Development and characterization of 3D semiconductor X-rays detectors for medical imaging

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Outlines

- Problematic
- 3D detector process
- 3D CdTe detector
- First results for 3D GaAs detector

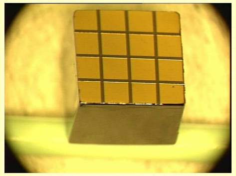
Study context and problematic

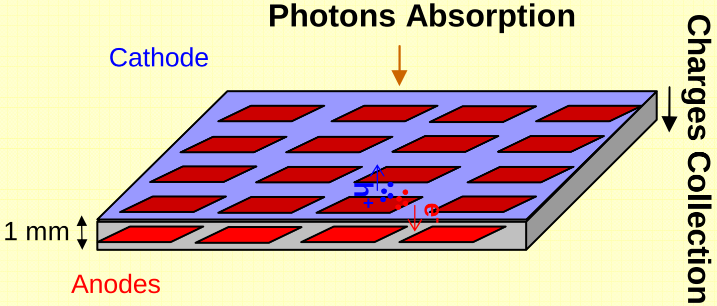
- **Application:** Radiography X-rays detectors (20-60 keV energy range) using
  - A semiconductor material
  - A micro-structured detection geometry

Study context and problematic

- **Application:** Radiography X-rays detectors (20-60 keV energy range) using
  - A semiconductor material
  - A micro-structured detection geometry
- **Problematic :**

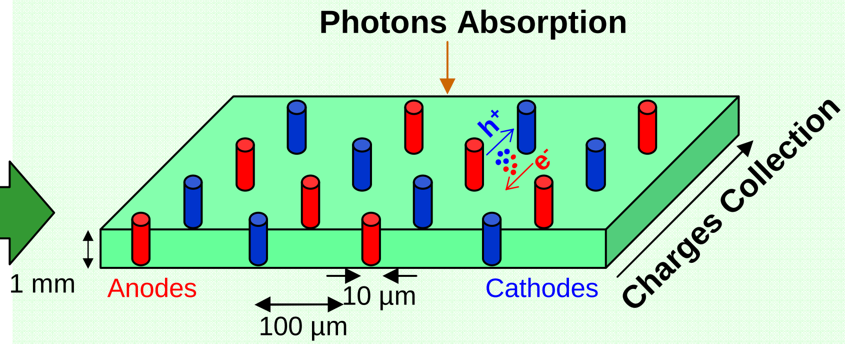
State of the art : planar geometry





Trade-off between **absorption of incident photons efficiency** (which increases with material thickness) and **collection of free charge carrier efficiency** (which decreases when material thickness increases), resulting in a limited choice of detection materials

3D geometry*



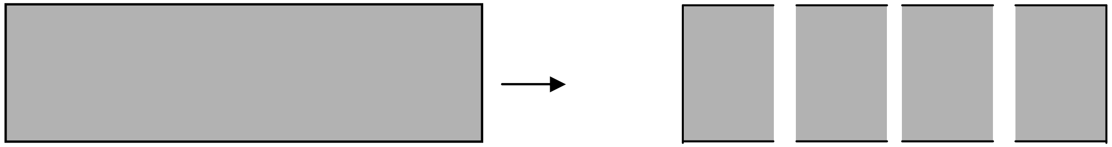
Decoupling photons absorption and charges collection
Electrodes placed into the detection volume

* S.I. Parker *et al.*, NIM-A, 395, 1997

3D detector process

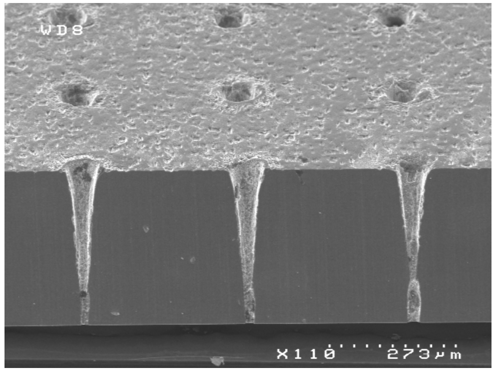
Bulk Semiconductor

3D detector process



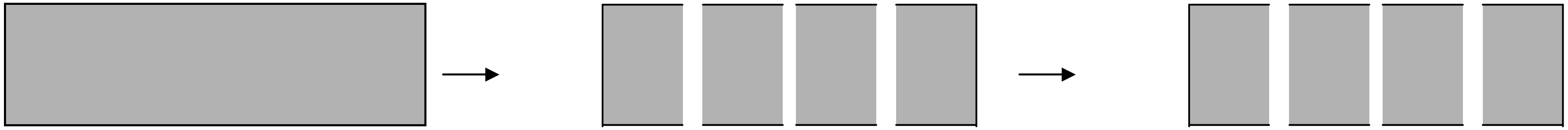
Bulk Semiconductor

Laser drilling* by a Nd-YLF laser
(@263 nm, 40 ns, 600 µJ, 3 kHz)
in percussion mode



*D. Farcage, CEA-Saclay, LILM

3D detector process



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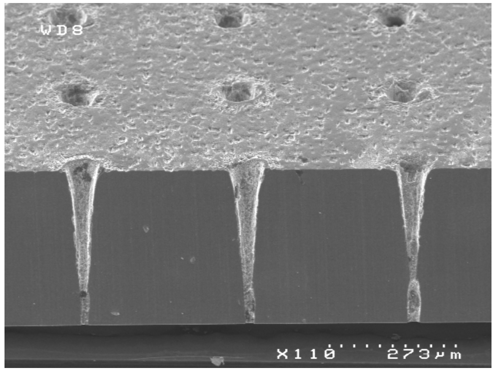
Chemical etch to clean surface and holes



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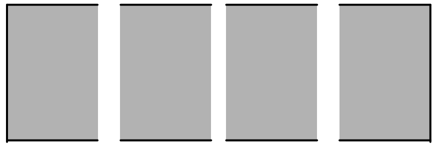

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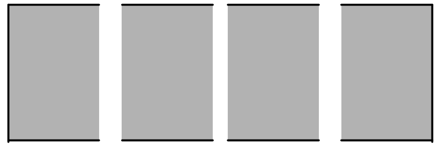

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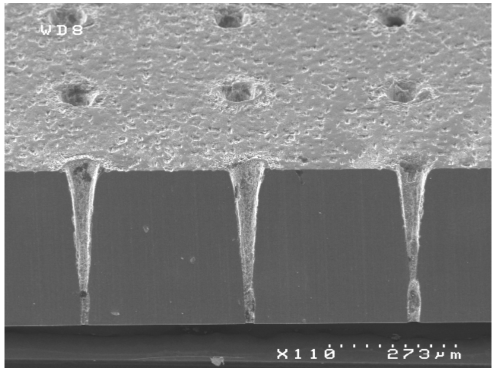

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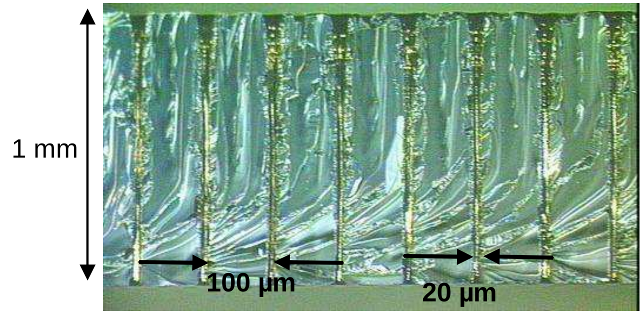
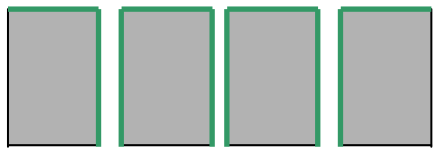
Aspect ratio until 50 : 1

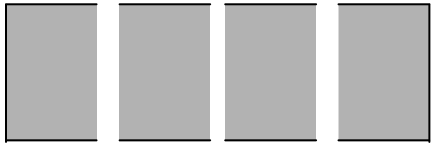




Metal electrodes deposition by electroless or sputtering

3D detector process

Bulk Semiconductor



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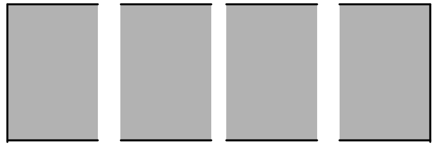

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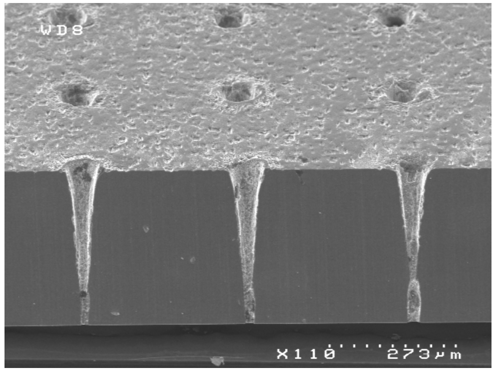

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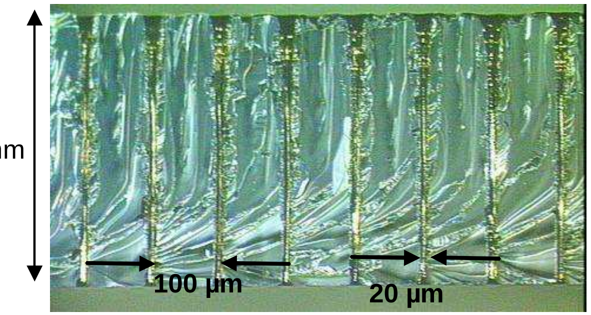
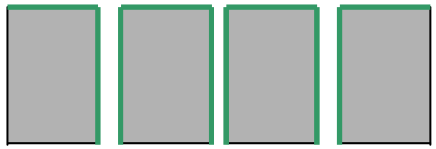
1 mm





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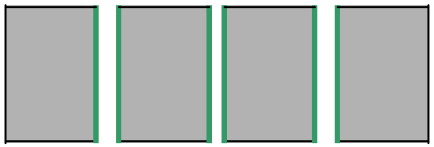
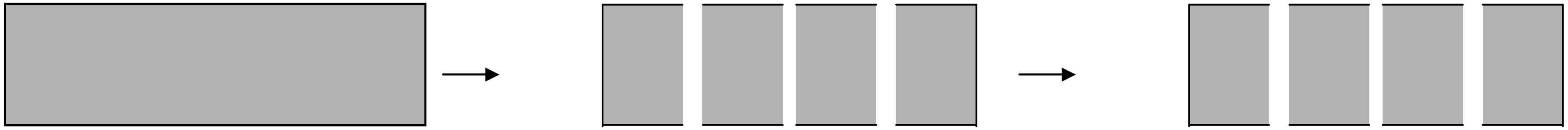
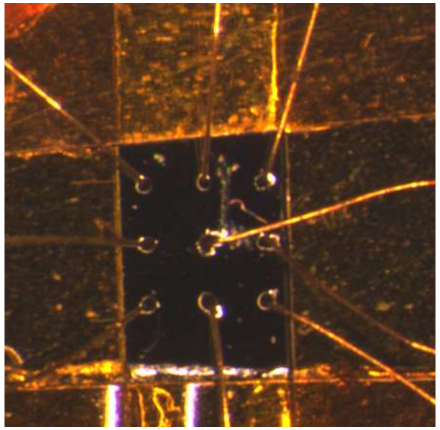


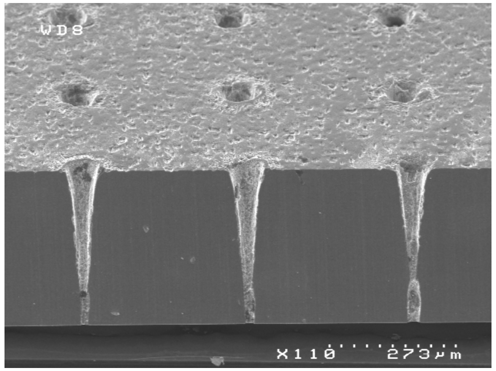
Surface clean-up

3D detector process



Bulk Semiconductor → Laser drilling* by a Nd-YLF laser (@263 nm, 40 ns, 600 µJ, 3 kHz) in percussion mode → Chemical etch to clean surface and holes





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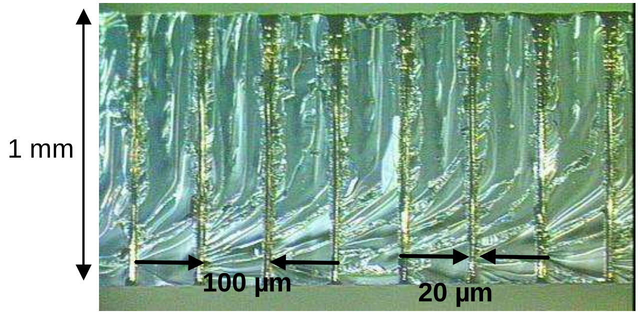
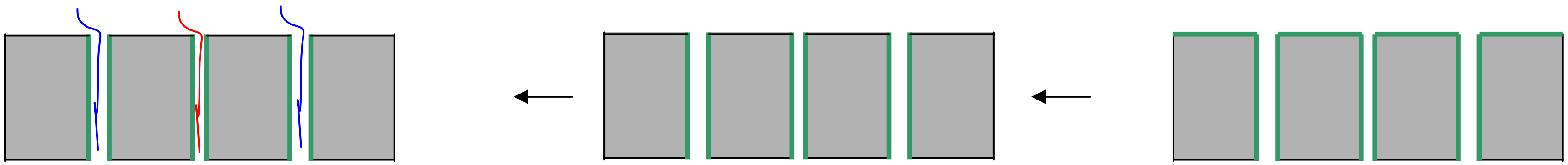


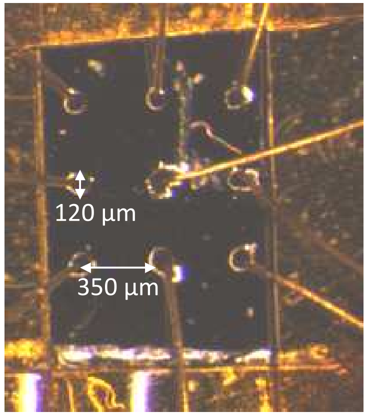


Connection to read-out electronics using gold wires ← Surface clean-up ← Metal electrodes deposition by electroless or sputtering

3D CdTe detector

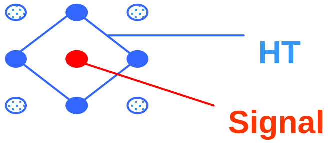
Sample

- CdTe (Cl) Acrorad ; thickness = 1,6 mm
- 3x3 holes matrix (Φ entrance = 120 / Φ exit = 40 µm ; pitch = 350 µm)
- Electrodes : gold electroless + gold wires (Φ = 25 µm)

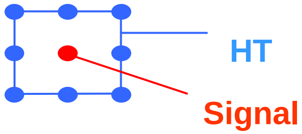


Biasing configurations :

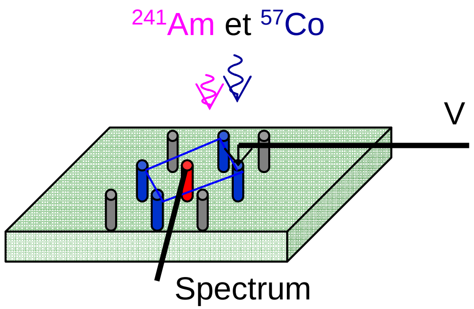
Diamond-shaped biasing

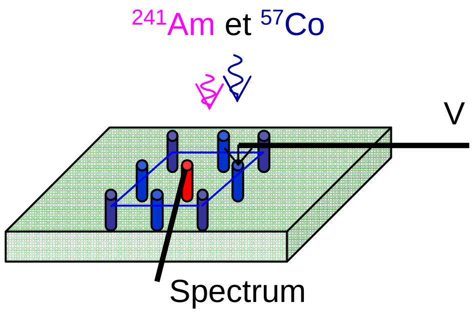


Square-shaped biasing



Measurement under ^{241}Am and ^{57}Co gamma ray irradiation

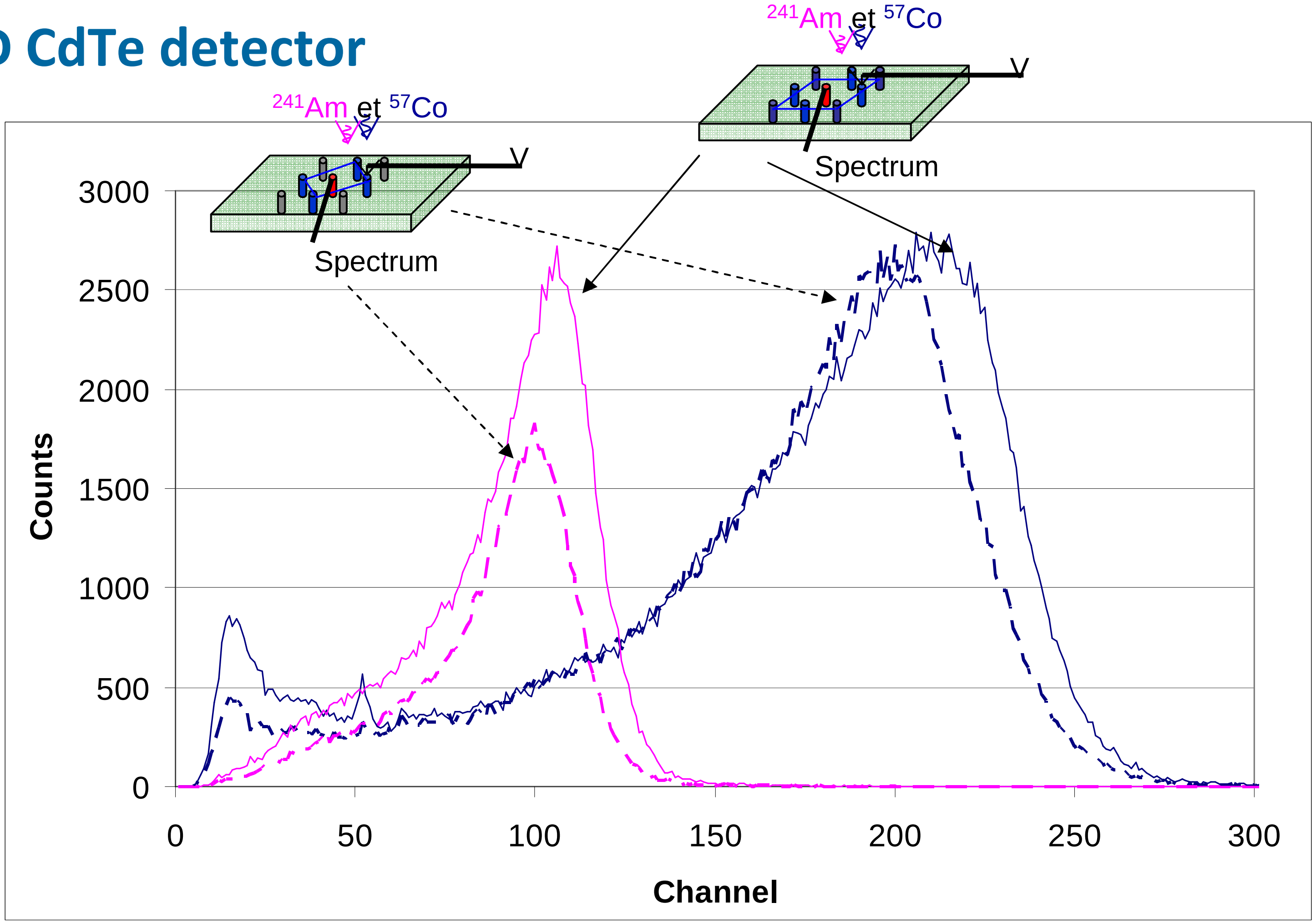




Measurement under synchrotron X-ray irradiation

- Mapping the detection response : measurement of charge efficiency
- Comparison with charge efficiency simulation

3D CdTe detector



- Demonstration of photon-counting ability using a non-optimized design (electrode diameter and pitch have to be optimized)
- Energy discrimination for both biasing configurations
- FWHM = 7 keV @ 60 keV and 16 keV @ 122 keV
- Spectrum tails due to inhomogeneous regions of charge collection and fluorescence in CdTe

3D CdTe detector

Synchrotron beam (ID6 beamline at ESRF) :

- Energy : 60 keV (radiography energy)
- Size : 20 x 20 µm²
- Input rate : 10^5 photons/s

Scan parameters :

- 32 x 32-position top-surface scan of the detector at a pitch of 25 µm
- Spectrum collected for 10 s

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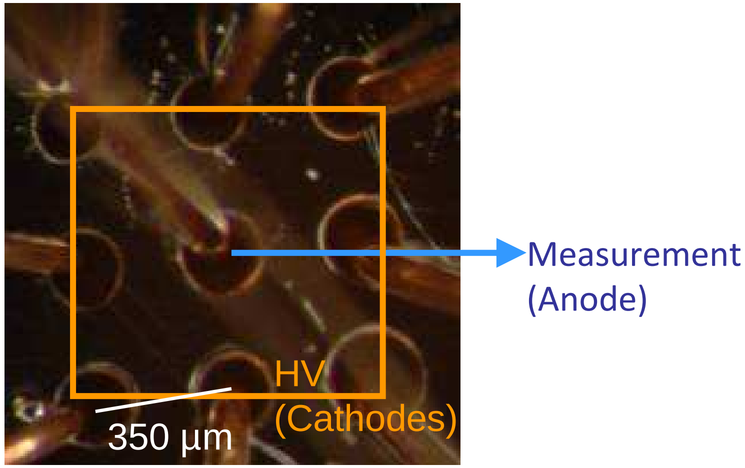
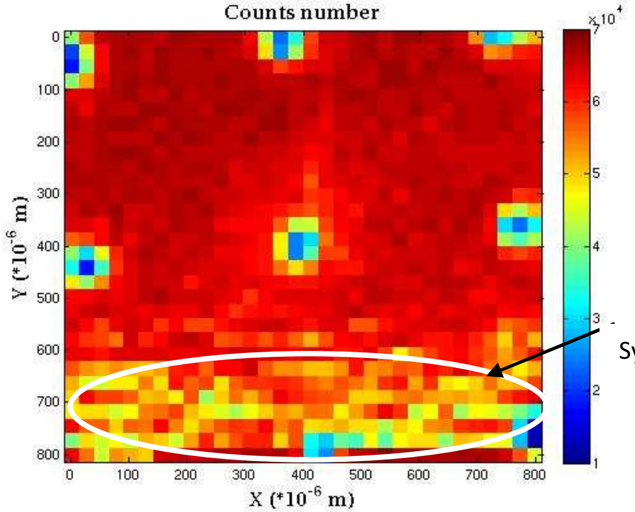


Total count map

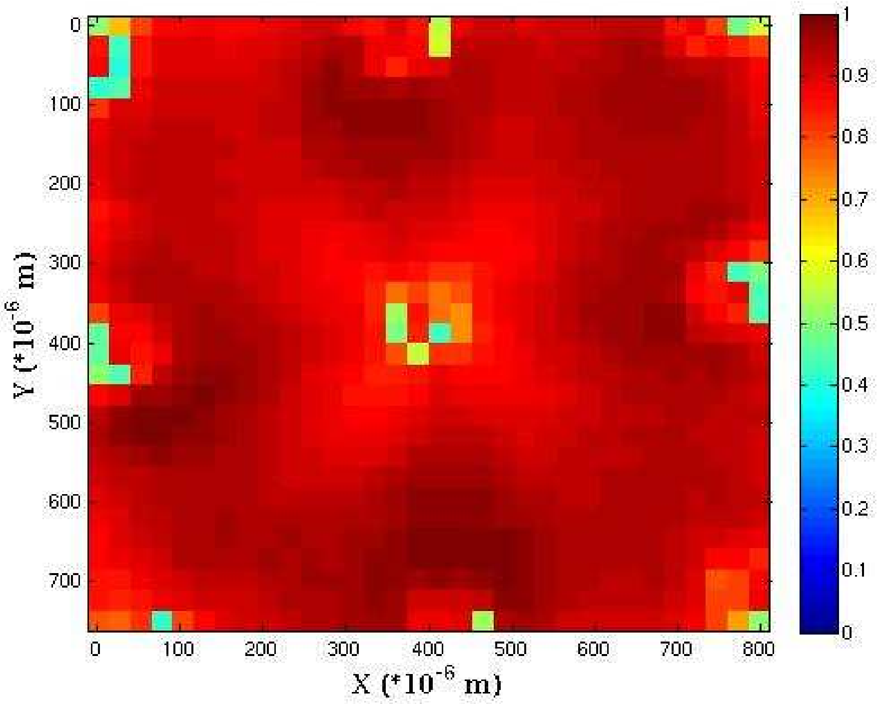


Incident photon absorption efficiency is homogeneous over the whole surface of the detector

3D CdTe detector

Measurement of the absorbed charge : normalized peak channel (calibrated measurement set-up)

Measurement (-20 V)



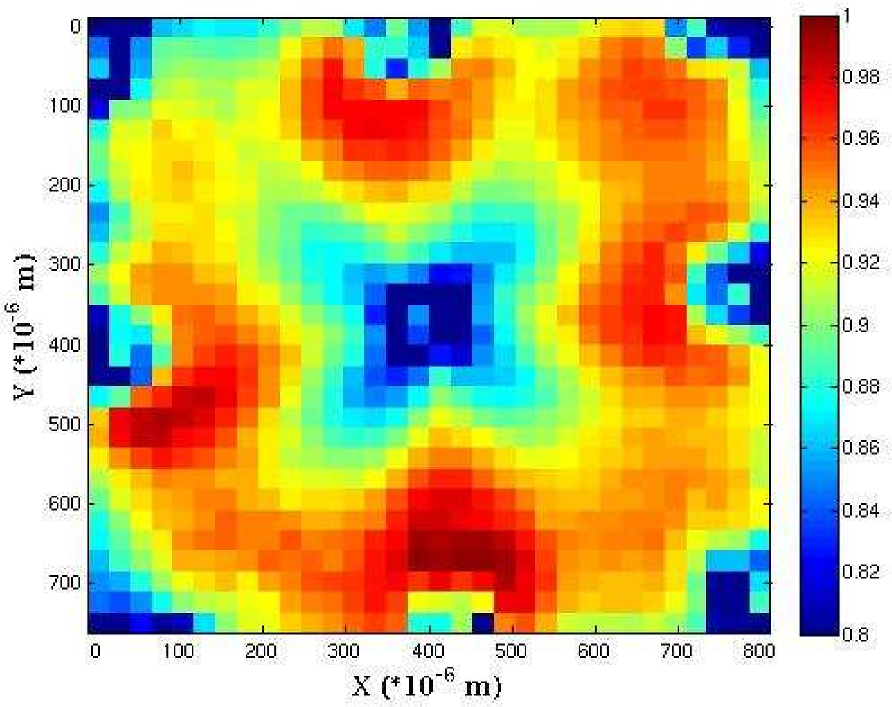
The normalized peak channel is greater than 0.8 ➔ good collection for both carriers

The detector response is homogeneous

3D CdTe detector

Measurement of the absorbed charge and comparison with simulated Charge Induction Efficiency

Measurement (-20 V)



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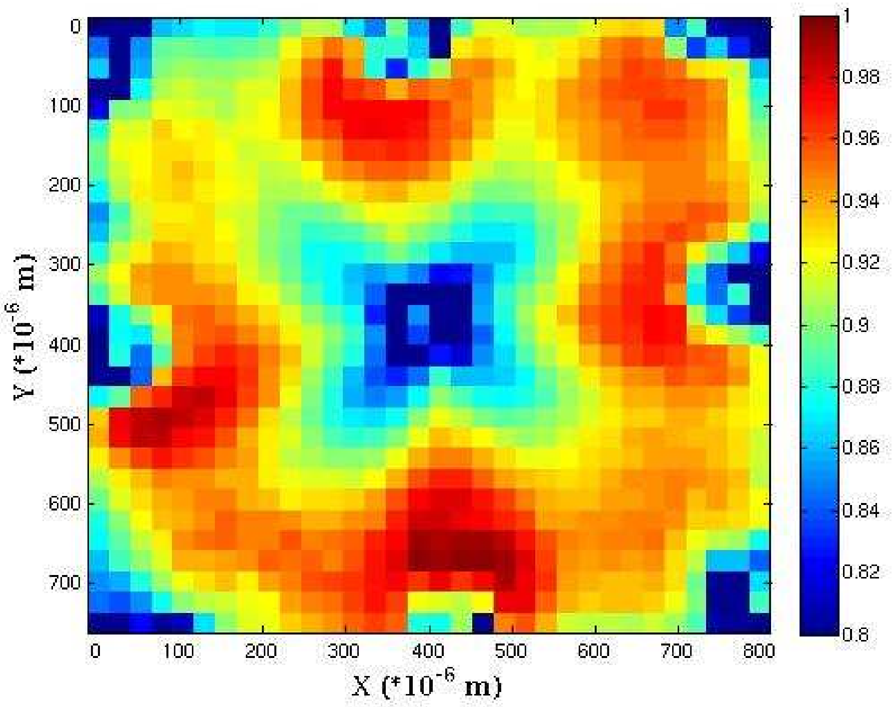
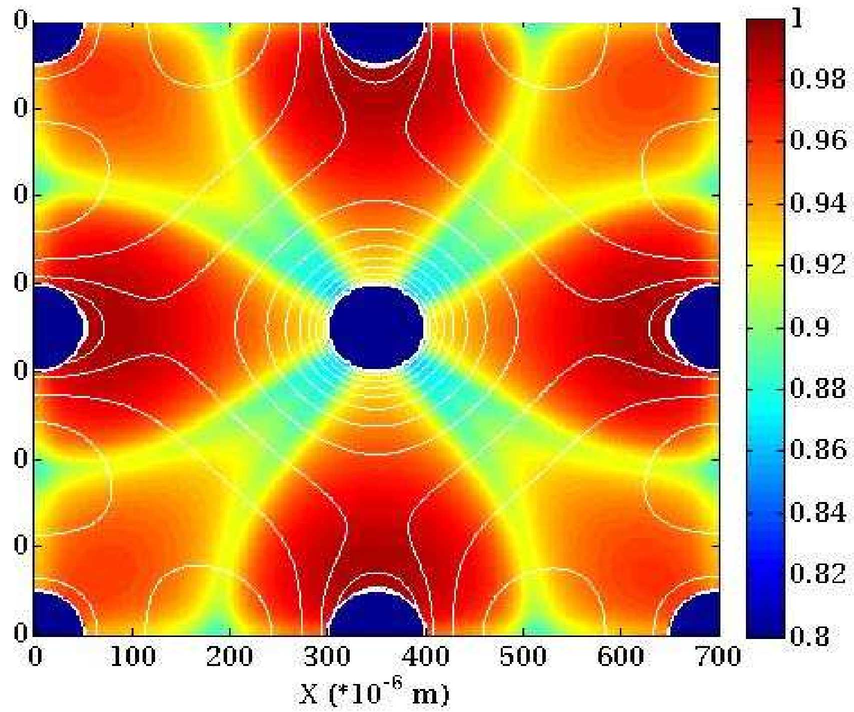


Simulation (-20 V)

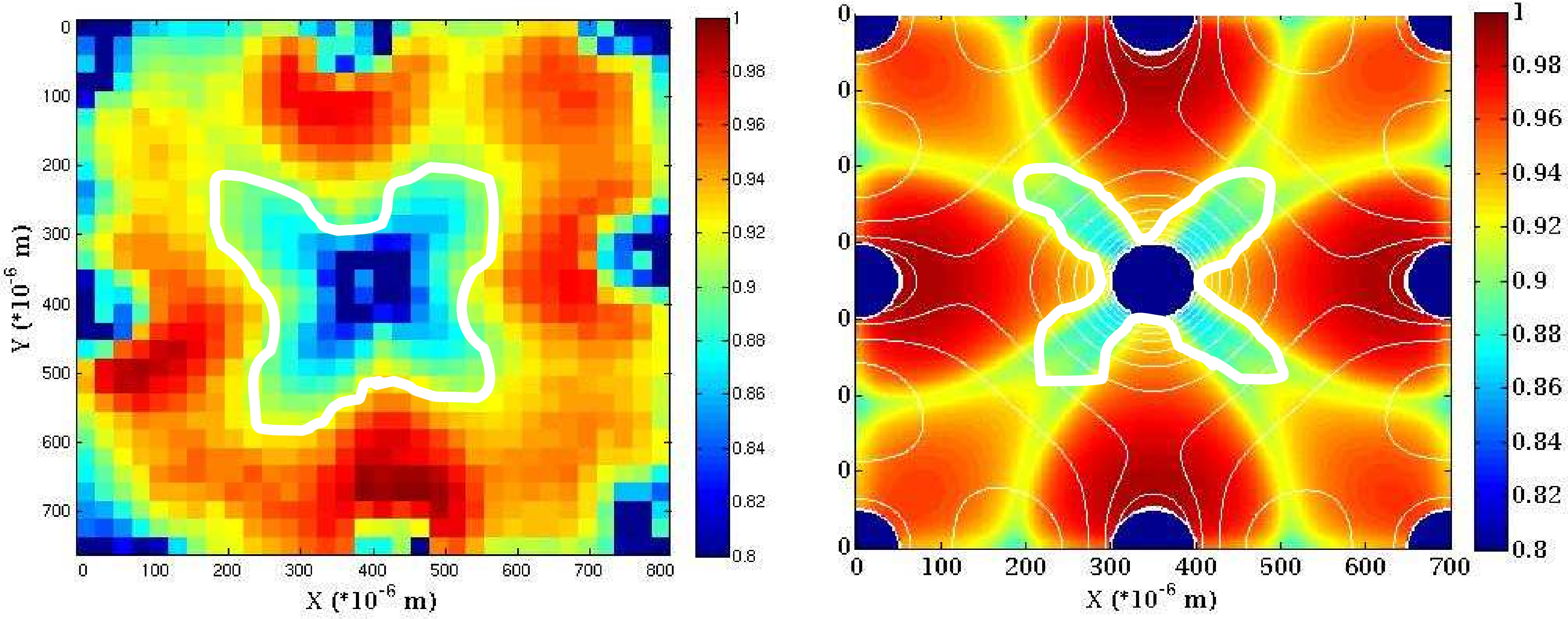


M. Ruat et al., "3D Semiconductor radiation detectors for medical imaging: simulation and design", *IEEE Nucl. Sci. Symposium Conference Record*, 2009

3D CdTe detector

Measurement of the absorbed charge and comparison with simulated Charge Induction Efficiency

Measurement (-20 V) Simulation (-20 V)



Four-leaf clover shape around central anode in experimental and simulated scan due to electric field distribution in biased 3D structure

M. Ruat et al., "3D Semiconductor radiation detectors for medical imaging: simulation and design", *IEEE Nucl. Sci. Symposium Conference Record*, 2009

3D CdTe detector

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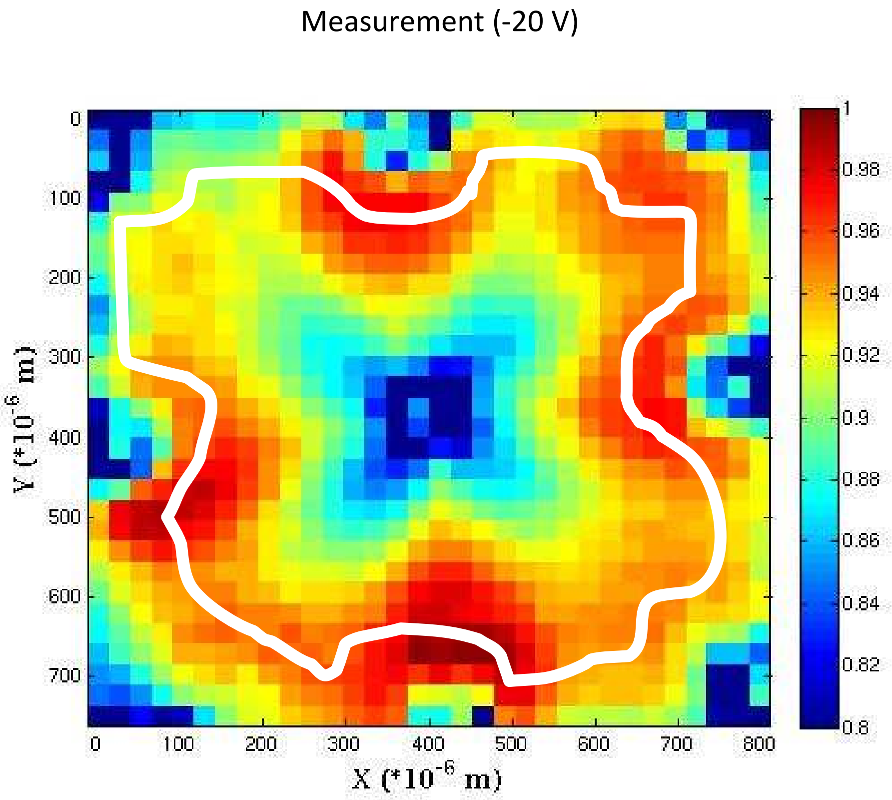

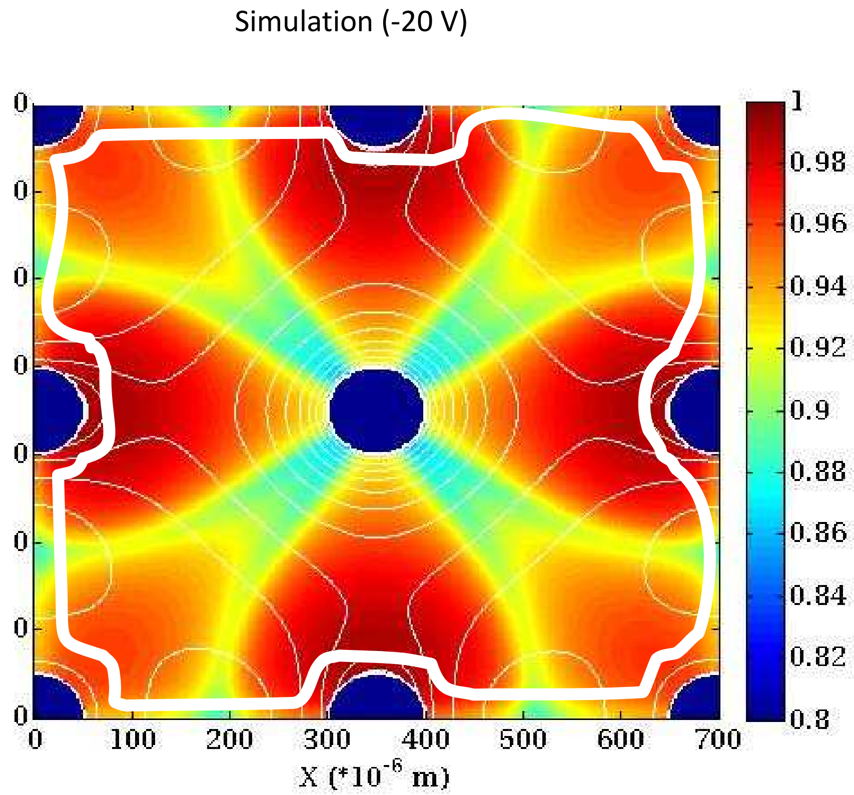

Highest values of charge efficiency around cathodes due to transport properties of electrons upper the holes transport properties in CdTe

M. Ruat et al., "3D Semiconductor radiation detectors for medical imaging: simulation and design", *IEEE Nucl. Sci. Symposium Conference Record*, 2009

3D CdTe detector

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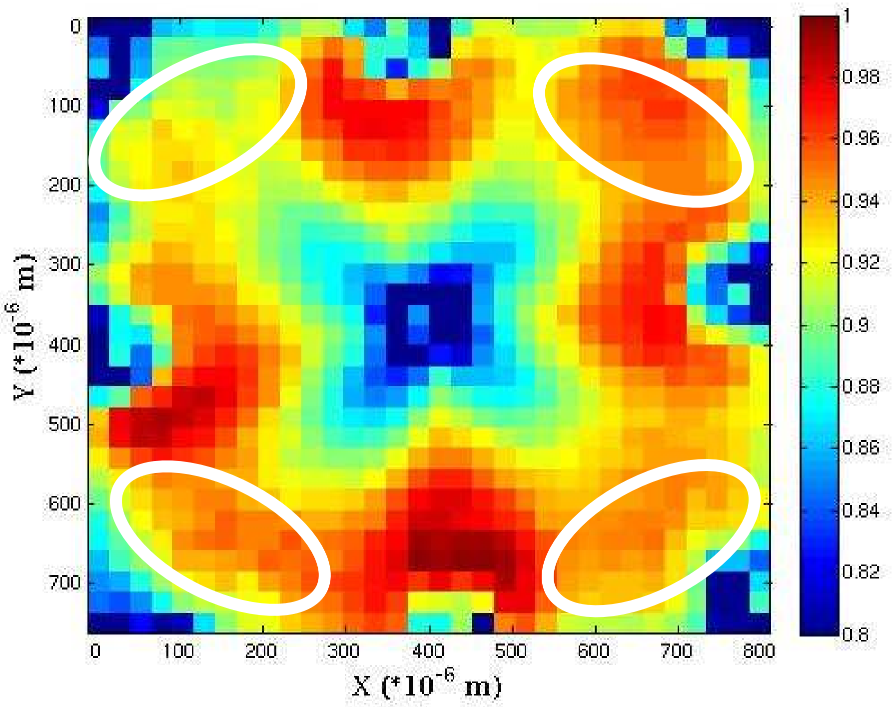

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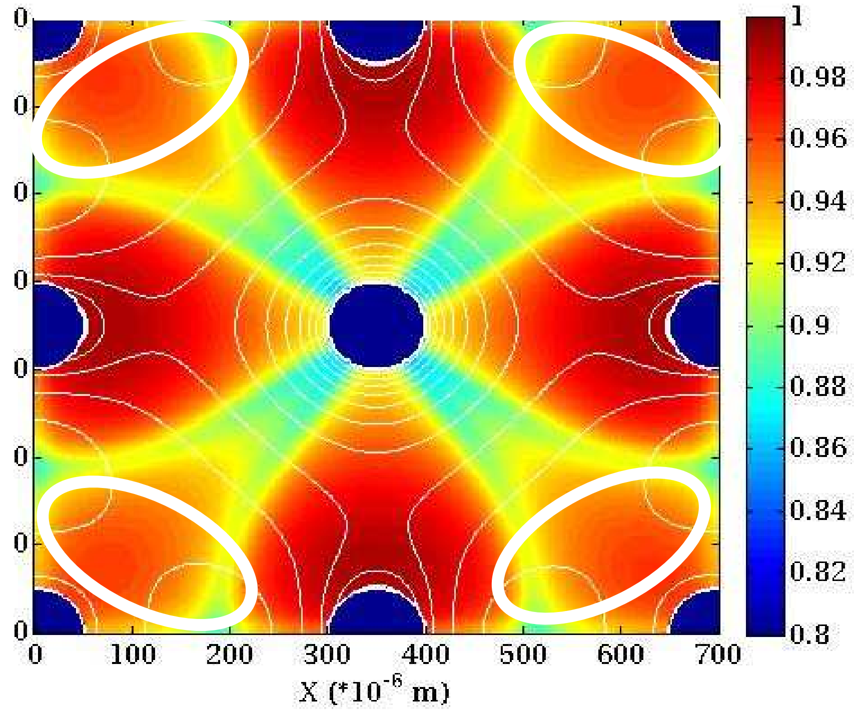
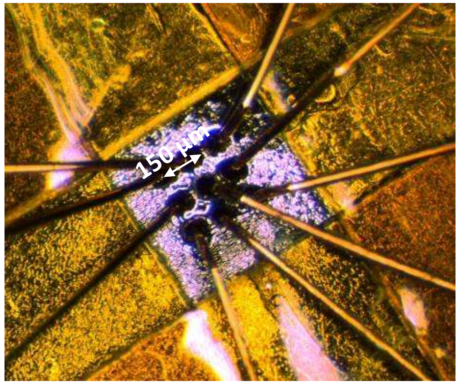


Low electric field and diffusion-dominated regions in the corner of square-shaped configuration: enhanced trapping and reduced charge collection efficiency

M. Ruat et al., "3D Semiconductor radiation detectors for medical imaging: simulation and design", *IEEE Nucl. Sci. Symposium Conference Record*, 2009

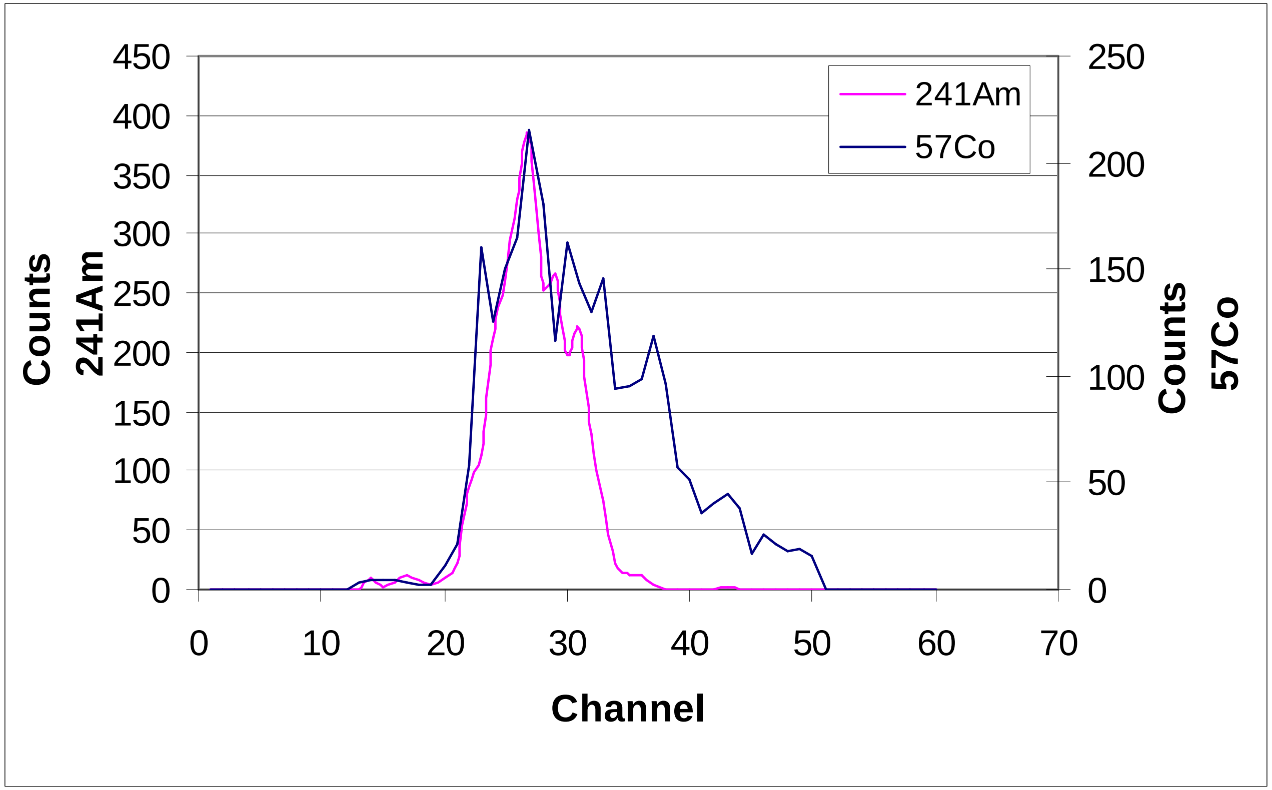
First results for 3D GaAs detector



GaAs 3D prototype :

- Semi-insulating GaAs Freiberger ; thickness = 600 µm
- 3x3 holes matrix :
  - Entrance diameter = 100 µm / Exit diameter = 50 µm
  - Pitch: 150 µm
- Electrodes : Gold electroless

Results under gamma rays irradiation (^{241}Am et ^{57}Co) : Square-shaped biasing configuration @ -60 V



Demonstration of photon-counting ability

Efficiency for 60 keV = 2%

Conclusion

3D geometry :

Alternative detector for X-rays medical imaging applications for semiconductor whose transport properties are lower (than CdTe for example)

Requires technical effort

3D CdTe detector :

Proof of concept for 3D geometry

Photon-counting ability

60 keV and 122 keV energy discrimination

Homogeneous absorption and charge collection under X-rays irradiation

3D **Semi-insulating GaAs detector :**

First prototype has been developed

Photons counting under gamma rays irradiation

Perspectives :

- Electrode : Ti/Pt/Au sputtering
- Chemical etch or Reactive Ion Etching to clean holes surface
- Holes filling with metal and bonding

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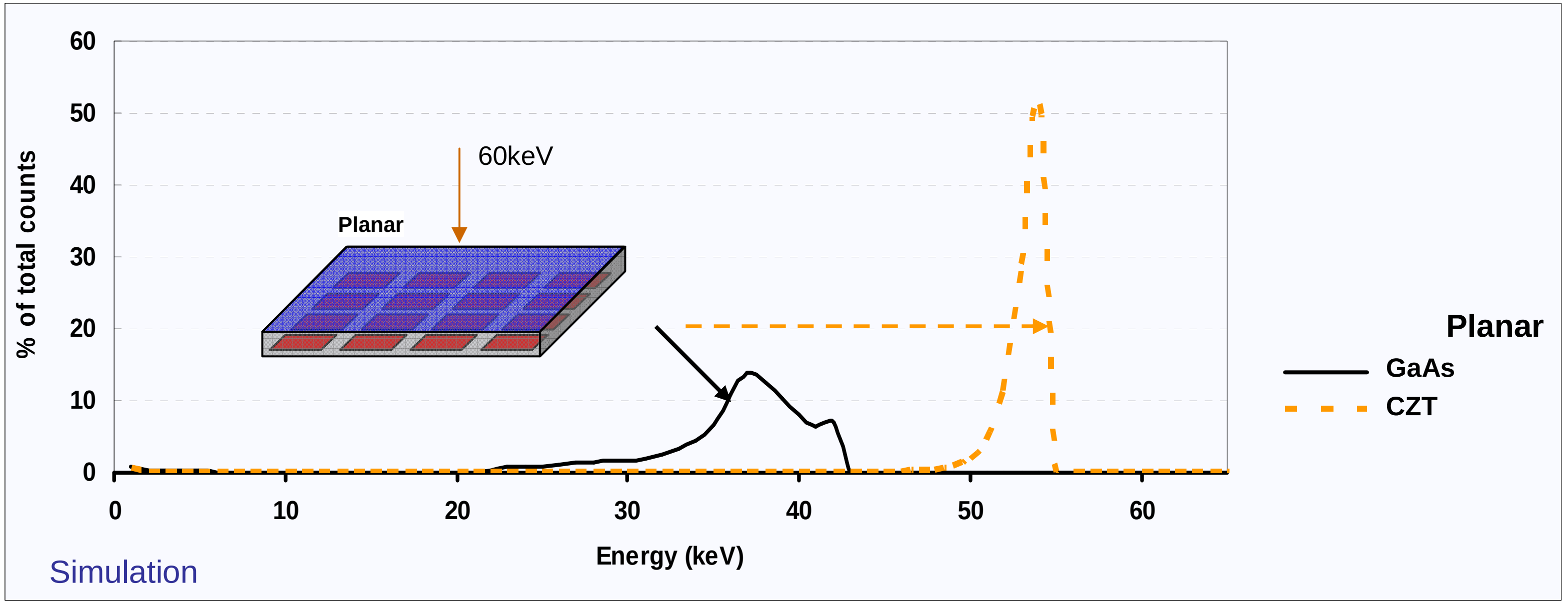
Thank you for your attention

Contribution of 3D geometry for GaAs

	CdZnTe (single crystal)	GaAs (epitaxy*)
$(\mu\tau)_e$ (cm²/V)	3.10^{-3}	8.10^{-5}
$(\mu\tau)_h$ (cm²/V)	5.10^{-6}	4.10^{-5}

*Epitaxy GaAs: G.C. Sun *et al.*, NIM-A, 546, 2005



Hypothesis: full depletion

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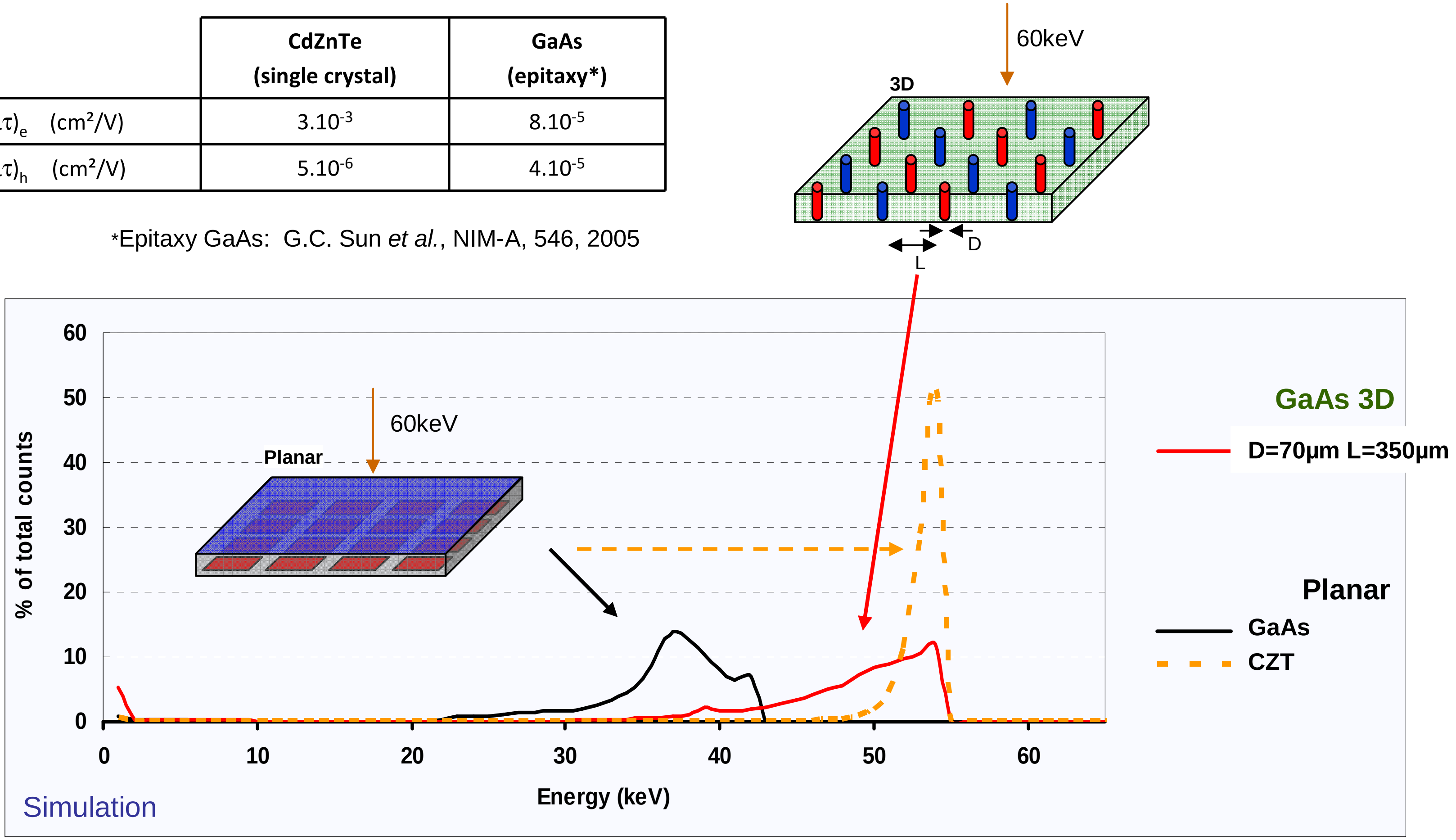

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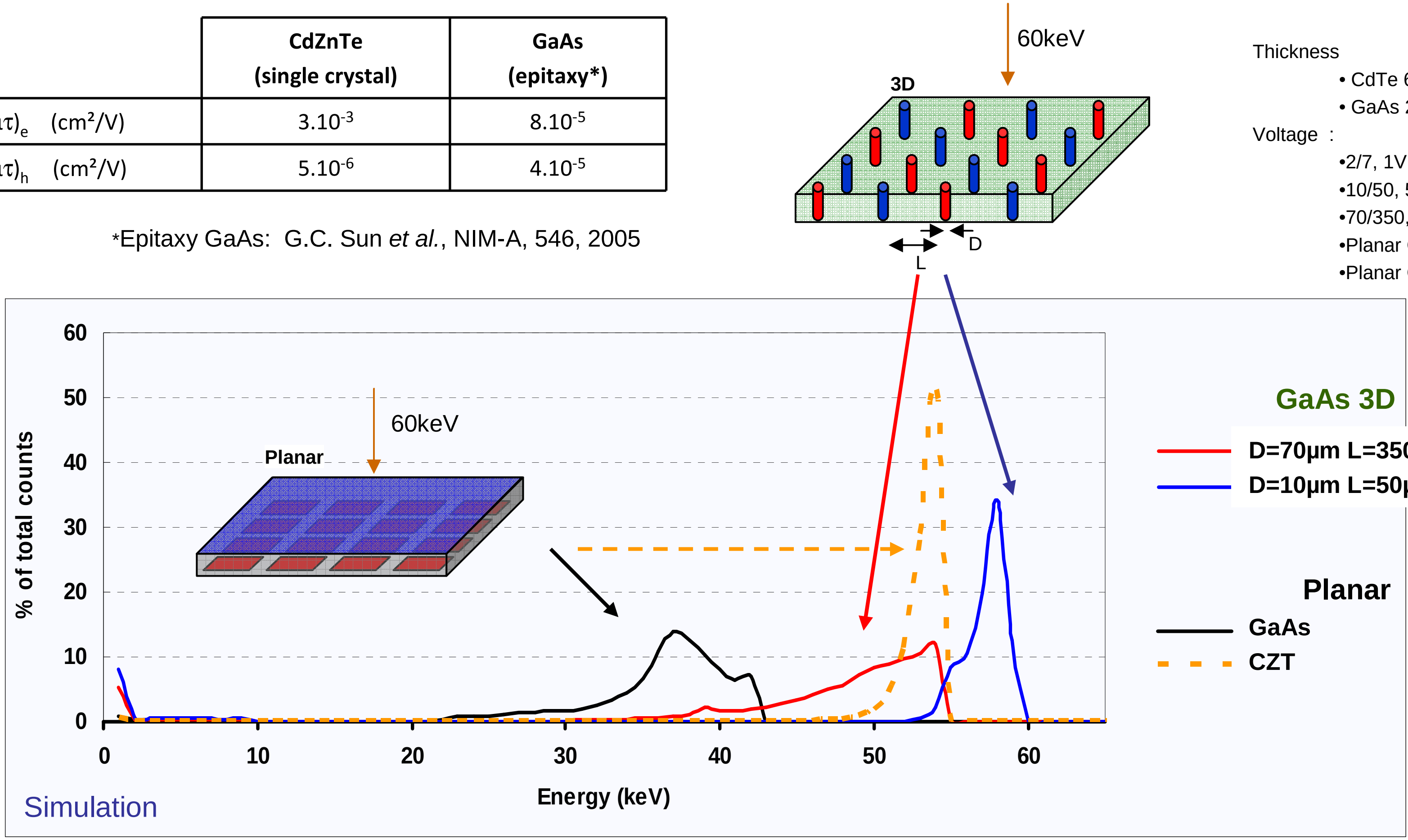
Thickness
- CdTe 640µm
- GaAs 2.3mm

Voltage :
- 2/7, 1V
- 10/50, 5V
- 70/350, 50V
- Planar CdTe 200V
- Planar GaAs 720V



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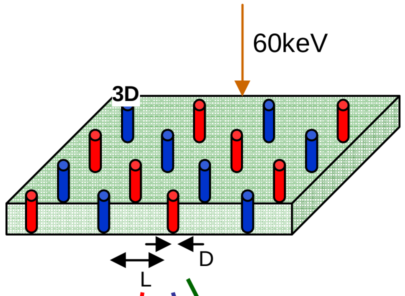

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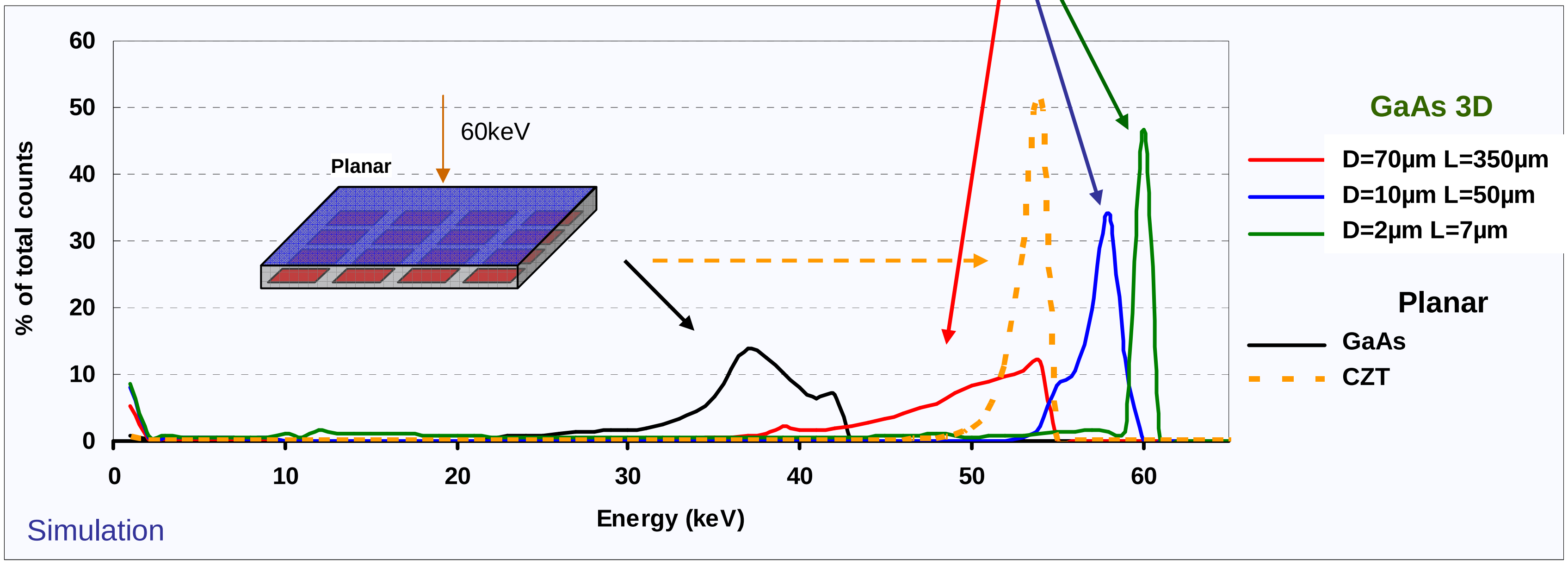


Structuring detector can make spectrometric a material whose transport properties are lower than CdZnTe

Characterization of laser drilling

Available Techniques :

- Dry etching
- Chemical etching
- Mechanical drilling
- **Laser drilling**

Mainly developed for Silicon (Dry etching, Chemical etching, Mechanical drilling)

Advantages / disadvantages laser drilling :

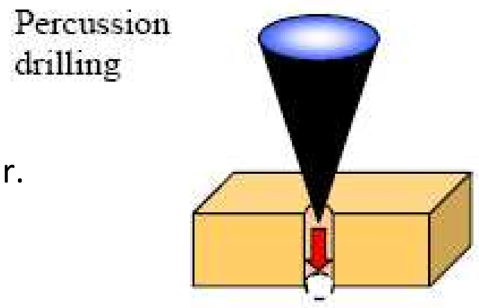
+ : High aspect ratio
+ : Material independent
- : Damaged holes sides
- : Holes tapering
- : Serial process

Laser drilling system : (CEA-Saclay)

A Nd-YLF pulsed laser has been used, exhibiting the following parameters:

- Wavelength = 263 nm, enabling a small spot size and small hole diameter
- Pulse energy = 600 µJ
- Rate = 3 kHz
- Pulse width = 40 ns

Holes are realised by laser beam percussion and samples are placed in the air.



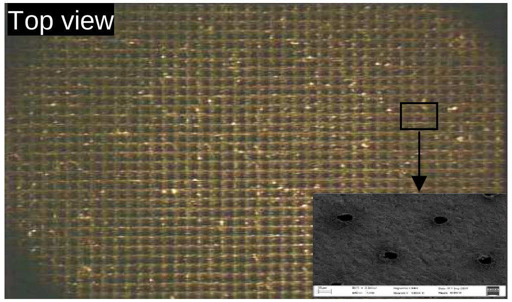
Characterization of laser drilling

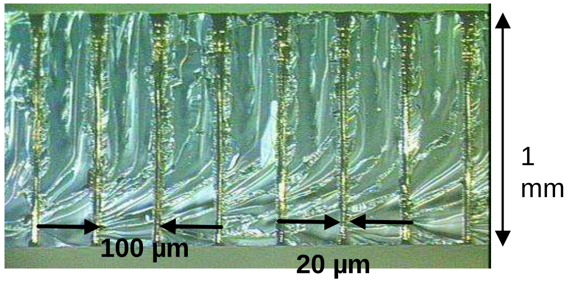
Feasibility of laser drilling

60 000 holes matrix drilled into 1 mm of CdTe with :
- Φ = 20 µm
- Pitch = 100µm

➔ **High aspect ratio 50 : 1**

Gold has been properly deposited over the whole surface and length of the holes



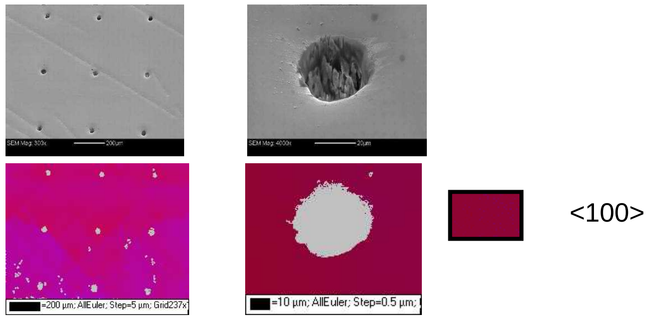


Study of Heat Affected Zone (HAZ) : Crystallographic information (Electron Back-Scattering Diffraction SEM)

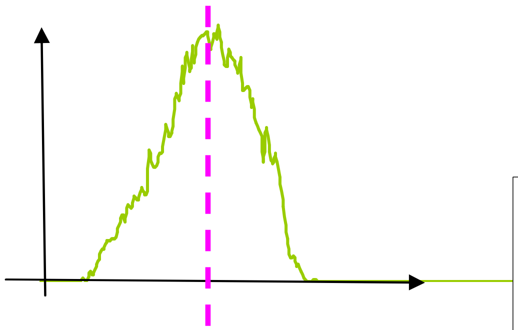
3 x 3 holes matrix drilled into 500 µm of GaAs
Chemical etch with Br in methanol

- No recrystallisation and no amorphous area around laser drilled holes
- GaAs stays single crystal <100>

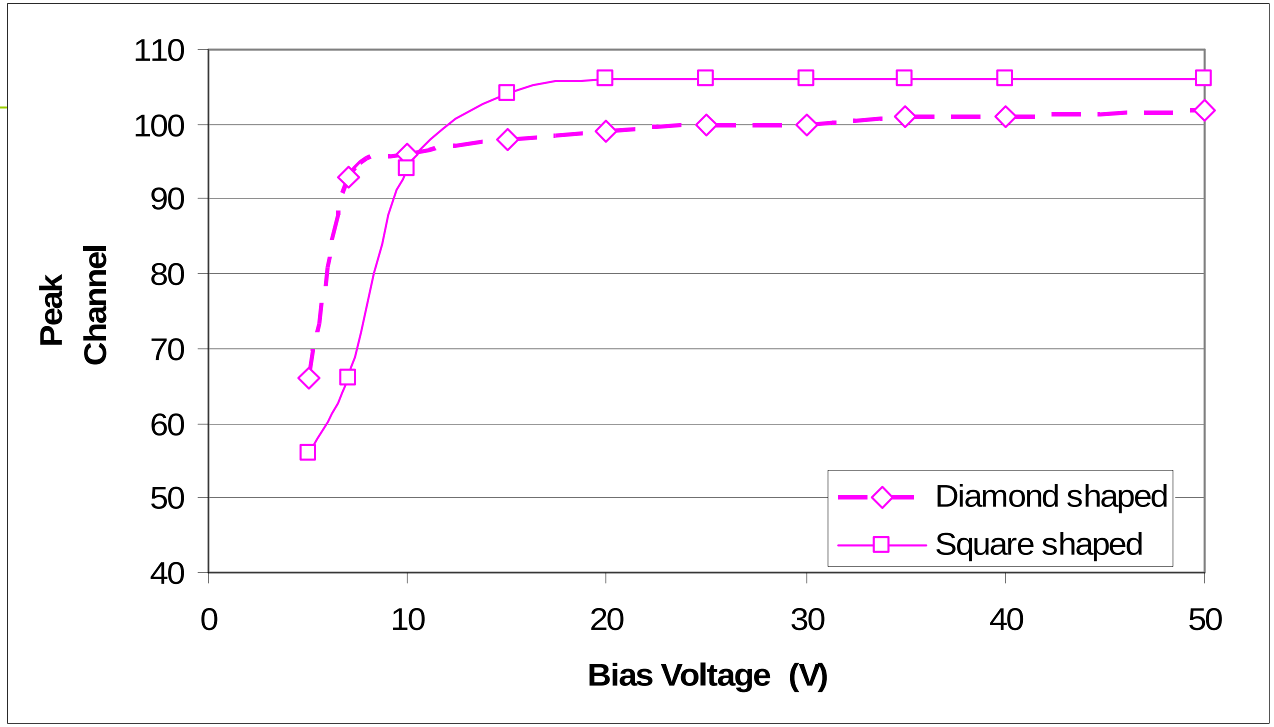
No critical HAZ : HAZ suppressed by chemical treatment



3D CdTe detector



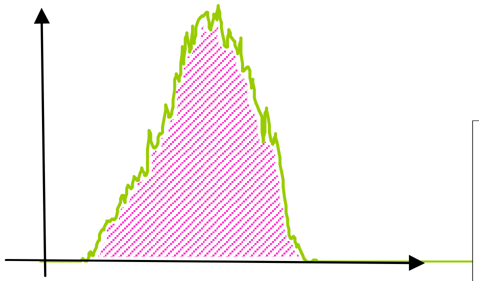
^{241}Am

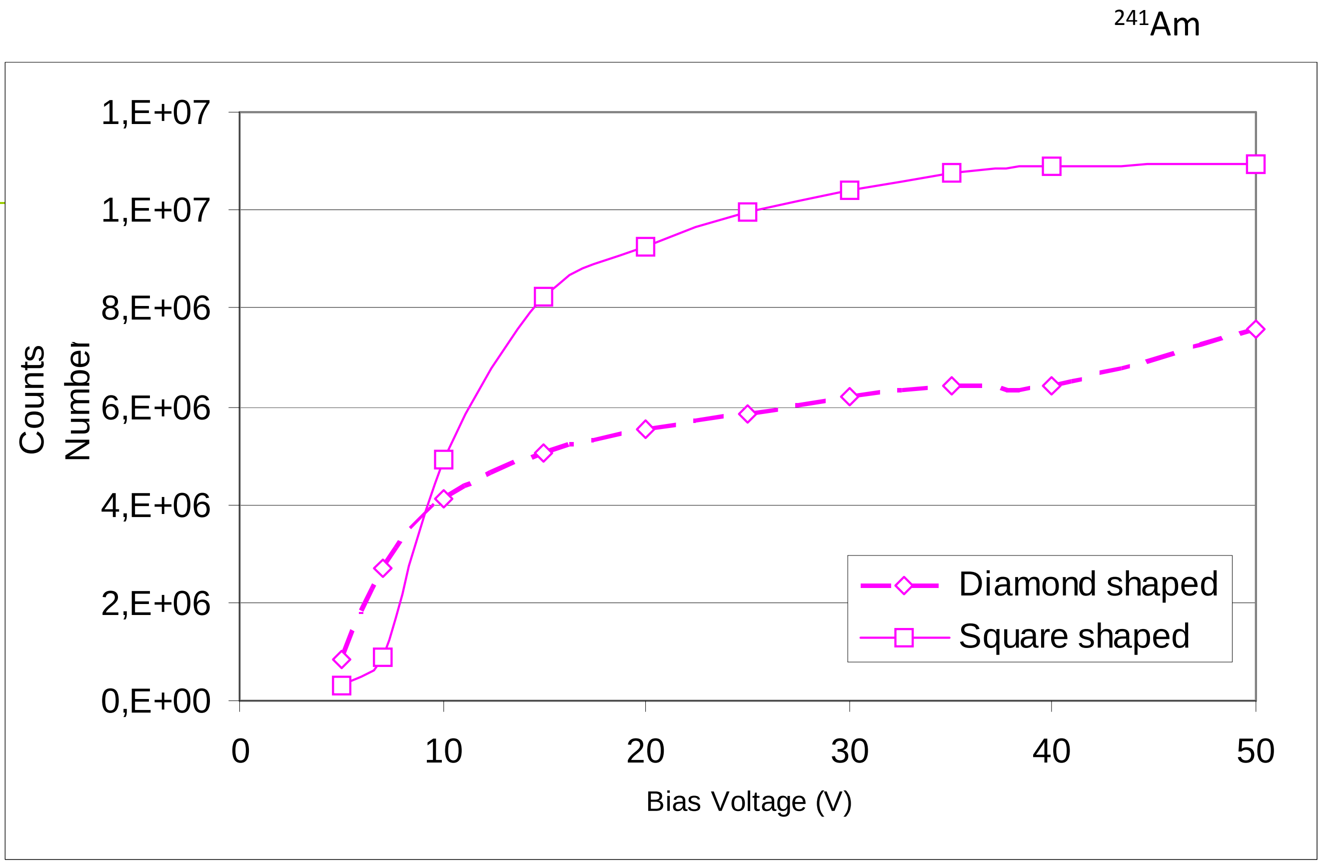


Stabilization of the peak channel in both bias configuration above -10 V ➔ full charge collection

Square-shaped bias configuration slightly more efficient than diamond-shaped bias configuration

3D CdTe detector





Stabilization of counts number
for both bias configuration
In the -20 to -50 V range

At -20V, ratio of total counts = 1.7

Demonstration of photon counting and ^{241}Am / ^{57}Co peak energy discrimination using a non-optimized design (electrode diameter and pitch have to be optimized)

3D CdTe detector