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

Marie-Laure Avenel, Eric Gros d’Aillon
CEA-LETI, DETectors Laboratory
marie-laure.avenel@cea.fr
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**:

  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

  *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

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

*D. Farcage, CEA-Saclay, LILM
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

Aspect ratio until 50 : 1

Metal electrodes deposition by electroless or sputtering

*D. Farcage, CEA-Saclay, LILM
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

Surface clean-up

Metal electrodes deposition by electroless or sputtering

* D. Farcage, CEA-Saclay, LILM

Aspect ratio until 50 : 1

1 mm

100 µm

20 µm
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

Aspect ratio until 50 : 1

Connection to read-out electronics using gold wires

Surface clean-up

Metal electrodes deposition by electroless or sputtering

*D. Farcage, CEA-Saclay, LILM
3D CdTe detector

Sample
- CdTe (C) 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
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
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

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)
3D CdTe detector

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

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

3D CdTe detector

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

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

![Graphs showing measurement and simulation results.]

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

3D CdTe detector

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

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

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

3D CdTe detector

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

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

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

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
Thank you for your attention
Contribution of 3D geometry for GaAs

<table>
<thead>
<tr>
<th></th>
<th>CdZnTe (single crystal)</th>
<th>GaAs (epitaxy*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\mu\tau)_e$ (cm$^2$/V)</td>
<td>$3 \times 10^{-3}$</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$(\mu\tau)_h$ (cm$^2$/V)</td>
<td>$5 \times 10^{-6}$</td>
<td>$4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

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

Hypothesis: full depletion
Contribution of 3D geometry for GaAs

<table>
<thead>
<tr>
<th></th>
<th>CdZnTe</th>
<th>GaAs (epitaxy*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(µτ)_e (cm²/V)</td>
<td>3.10⁻³</td>
<td>8.10⁻⁵</td>
</tr>
<tr>
<td>(µτ)_h (cm²/V)</td>
<td>5.10⁻⁶</td>
<td>4.10⁻⁵</td>
</tr>
</tbody>
</table>

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

Hypothesis: full depletion
Contribution of 3D geometry for GaAs

<table>
<thead>
<tr>
<th></th>
<th>CdZnTe (single crystal)</th>
<th>GaAs (epitaxy*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\mu\tau)_e$ (cm$^2$/V)</td>
<td>3.10$^{-3}$</td>
<td>8.10$^{-5}$</td>
</tr>
<tr>
<td>$(\mu\tau)_h$ (cm$^2$/V)</td>
<td>5.10$^{-6}$</td>
<td>4.10$^{-5}$</td>
</tr>
</tbody>
</table>

Hypothesis: full depletion
Contribution of 3D geometry for GaAs

<table>
<thead>
<tr>
<th></th>
<th>CdZnTe (single crystal)</th>
<th>GaAs (epitaxy*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\tau_e$ (cm²/V)</td>
<td>3.10^{-3}</td>
<td>8.10^{-5}</td>
</tr>
<tr>
<td>$\mu\tau_h$ (cm²/V)</td>
<td>5.10^{-6}</td>
<td>4.10^{-5}</td>
</tr>
</tbody>
</table>

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

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

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:
- \( \Phi = 20 \mu m \)
- Pitch = 100\( \mu m \)
⇒ 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 \( \mu m \) 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
Stabilization of the peak channel in both bias configurations 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 -20 V, 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