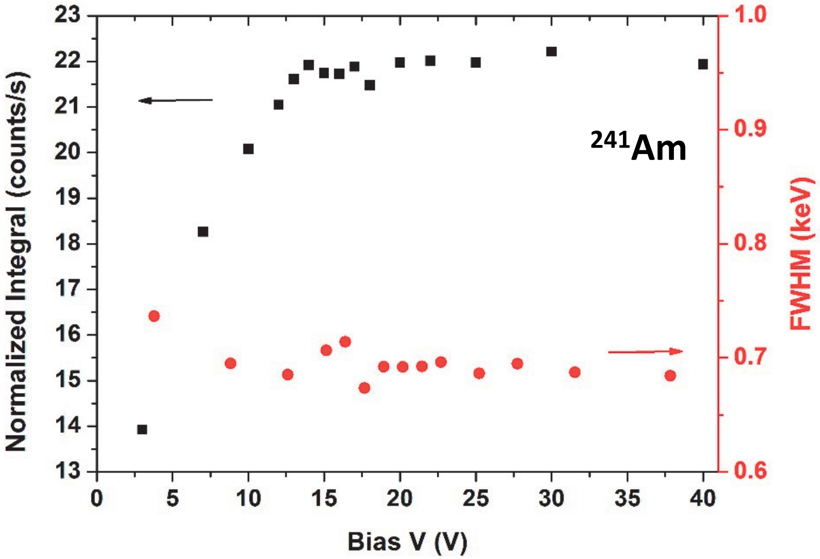
from W. Raniero (LNL - INFN) PSeGe 2019

Test of small HPGe prototype: detector configuration

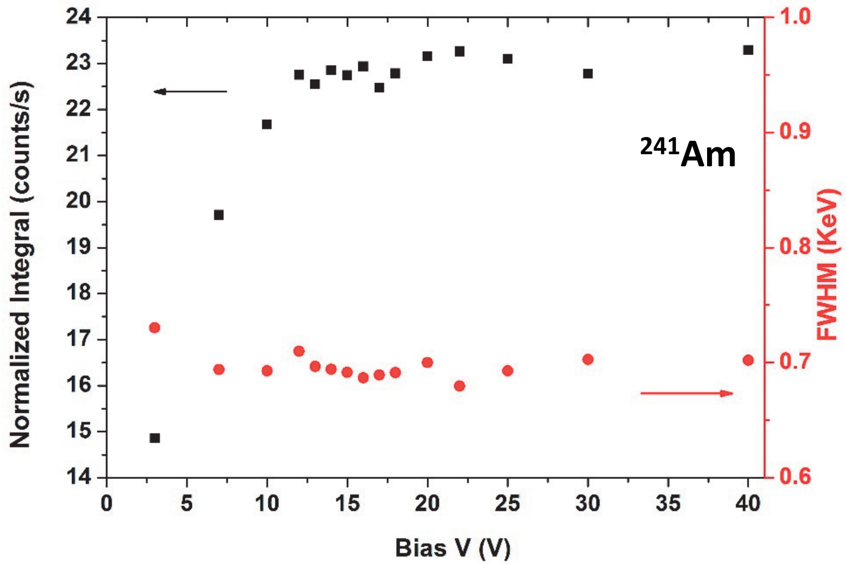
gap 0.4mm

Depletion Voltage - Energy resolution

Seg 1



Seg 2



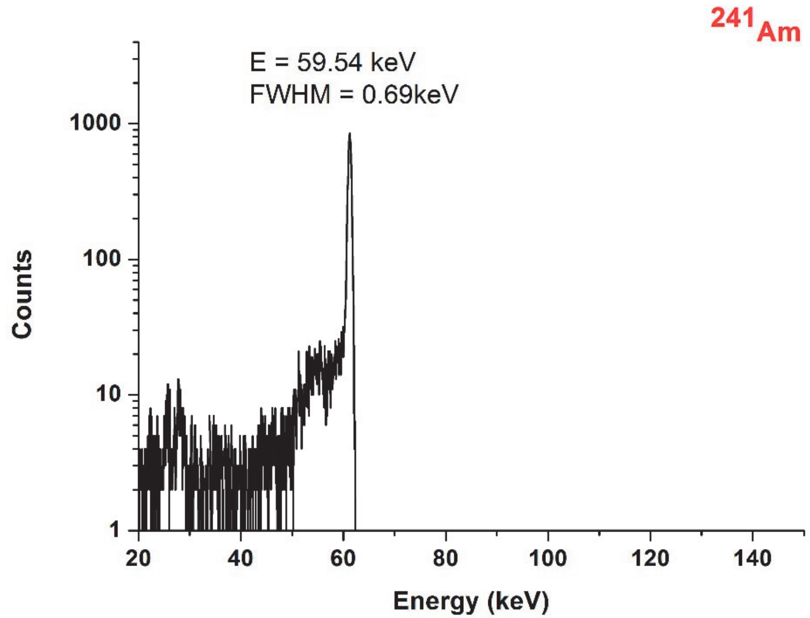
0.7 keV @ 59.54 keV (^{241}Am)

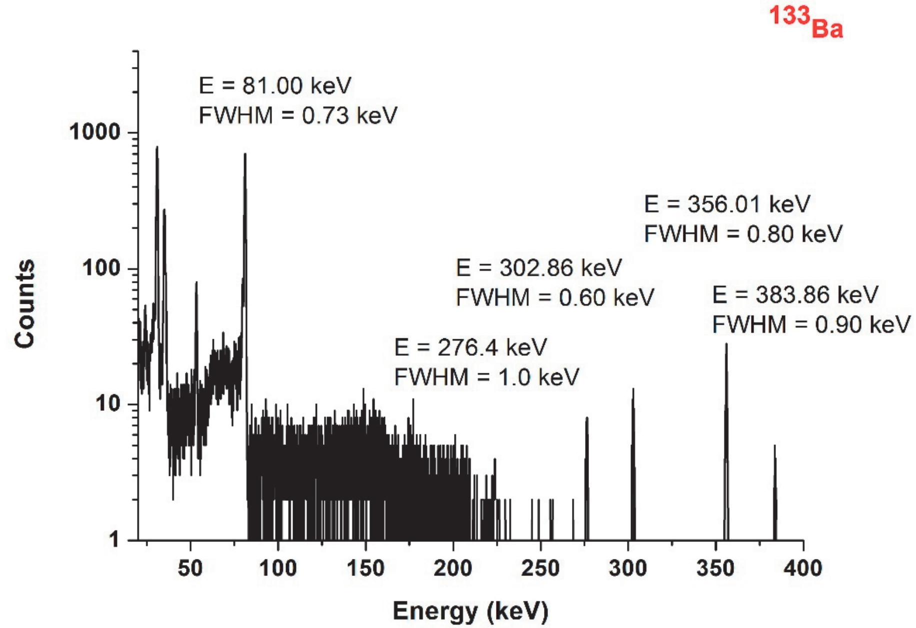
- detector fully depleted
- very good energy resolution

from W. Raniero (LNL - INFN) PSeGe 2019

Test of small HPGe prototype: detector configuration

Segment **1** **gap** **0.4mm**



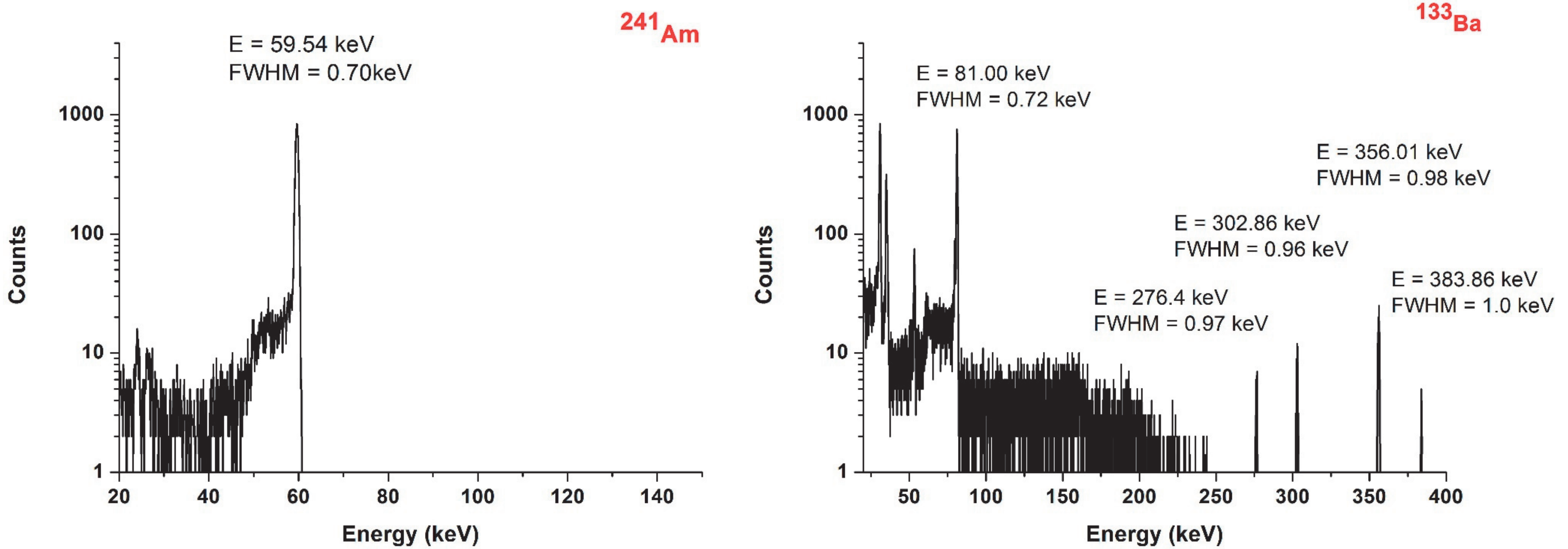


Good energy resolution in all the energy range up to 400KeV

from W. Raniero (LNL - INFN) PSeGe 2019

Test of small HPGe prototype: detector configuration

Segment **2** **gap**
0.4mm



Good energy resolution in all the energy range up to 400KeV

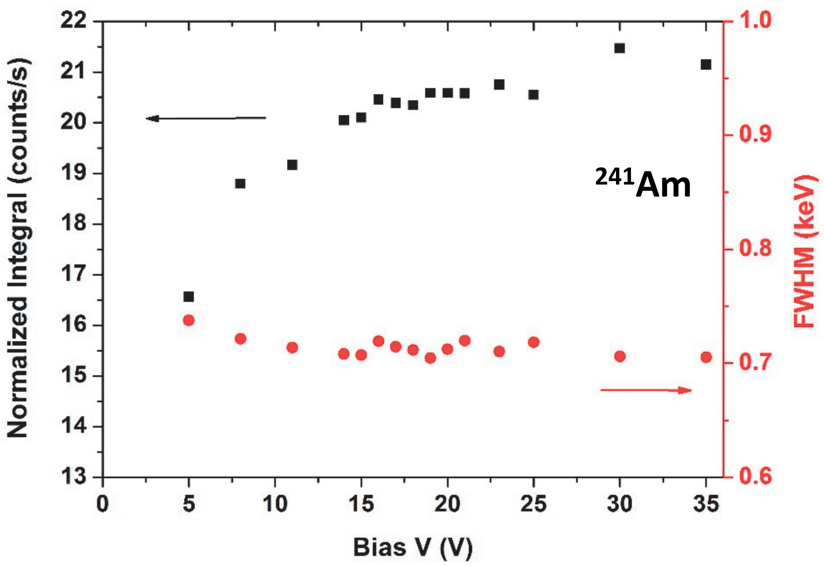
from W. Raniero (LNL - INFN) PSeGe 2019

Test of small HPGe prototype: detector configuration

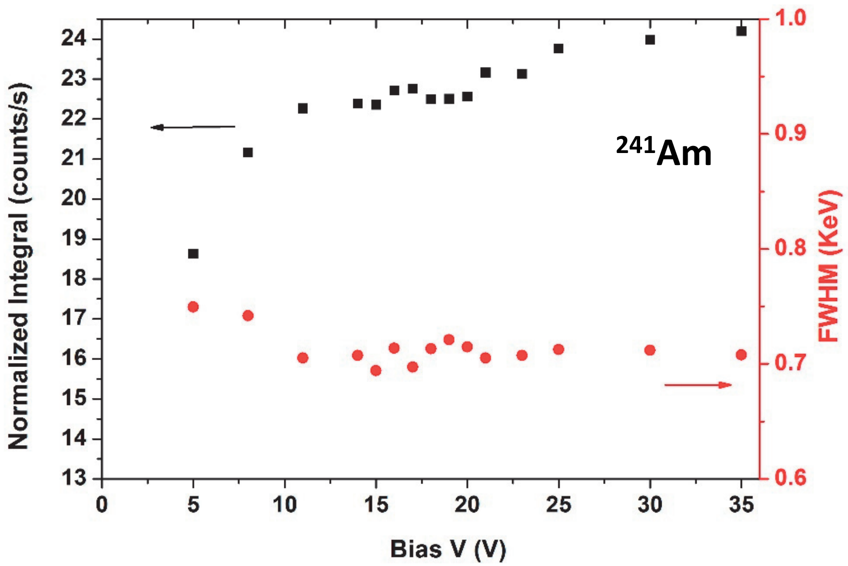
gap 0.2mm

Depletion Voltage - Energy resolution

Seg.1



Seg.2

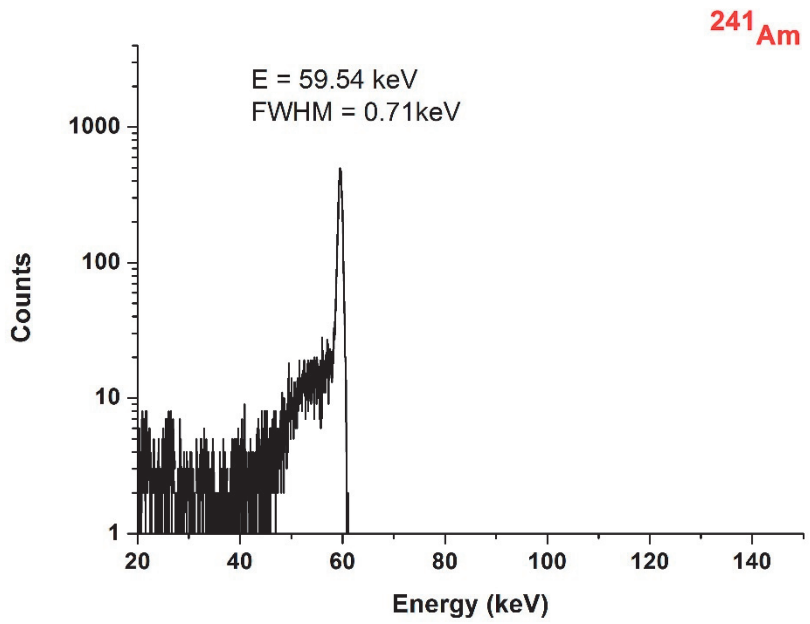


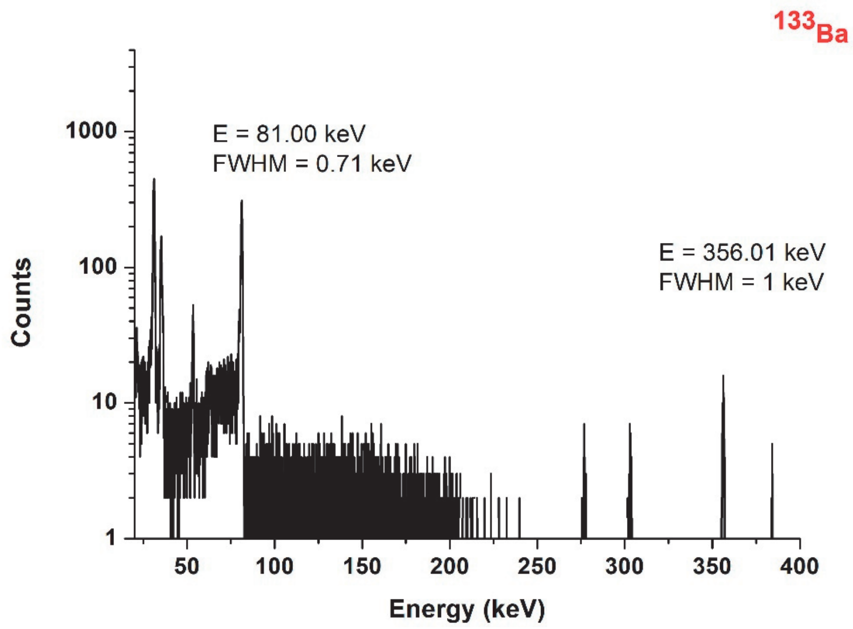
- ➢ detector fully depleted
- ➢ good energy resolution

from W. Raniero (LNL - INFN)   PSeGe 2019

Test of small HPGe prototype: detector configuration

gap 0.2mm





Good energy resolution in all the energy range up to 400KeV

from W. Raniero (LNL - INFN) PSeGe 2019

SUMMARY

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Conclusions

- The combination of Sb deposition and PLM provides an extremely efficient doping technique.
- Carrier concentration up to $3\text{x}10^{20}\text{cm}^{-3}$ with record low resistivity and excellent mobility
- No bulk contamination as consequence of PLM

IOP Publishing
Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **52** (2019) 035104 (11pp)
https://doi.org/10.1088/1361-6463/aae9c0

Characterization and modeling of thermally-induced doping contaminants in high-purity germanium

V Boldrini[1,2,4], G Maggioni[1,2], S Carturan[1,2]
R Milazzo[1], D R Napoli[2], E Napolitani[1,2], R C
and D De Salvador[1,2]

Eur. Phys. J. A (2018) **54**: 34
DOI 10.1140/epja/i2018-12471-0
THE EUROPEAN PHYSICAL JOURNAL A

Special Article – New Tools and Techniques

Pulsed laser diffusion of thin hole-barrier contacts in high purity germanium for gamma radiation detectors

G. Maggioni[1,2,a], S. Carturan[1,2], W. Raniero[2], S. Riccetto[3], F. Sgarbossa[1,2], V. Boldrini[1,2], R. Milazzo[1], D.R. Napoli[2], D. Scarpa[2], A. Andrighetto[2], E. Napolitani[1,2], and D. De Salvador[1,2]

from C. Carraro (Unipd, INFN-LNL)
PSeGe 2019

Conclusions

- The combination of Sb deposition and PLM provides an extremely efficient doping technique.
- Carrier concentration up to $3 \times 10^{20} cm^{-3}$ with record low resistivity and excellent mobility
- No bulk contamination as consequence of PLM
- Pseudomorphic layers Ge:Sb layers with no extended defects
- FTIR reports plasma wavelengths below 3 µm in the MIR range useful for gas sensing applications
- Inactive Sb is nearly substitutional with small displacement, compatible with very small Sb_nV clusters.

from C. Carraro (Unipd, INFN-LNL)
PSeGe 2019

Summary

- Several passivation routes have been applied to a planar HPGe detector and their effects on the detector characteristics have been investigated.
- Lateral scan measurements highlighted the electrical nature of the passivated surface (either n-type or p-type) and its influence with bulk propertis of Ge dets.
- Hydride-based passivations are the bests to reduce dead layers in HPGe dets.
- A detector coating has been developed to substitute the mechanical incapsulation for protecting and stabilizing the passivated surfaces (also in between segments!)
- A new method to produce contacts based in laser annealing techniques is very promising. A novel Sb contact has been developed.

Work in progress

- Development of planar detectors with laser-annealed Sb contacts (scaling up)
- Development of detector samples with novel contacts using different deposition methods (vacuum evaporation, spin coating, etc.) and different doping elements (P, As for n contacts and B, Ga for p contacts).

SIMULATED AND MEASURED SIGNALS FROM SEGMENTED DETECTORS

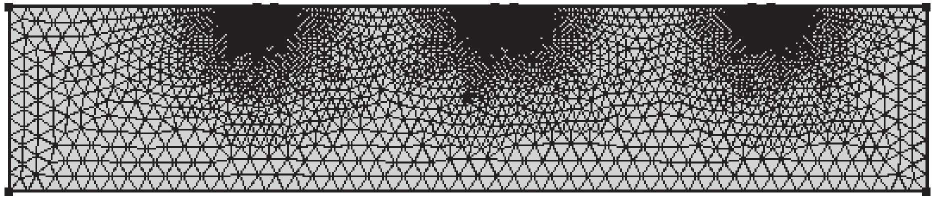
GOALS

- Laser annealed junctions
- Segmentation of junctions with good passivation
- Accurate simulation of the detector behavior
- Simulated signals from segments

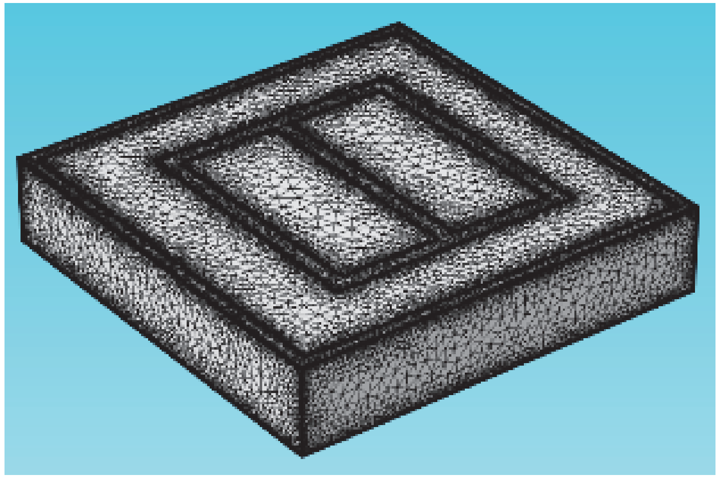
from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

SUMMARY

- Goals of this simulation tool
- Models used
- 2D simulation of a fictional detector
  - Depletion process
  - Weighting potentials
  - Simulated trajectories
  - Simulated signals
  - Gap study

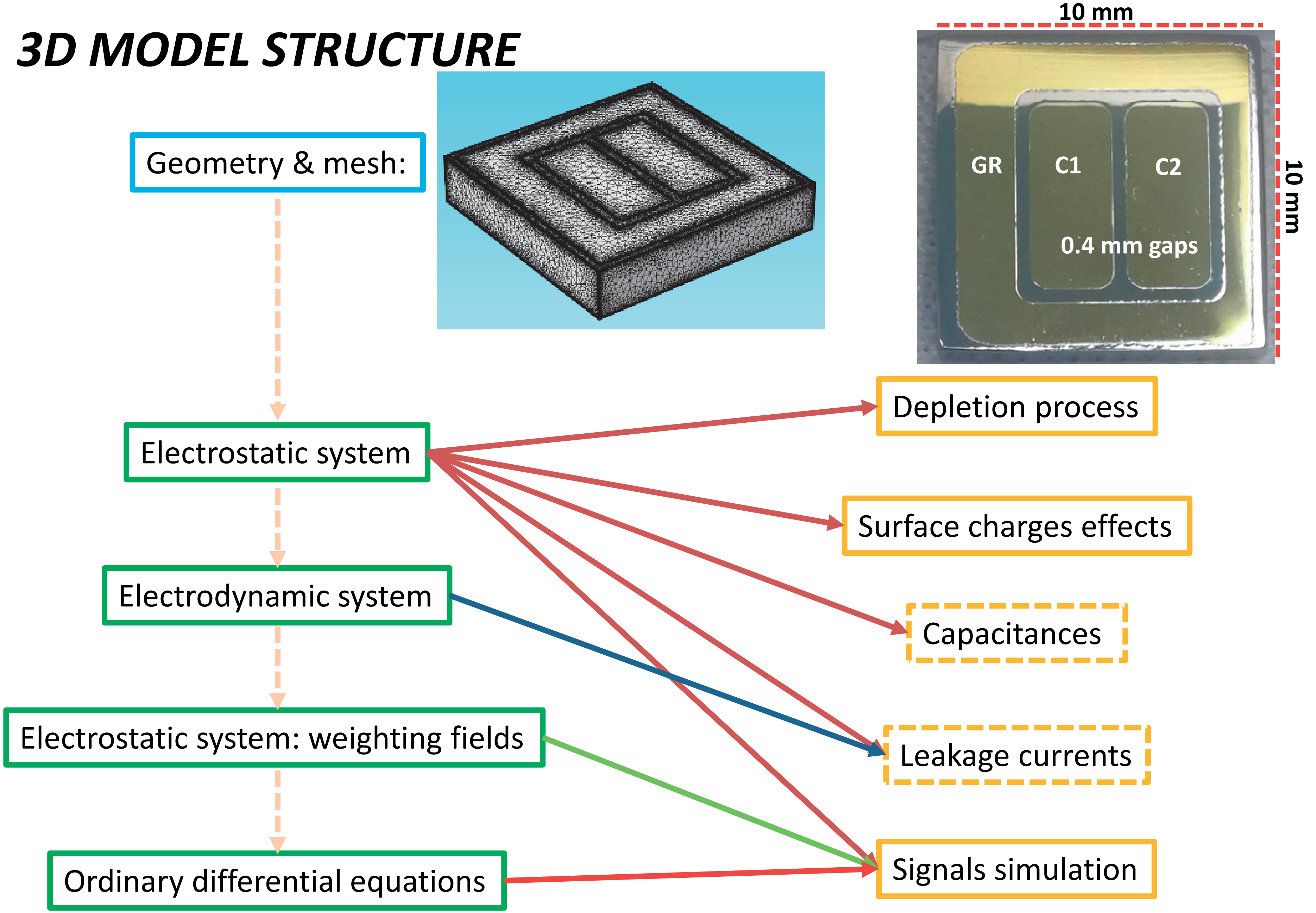


- 3D simulation of a real detector
  - Model outline
  - Depletion process
  - Weighting potentials
  - Passivation study
  - Simulated signals
  - Comparison with experimental signals



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

3D MODEL STRUCTURE



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

DRIFT WITHOUT DIFFUSION

Approximations:

- Electric field not influenced by charges movement
- Point charge

$$\dot{\vec{x}}_e(t) = -\mu_e \vec{E}(\vec{x}_e(t))$$

$$\dot{\vec{x}}_h(t) = \mu_h \vec{E}(\vec{x}_h(t))$$

POISSON EQUATION

$$\nabla^2 \mathrm{V}(\vec{x}) = \mathrm{N_b}[1 - e^{-\frac{q\mathrm{V}(\vec{x})}{k_B T}}]$$

$$i_n(t) = q[\mu_e \vec{E}(\vec{x}_e(t)) \cdot \overrightarrow{E_n}(\vec{x}_e(t)) + \mu_h \vec{E}(\vec{x}_h(t)) \cdot \overrightarrow{E_n}(\vec{x}_h(t))]$$

$$Q_n(t) = \int_0^t i_n(\tau) d\tau$$

DRIFT WITH DIFFUSION

Approximations:

- Einstein relation (diffusion proportional to mobility)
- Isotropic diffusion

$$\dot{c}_e(\vec{x}, t) - \nabla[D_e \, \nabla c_e(\vec{x}, t) - \mu_e c_e(\vec{x}, t) \nabla \mathrm{V}(\vec{x})] = 0$$

$$\dot{c}_h(\vec{x}, t) - \nabla[D_h \, \nabla c_h(\vec{x}, t) + \mu_h c_h(\vec{x}, t) \nabla \mathrm{V}(\vec{x})] = 0$$

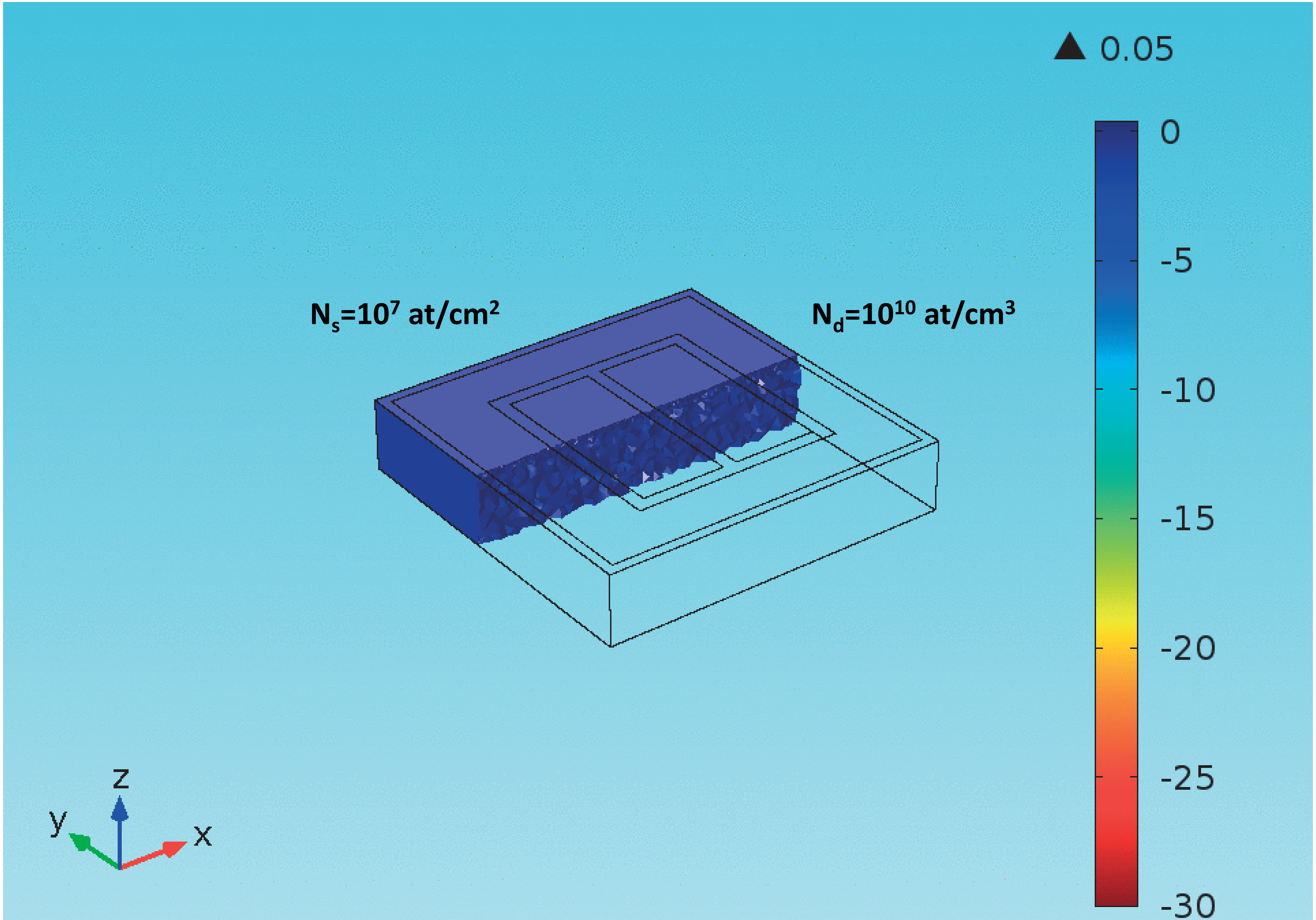
POISSON EQUATION

$$\nabla^2 \mathrm{V}(\vec{x}) = \mathrm{Nb}[1 - e^{-\frac{q\mathrm{V}(\vec{x})}{k_B T}}]$$

$$i_n(t) = \int_\Omega [\mu_e c_e(\vec{x}, t) \vec{E}(\vec{x}) \cdot \overrightarrow{E_n}(\vec{x}) + \mu_h c_h(\vec{x}, t) \vec{E}(\vec{x}) \cdot \overrightarrow{E_n}(\vec{x})] \, d\vec{x}$$

$$Q_n(t) = \int_0^t i_n(\tau) d\tau$$

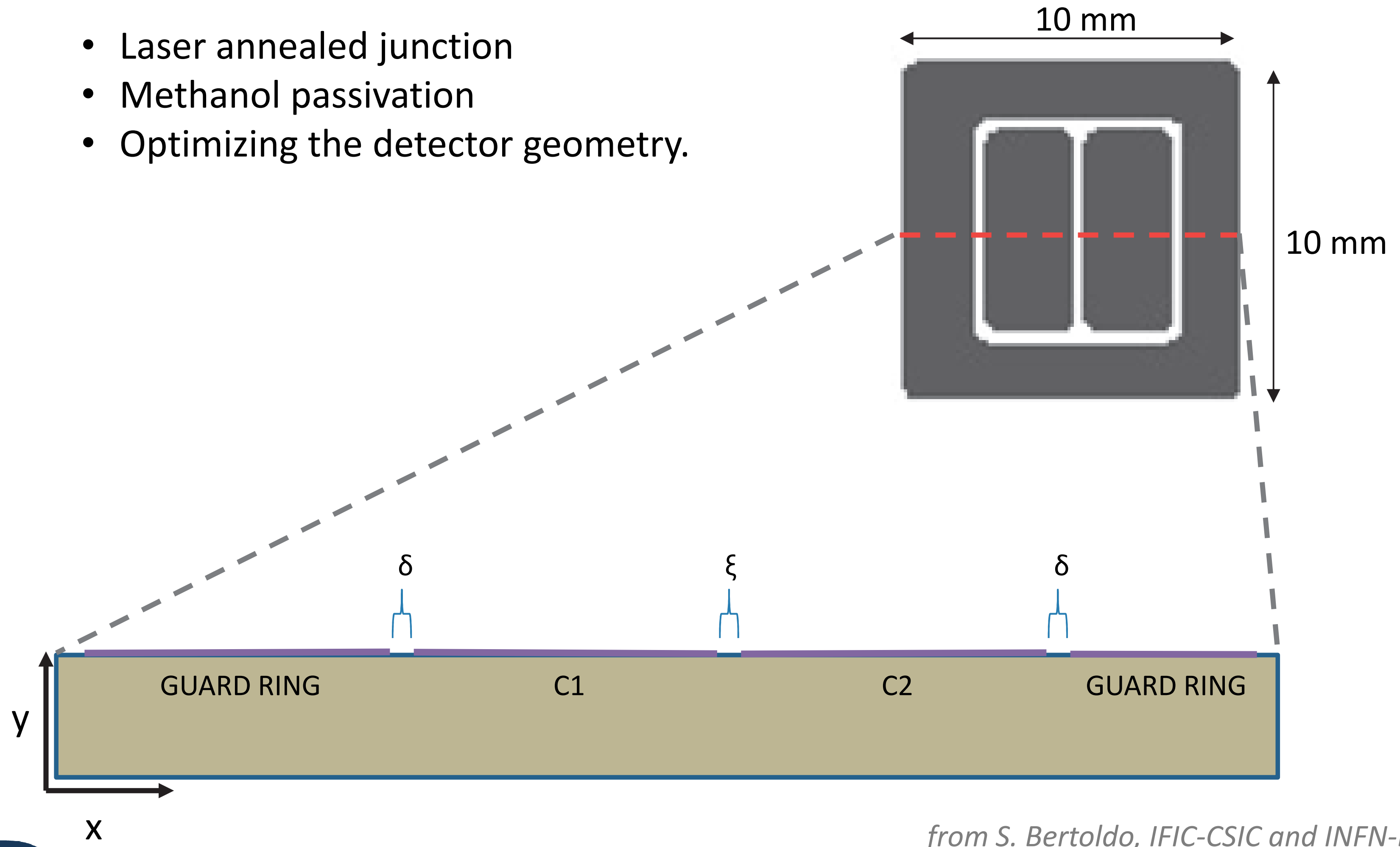
from S. Bertoldo, IFIC-CSIC and INFN-LNL) PSeGe 2019



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

SEGMENTED p-TYPE DETECTOR

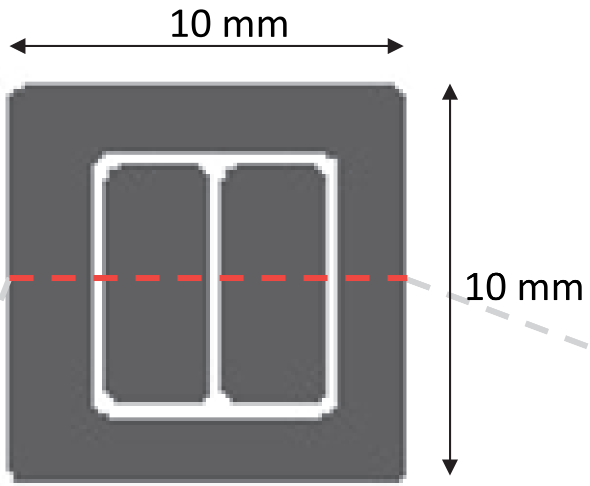
- Laser annealed junction
- Methanol passivation
- Optimizing the detector geometry.



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

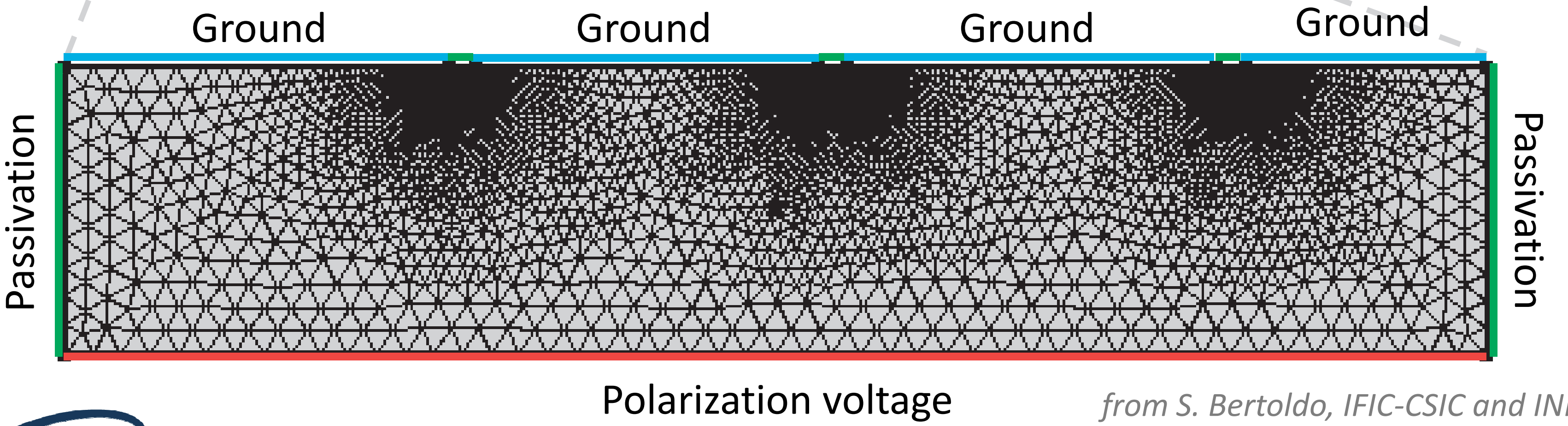
GEOMETRY AND MESH

2D simulation → central zone approximation

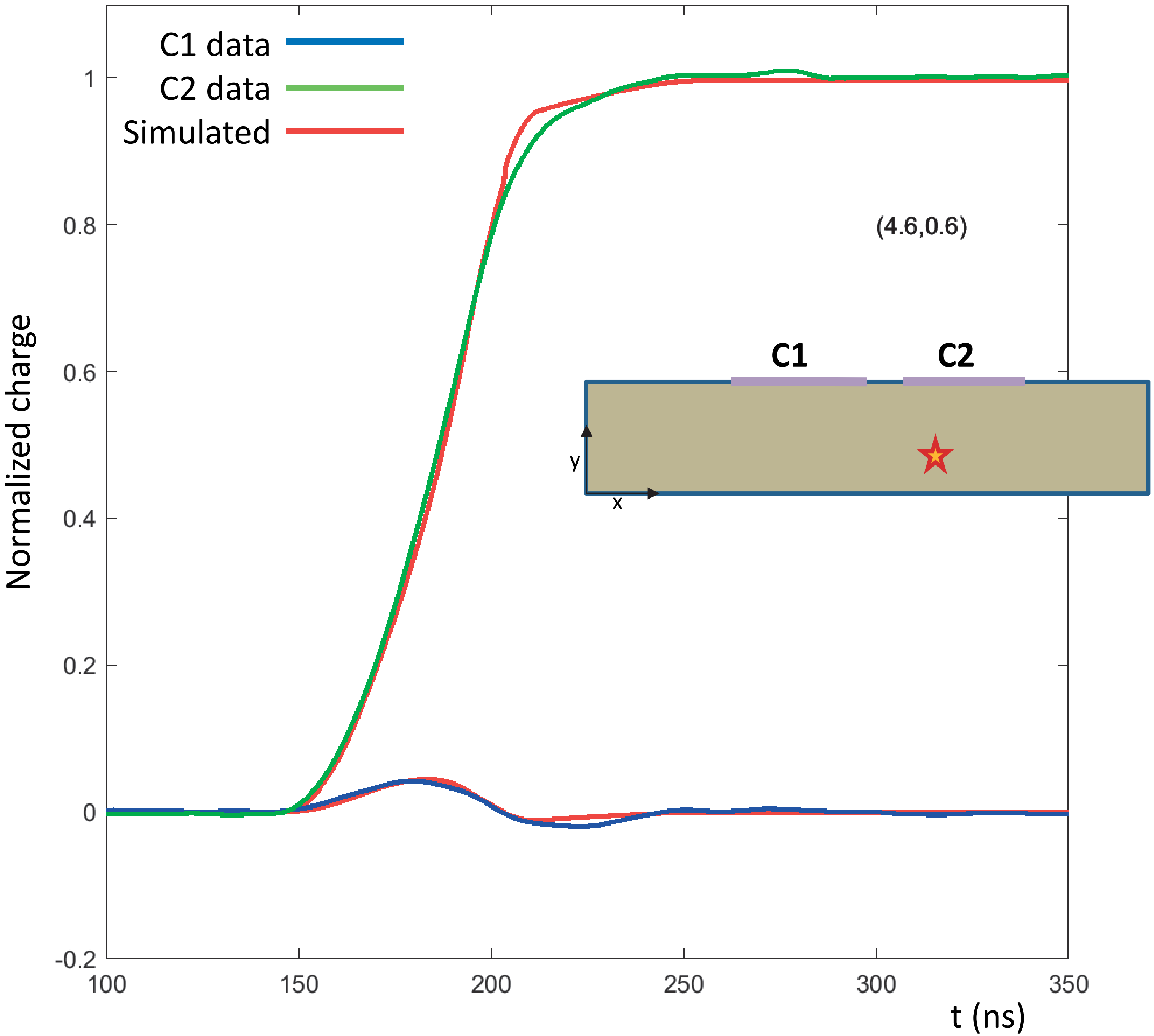


First model:
p+/p/n+ detector (2D)

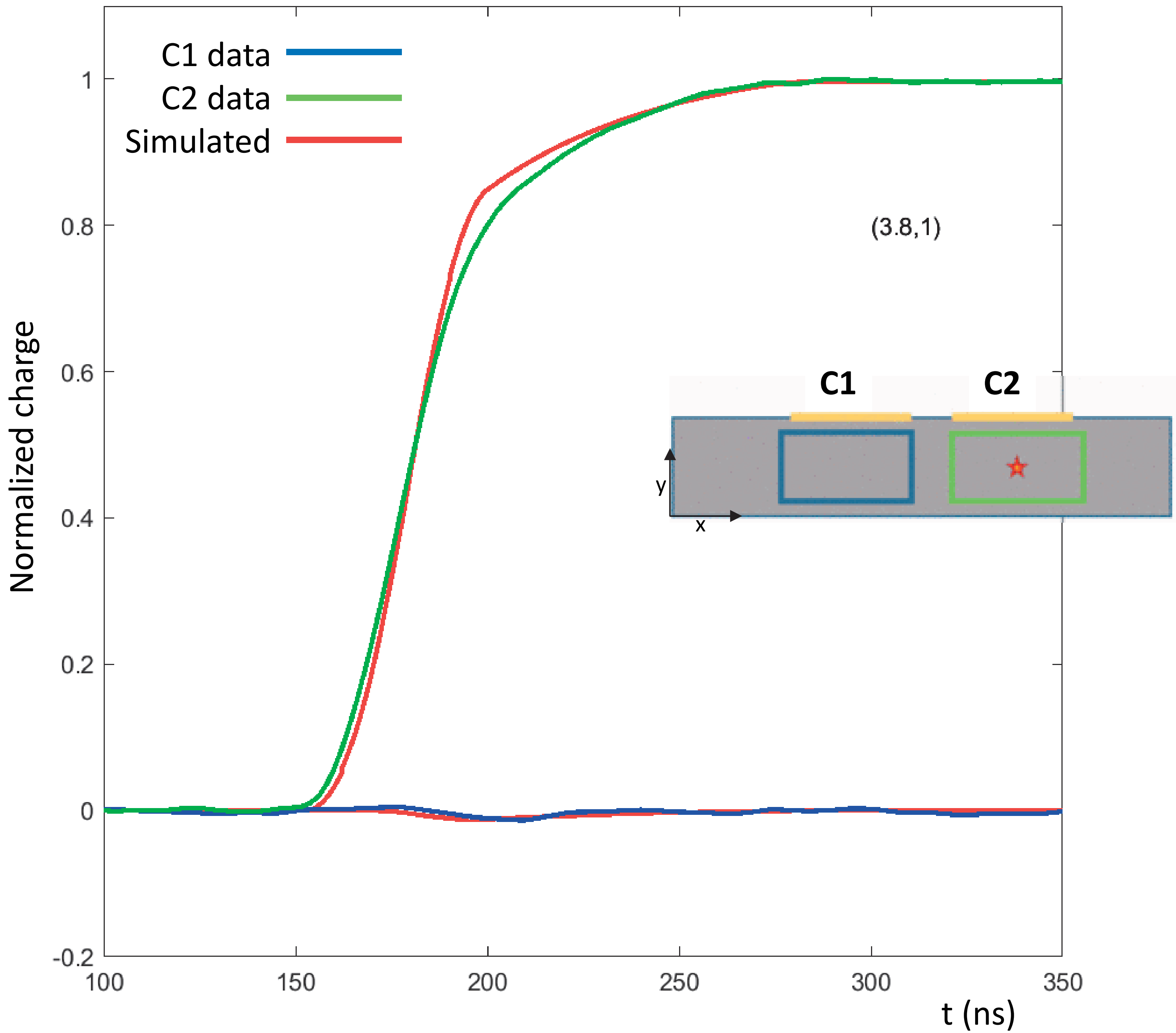
N_s=10^8 at/cm^2



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019



C1 data
C2 data
Simulated
(4.6,0.6)
C1
C2
y
x
Normalized charge
t (ns)
1
0.8
0.6
0.4
0.2
0
-0.2
100
150
200
250
300
350



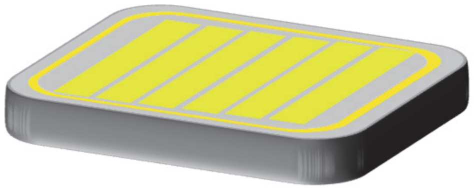
C1 data
C2 data
Simulated
1
0.8
0.6
0.4
0.2
0
-0.2
Normalized charge
(3.8,1)
C1
C2
y
x
100
150
200
250
300
350
t (ns)

FUTURE IMPROVEMENTS

- **Interpolating algorithm**
- **Electronic filtering**

- Model refinement: recombination and generation processes
- C-V,I-V characteristics simulation and surface states dependency
- Leakage current model simulation
- New segmentation geometries

Rescaling (strip number, sizes) for the design of better detectors.



from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

DRIFT WITHOUT DIFFUSION

Approximations:
- Electric field not influenced by charges movement
- Point charge

$$\dot{\vec{x}_e}(t) = -\mu_e \vec{E}(\vec{x}_e(t))$$
$$\dot{\vec{x}_h}(t) = \mu_h \vec{E}(\vec{x}_h(t))$$

POISSON EQUATION

$$\nabla^2 V(\vec{x}) = N_b[1-e^{-\frac{qV(\vec{x})}{k_B T}}]$$

$$i_n(t) = q[\mu_e \vec{E}(\vec{x}_e(t)) \cdot \overrightarrow{E_n}(\vec{x}_e(t)) + \mu_h \vec{E}(\vec{x}_h(t)) \cdot \overrightarrow{E_n}(\vec{x}_h(t))]$$
$$Q_n(t) = \int_0^t i_n(\tau) d\tau$$

DRIFT WITH DIFFUSION

Approximations:
- Einstein relation (diffusion proportional to mobility)
- Isotropic diffusion

$$\dot{c_e}(\vec{x},t) - \nabla[D_e \nabla c_e(\vec{x},t) - \mu_e c_e(\vec{x},t) \nabla V(\vec{x})] = 0$$
$$\dot{c_h}(\vec{x},t) - \nabla[D_h \nabla c_h(\vec{x},t) + \mu_h c_h(\vec{x},t) \nabla V(\vec{x})] = 0$$

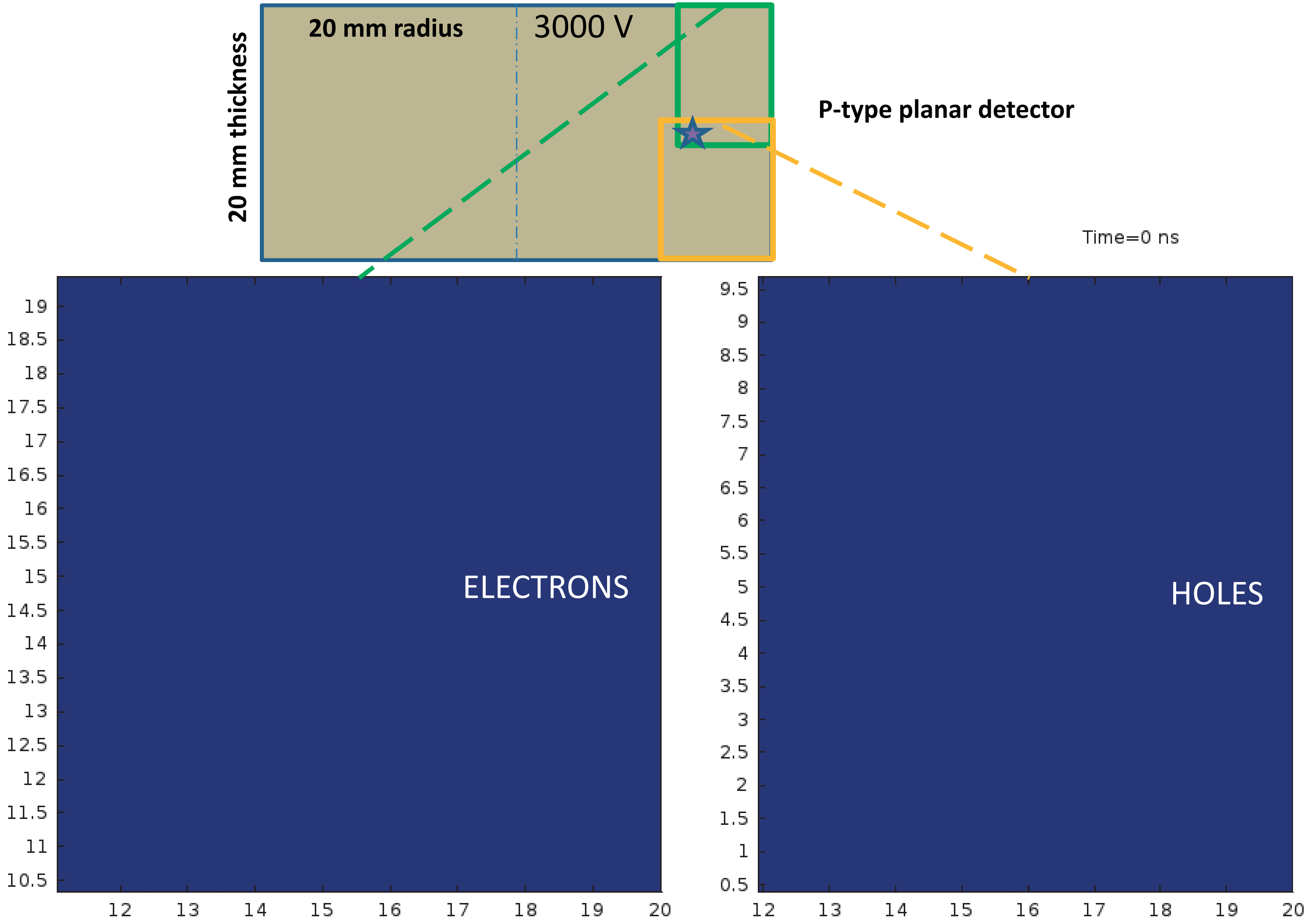
POISSON EQUATION

$$\nabla^2 V(\vec{x}) = Nb[1-e^{-\frac{qV(\vec{x})}{k_B T}}]$$

$$i_n(t) = \int_\Omega [\mu_e c_e(\vec{x},t) \vec{E}(\vec{x}) \cdot \overrightarrow{E_n}(\vec{x}) + \mu_h c_h(\vec{x},t) \vec{E}(\vec{x}) \cdot \overrightarrow{E_n}(\vec{x})]\, d\vec{x}$$
$$Q_n(t) = \int_0^t i_n(\tau) d\tau$$

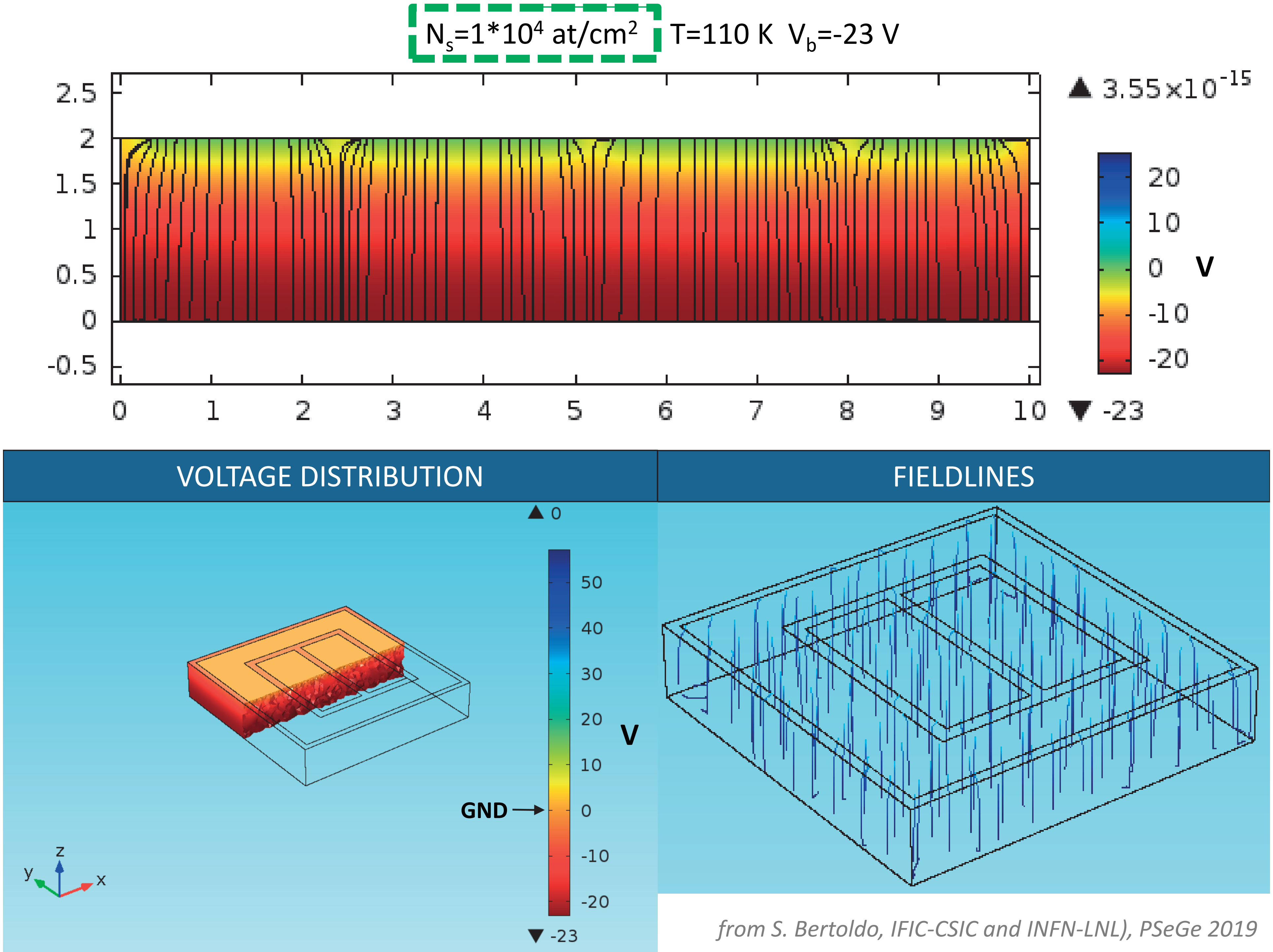
from S. Bertoldo, IFIC-CSIC and INFN-LNL)
PSeGe 2019

DRIFT WITH DIFFUSION MODEL



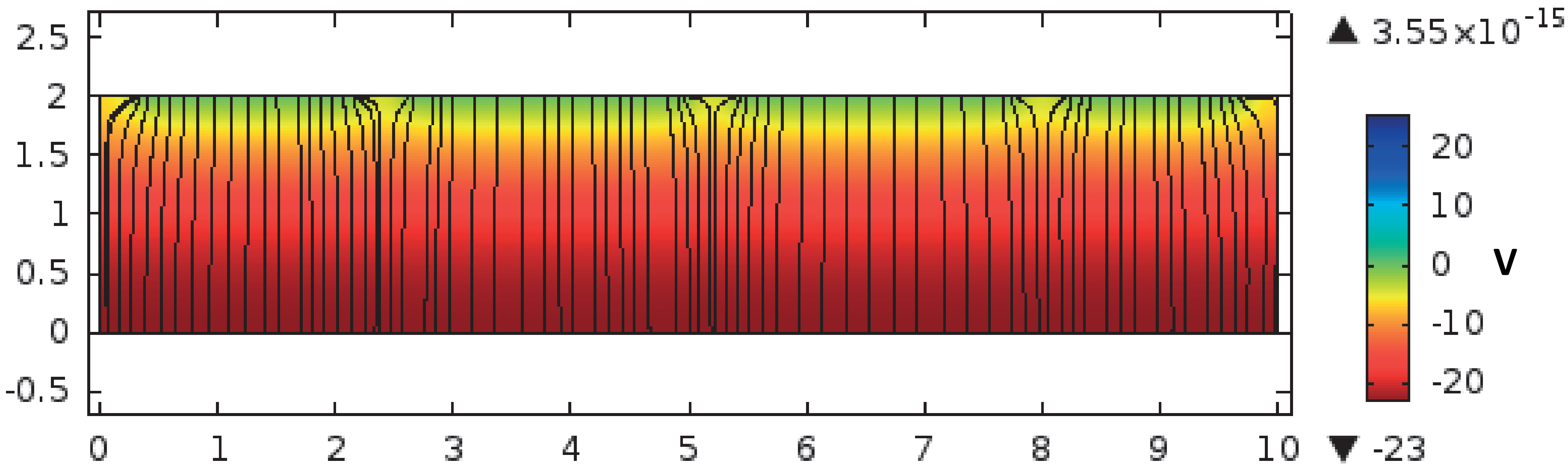
SIMULATED AND MEASURED SIGNALS FROM SEGMENTED DETECTORS

Residual charge in passivated surfaces

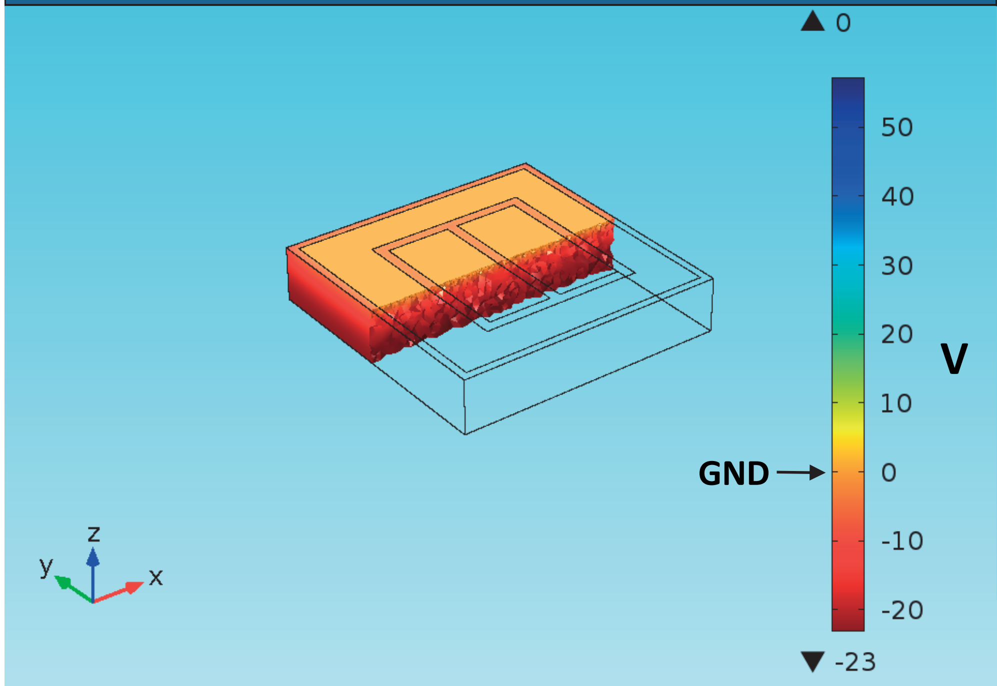


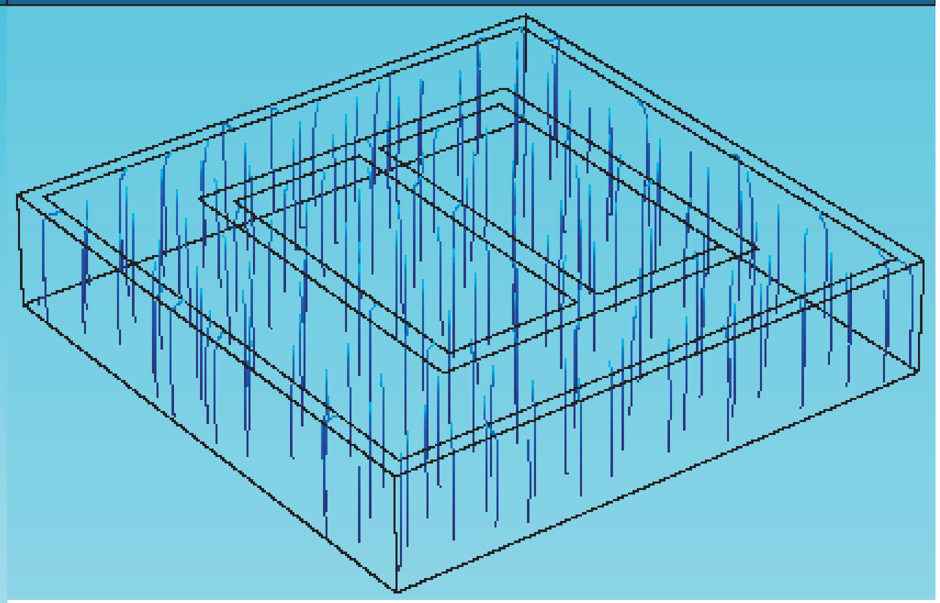
from S. Bertoldo, IFIC-CSIC and INFN-LNL), PSeGe 2019

$N_s = 1*10^7$ at/cm^2 T=110 K V_b=-23 V

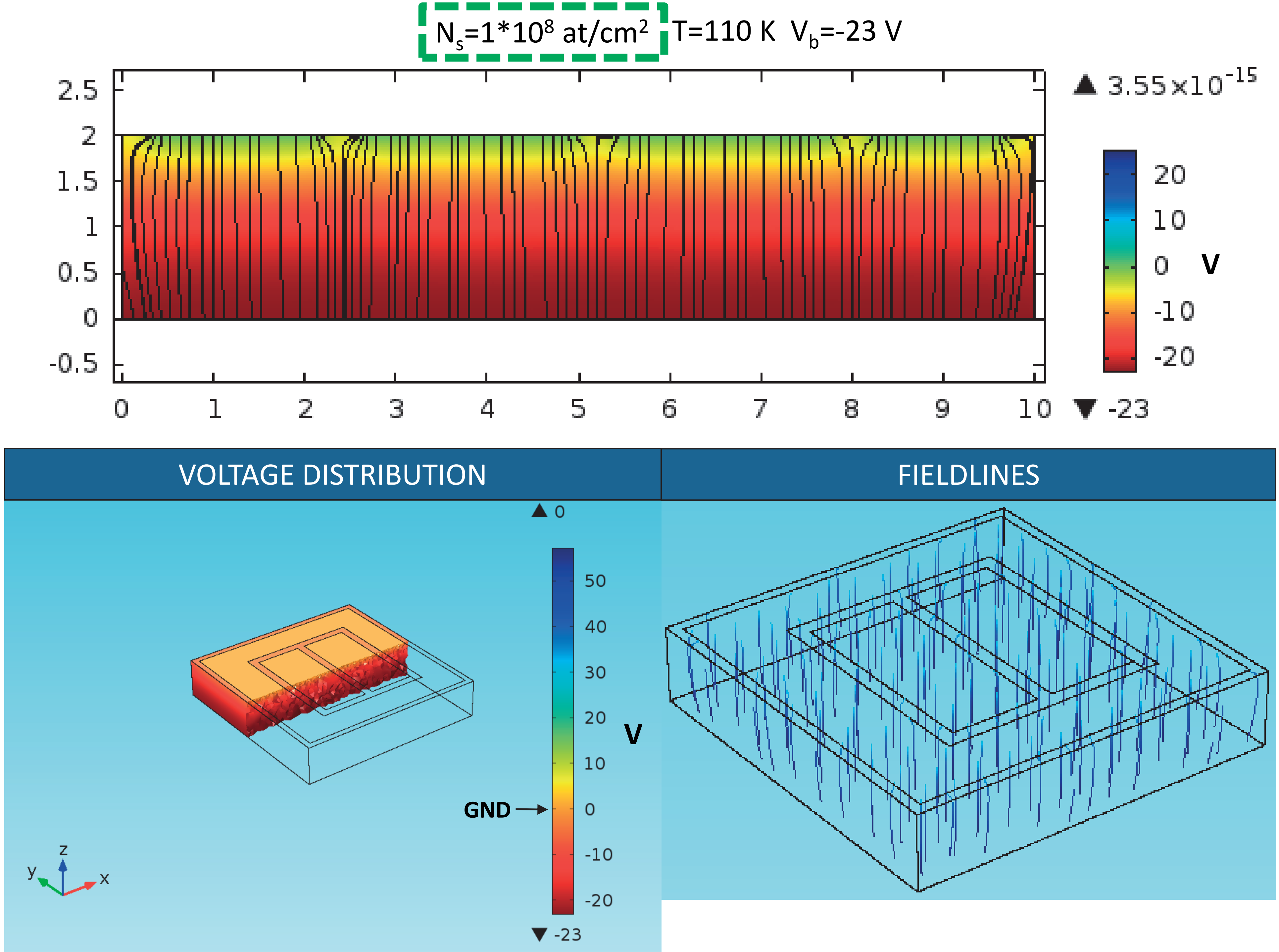


VOLTAGE DISTRIBUTION	FIELDLINES



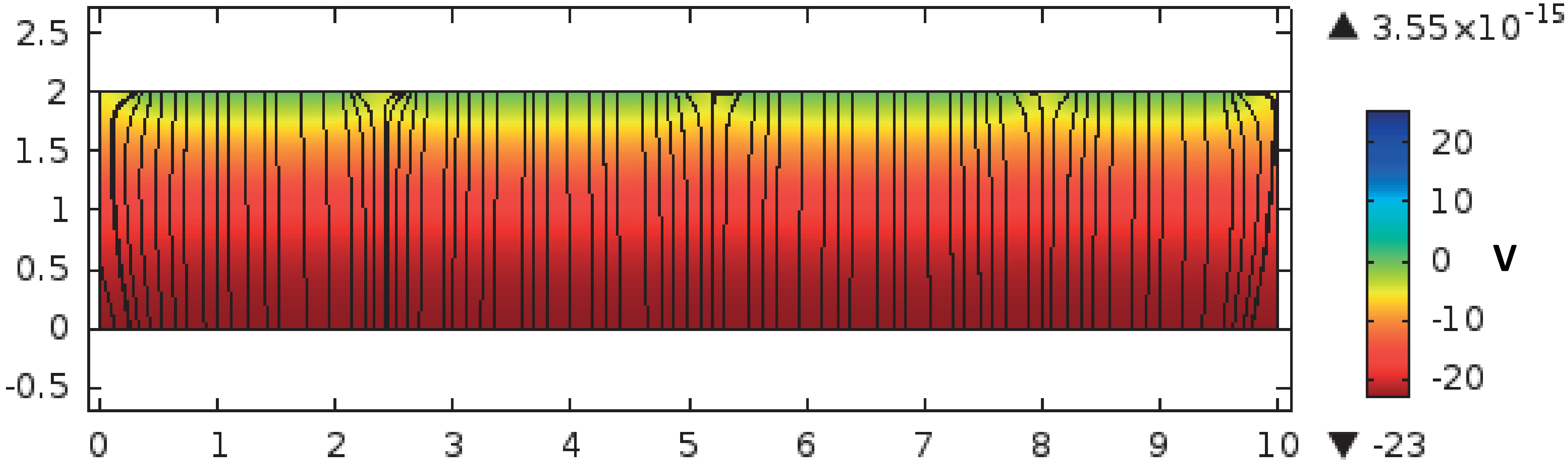


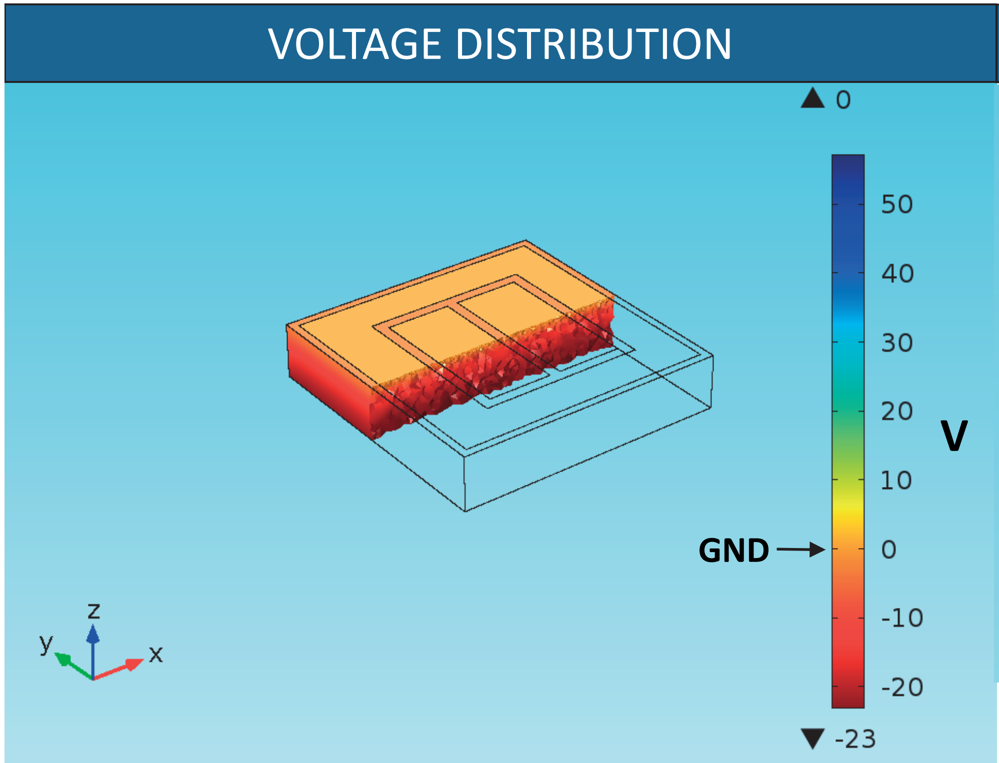
from S. Bertoldo, IFIC-CSIC and INFN-LNL), PSeGe 2019

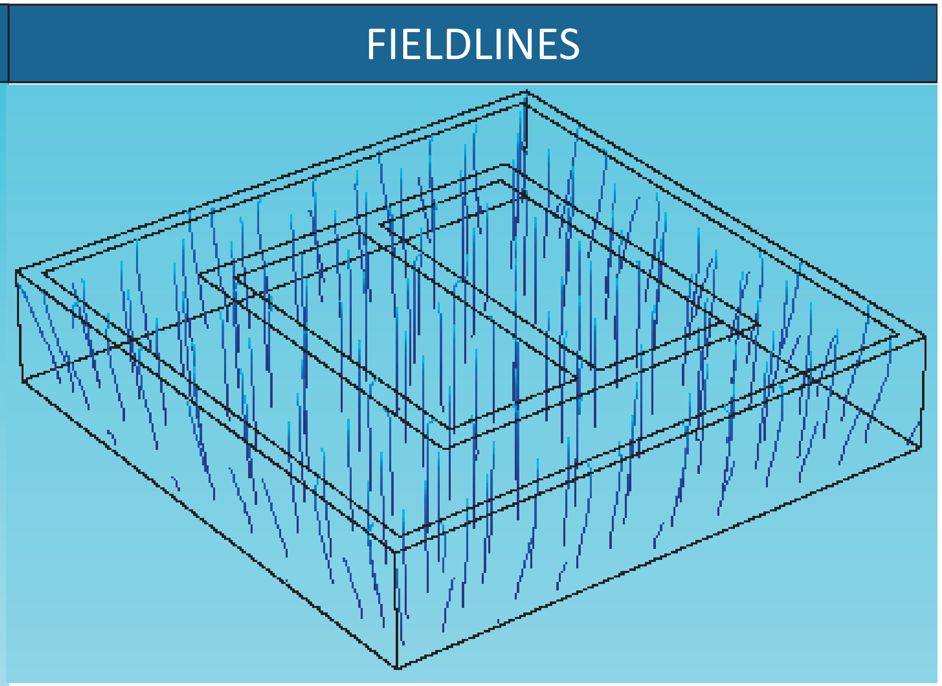


N_s=1*10^8 at/cm^2
T=110 K V_b=-23 V
▲ 3.55x10^-15
20
10
0
-10
-20
V
▼ -23
2.5
2
1.5
1
0.5
0
-0.5
0 1 2 3 4 5 6 7 8 9 10
VOLTAGE DISTRIBUTION
FIELDLINES
▲ 0
50
40
30
20
10
0
-10
-20
V
GND
▼ -23
z
y
x

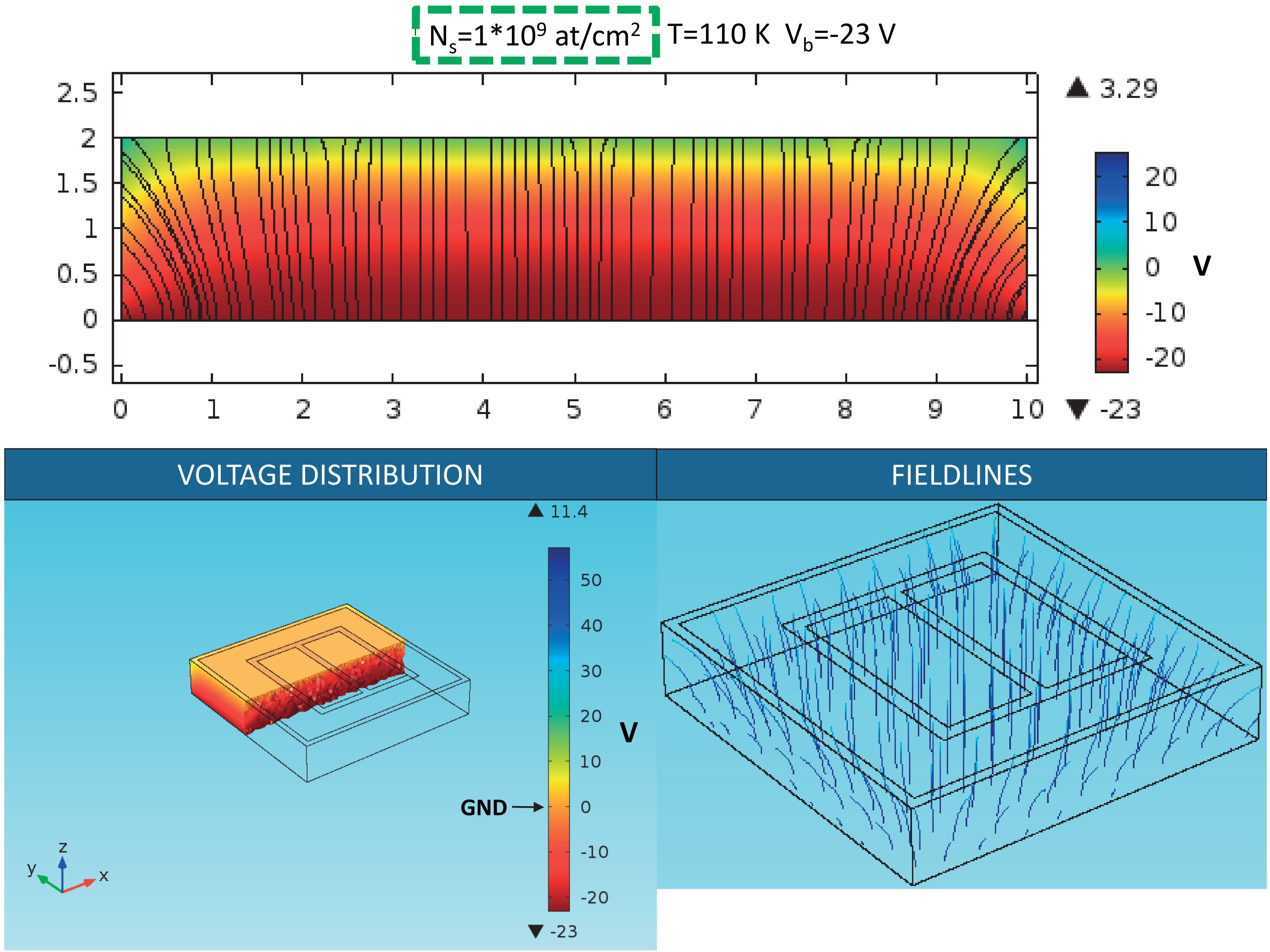
$N_s = 3.2 * 10^8$ at/cm^2 T=110 K V_b=-23 V



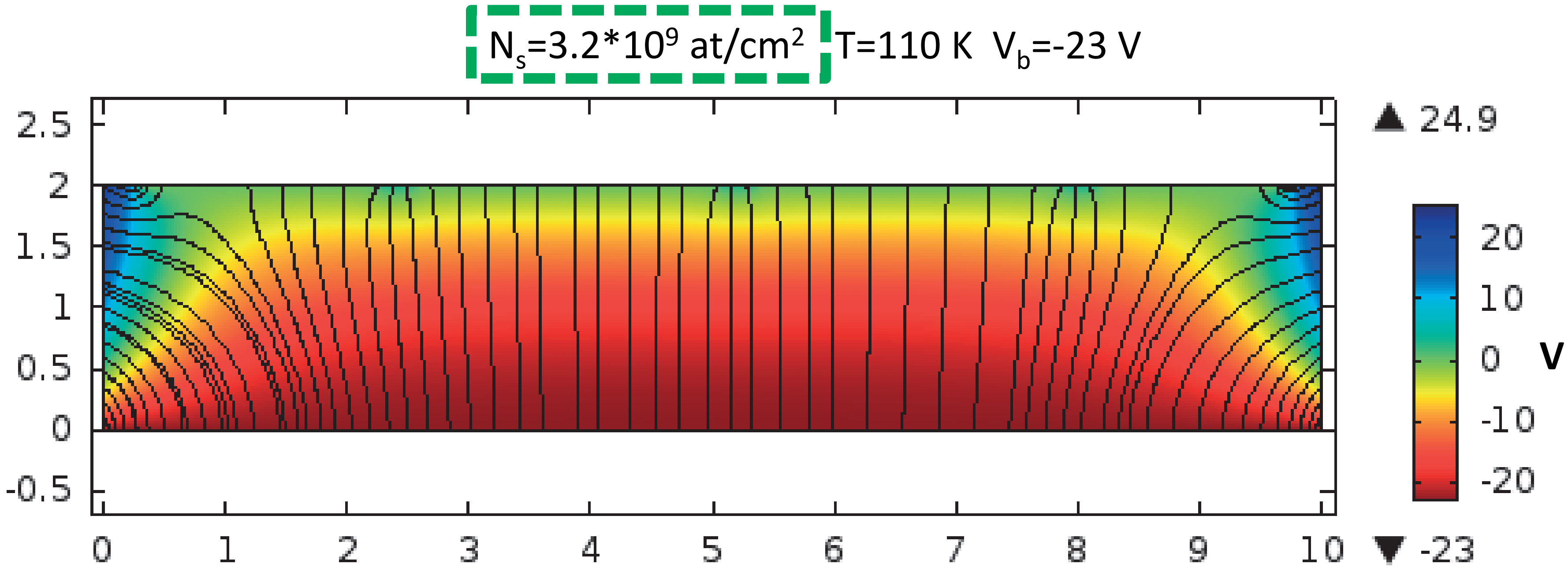


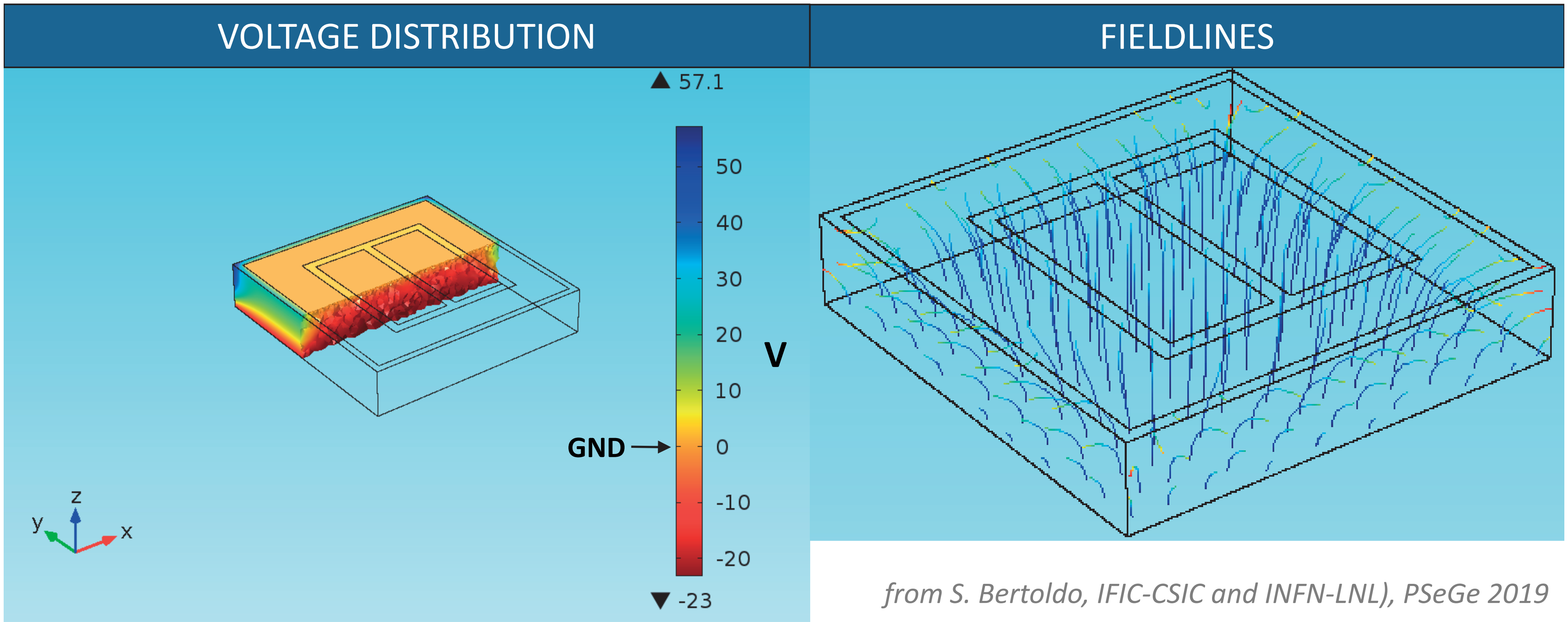


from S. Bertoldo, IFIC-CSIC and INFN-LNL), PSeGe 2019



Ns=1*10^9 at/cm^2 T=110 K Vb=-23 V
2.5
2
1.5
1
0.5
0
-0.5
0 1 2 3 4 5 6 7 8 9 10
▲ 3.29
20
10
0
-10
-20
V
▼ -23
VOLTAGE DISTRIBUTION
FIELDLINES
▲ 11.4
50
40
30
20
10
0
-10
-20
V
GND
▼ -23
z
y
x





from S. Bertoldo, IFIC-CSIC and INFN-LNL), PSeGe 2019

Multidisciplinary Team

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

Thank you for
the attention!