Performance of semi-insulating GaAs-based radiation detectors: Role of key physical parameters of base material

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OUTLINE

➢ MOTIVATION

➢ RADIATION DETECTOR CHARACTERISTICS
  • Key detector-grade material aspects

➢ APPLICATIONS
  • Monolithic LEC SI GaAs strip line in edge-on configuration
  • Line concept of SI GaAs chip
  • First “quantum” X-ray images
  • “Quantum” X-CT: preliminary

➢ GaAs MATERIAL FOR RADIATION DETECTORS
  • Key material characteristics
  • Characteristics summary
  • Performances of fabricated detectors

➢ CONCLUSIONS
Motivation I: New applications of semiconductor monolithic array detectors in X- and gamma-ray detection

NEW DETECTOR APPLICATIONS

• BASIC KNOWLEDGE: Experiments in physics
  X-ray astronomy, ...
  $^{115}$InP: Solar neutrino astrophysics

• MEDICINE Digital X-ray radiology (stomatology, mammography), XCT
  Positron emission tomography

• NONDESTRUCTIVE ON-LINE CONTROL Material
defect and process control

• SECURITY
  Contraband inspections: cargo control
  Detection of drugs and plastic explosives
  Cultural heritage’s study

• MONITORING
  Environmental control and radioactive waste
  management
  Metrology (testing of radioactive sources, spectrometry...)

IMPROVEMENTS IN X-RAY DIGITAL RADIOLOGY USING SEMICONDUCTOR DETECTORS

• LOWER DOSE TO PATIENT

• MUCH BETTER RESOLUTION IN CONTRAST
  (more than 2 orders of magnitude)

• DETERMINATION OF THE OBJECT DENSITY
  (Dual X-ray or “colour” imaging technique)

• 3-D IMAGE POSSIBLE USING CT METHOD

• NO POLLUTION DUE TO CHEMICAL PROCESSING
  (Necessary in the case of film application)

• SIMPLE AND SPACE SAVING STORAGE OF
  DIGITAL DATA

• ON-LINE PROCESS CONTROL & DIAGNOSTICS
  OTHERS...???

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„COLOUR IMAGING“ in digital radiography

Application 1: Simultaneous measurement of images at different energy regions — Energy-differentiated RT images —

Images were measured by linear scanning over radioisotopes (RI) with the radiation line sensor. Energy-differentiated imaging allows color visualization and identification of different radioisotopes. Images from different radioisotopes can be visualized by energy discrimination for easy color identification.

Radioisotope arrangement

Energy-differentiated images

Composite image with energy-differentiation

Easy identification of radioisotopes

Images obtained without energy differentiation: shows only the radiation intensity distribution

Images obtained with $^{140}$Cs only (Energy: 140 keV or higher)

Images obtained with $^{54}$Fe only (Energy: 70 keV to 140 keV)

Images obtained with $^{109}$Cd only (Energy: 25 keV to 70 keV)

A, B: Dual energy digital radiographs

Application 2: Simultaneous measurement of images at different energy regions — Energy-differentiated RT images —

Application 3: Eliminating effect from beam scattering and hardening

Images obtained without energy differentiation are subject to effects from scattered rays and beam hardening. These scattered rays and beam hardening can be eliminated by setting the proper energy differentiation levels.

Sample of aluminum cylinder with a copper, iron, titanium and carbon rods inserted inside the cylinder

Image obtained without energy differentiation (20 keV to 150 keV)

Energy-differentiated image (90 keV or higher)

Application 4: Gamma-ray and X-ray spectrum measurement

Highly detailed spectrum measurements can be made by auto sweep of the comparator levels.

$^{60}$Co spectrum measurement

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MOTIVATION II

SI GaAs MATERIAL PROPERTIES

✓ Radiation hard
✓ Low cost
✓ Fast
✓ Wide band gap allows operation at RT
✓ Highly developed technology processing
✓ Easily commercially available
✓ Bulk material – no limitation in thickness
✓ HIGH QUALITY!!

LINE (2D) SCANNING TECHNIQUE IN RADIOGRAPHIC IMAGING

Quantum XCT

✓ Technical simplest imaging solution
✓ Lowest cost
✓ Useful for fast testing of detector applicability in X-ray imaging
✓ High quality of X-ray image (good scattered photons rejection)
✓ Useful in many industrial, medical and security applications
✓ Applicable in basic and space research

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Key semiconductor material and detector characteristics

REQUIREMENTS TO SEMICONDUCTOR DETECTOR-GRADE MATERIAL

\[ Z > 30; \quad E_G > 1.3 \text{ eV}, \quad \tau, \rho (RT), \quad \text{high } v_d, \mu_d \]

High homogeneity, low density of structural, space-charge and point defects, fast reaction

LOW COST

CANDIDATE SEMICONDUCTORS

\textbf{II-VI}: CdTe, CdZnTe, HgI\textsubscript{2},…

\textbf{III-V}: GaAs, InP, ?? GaP, GaN,…

OUT OF INTEREST: Si, Ge
Important material aspect: **Attenuation coefficient**

\[ A \sim Z^{4.5} \]

![Graph showing photon attenuation coefficient vs. photon energy for GaAs, InP, and CdTe.](image)

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**SI GaAs X- and gamma ray line detector: New topology 2003**

<table>
<thead>
<tr>
<th>Type of developed line SI GaAs detector</th>
<th>Number of strips in line</th>
<th>Pitch, mm</th>
<th>Absorption length, mm</th>
<th>Chip dimensions, mm</th>
<th>Effective absorption volume of strip, mm³</th>
<th>Maximal thickness of substrate base, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMO X</td>
<td>32 64 128</td>
<td>0.25 0.125/0.25* 0.125</td>
<td>2.5</td>
<td>16x3.5 16x3.5/32x3.5* 32x3.5</td>
<td>0.06 0.04/0.08 0.04</td>
<td>0.12 – 0.18</td>
</tr>
<tr>
<td>SAMO XS</td>
<td>32</td>
<td>5.9</td>
<td>1.25 2.5**</td>
<td>8x3.5</td>
<td>0.1 0.18</td>
<td>0.2 – 0.3</td>
</tr>
</tbody>
</table>

![Image of detector](image1)

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SI GaAs line X-ray detector chip mounted onto flexible PCB carrier: Original concept (top), final arrangement (down)

0.25 mm thick flexible PCB holder

GaAs line detector chip
Micro-Peltier
Heat sink

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SI GaAs DETECTOR APPLICATIONS

SINGLE PHOTON COUNTING = QUANTUM X-RAY SCANNER
QUANTUM X-CT: FIRST EXAMPLE
Portable digital X-ray scanner based on Si GaAs radiation detectors: Final set-up consists of 480 channels line, position control and communication
Photos of various selected test objects
Testing X-CT platform

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Requirements to SI GaAs detectors based on “detector grade” materials

*From the point of view statistical fluctuations:*

- Poisson’s limit: $S/N = (n)^{1/2}$
- Other goals: - production yield
- - stability in long-term operation
- - high homogeneity
Si GaAs

Role of key physical parameters of base materials
## GDMS analysis: Si GaAs materials

| Element | A1 | B | C | D1 | D2 | E | F | G | H | K | L | M* |
|---------|----|---|---|----|----|---|---|---|---|---|---|---|----|
| B       | 190| 303| 51| 1041| 966| 271| 301| 71| 470| n/a| 20 | 5600 |
| Na      | <1.5| <2| <1.7| 4| <2| 8| 3| <2| 4| <1.5| 3 | |
| Mg      | <2| <2| <2| <2| <2| 4| <1.9| <1.9| 5| <1.5| <2| |
| Al      | <1| 3| <1| 14| <1.4| 13| 3| 2| 3| <1| 9 | |
| Si      | <3| 11| <3| 142| 4| 212| 5| 20| 11| <3| 445| |
| P       | <3| <3.5| 4| 11| <2.8| 12| <3| 12| 20| <3| 110| |
| S       | <3| 21| 9| 7| 12| 25| 10| 10| 102| <3.5| 77| |
| Cl      | 14| 13| 9| 13| 16| <25| 12| 4| 13| 7| 11| |
| Ti      | <0.4| 2| <0.4| 3| <0.5| 1| <0.4| 1| <0.4| <0.4| |
| Cr      | <1.2| <1.2| <1.2| 1| <1| <1.2| <1.2| 70| <0.9| <1.5| |
| Fe      | <0.4| 1| <0.5| 1.8| 0.7| 1.4| 1.5| 0.8| 0.8| <0.4| 8 | |
| Cu      | <2.5| <3| <2.5| 26| 8| <3| <3| <2.5| <3| <2.5| <2.7| |
| Total:  | <447| <594| <312| <1515| <1258| <806| <576| <360| <953| <257| >6655| |

Following impurities were obtained in all samples under given detection limit: F<25, Li<6, Be<5, K<25, Ca<20, Mn<0.5, Ni<1.1, Zn<4, Ge<40, Se<13, Mo<1.8, Cd<0.5, In<100, Sn<4, Te<2, Sb<2, Pb<0.5, Bi<0.5. 

NOTICES: In the analysis there are not included C, N₂, O₂ as the background contaminants in GDMS and host atoms, Ga and As.

*Content of other important impurities (ppb at.) in the sample M is following: F 35, Mn 5, and Te 32.
High resolution DCT and LST: *SI GaAs materials*

a) SI GaAs: LEC (B) and VGF (D1) grown materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>FWHM DD, cm⁻²</th>
<th>DCT</th>
<th>PD, cm⁻³</th>
<th>LST</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>7.2 (2\times10^4)</td>
<td><img src="image1" alt="DCT image" /></td>
<td>n/a</td>
<td><img src="image2" alt="LST image" /></td>
</tr>
<tr>
<td>LEC</td>
<td></td>
<td><img src="image3" alt="DCT image" /></td>
<td></td>
<td><img src="image4" alt="LST image" /></td>
</tr>
<tr>
<td>D1</td>
<td>6.2 (4\times10^3)</td>
<td><img src="image5" alt="DCT image" /></td>
<td>4.3(\times10^7)</td>
<td><img src="image6" alt="LST image" /></td>
</tr>
<tr>
<td>VGF</td>
<td></td>
<td><img src="image7" alt="DCT image" /></td>
<td></td>
<td><img src="image8" alt="LST image" /></td>
</tr>
</tbody>
</table>
Capacitance study: *SI GaAs detectors*

**Figure 3.** Measured dependences of the capacitance per unit area on voltage of the back-to-back Schottky barrier structures in undoped semi-insulating GaAs from four different manufacturers measured at 420 K and frequency 130 Hz.

**Figure 4.** Calculated dependences of $S^3C^2$ on voltage of the back-to-back Schottky barrier structures in undoped semi-insulating GaAs from four different manufacturers measured at 420 K and frequency 130 Hz.
Basic electrical and material characteristics and detectors performances: 

**SI GaAs materials SUMMARY**

<table>
<thead>
<tr>
<th>Sample label</th>
<th>Growth Method</th>
<th>Doping, contamination</th>
<th>EPD cm$^{-2}$</th>
<th>Resistivity Ωcm (RT)</th>
<th>Hall mobility cm$^2$/Vs (RT)</th>
<th>Detection performances (RT)</th>
<th>CCE, %</th>
<th>HWHM, %</th>
<th>P/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>LEC</td>
<td>Non, Ti</td>
<td>&lt;4x10$^4$</td>
<td>9.2x10$^6$</td>
<td>7227</td>
<td>79</td>
<td>18.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;8x10$^4$</td>
<td>2.44x10$^7$</td>
<td>6040</td>
<td>65</td>
<td>14</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;4x10$^4$</td>
<td>1.15x10$^7$</td>
<td>7227</td>
<td>59</td>
<td>24</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>VGF</td>
<td>Non, Cu, Fe, Ti</td>
<td>&lt;5x10$^3$</td>
<td>8.8x10$^7$</td>
<td>5400</td>
<td>28</td>
<td>35</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>VGF</td>
<td>Non, Cu, Fe</td>
<td>&lt;4x10$^3$</td>
<td>4.63x10$^7$</td>
<td>6203</td>
<td>43</td>
<td>21</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>HP LEC</td>
<td>Non</td>
<td>&lt;6x10$^5$</td>
<td>2.95x10$^6$</td>
<td>6940</td>
<td>73</td>
<td>22.5</td>
<td>2.9</td>
<td></td>
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<tr>
<td>F</td>
<td>LP LEC</td>
<td>Non</td>
<td>&lt;2x10$^5$</td>
<td>1.06x10$^7$</td>
<td>5816</td>
<td>72</td>
<td>21.6</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;8x10$^4$</td>
<td>2.8x10$^8$</td>
<td>5122</td>
<td>42</td>
<td>no photopeak detected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>LEC</td>
<td>Cr</td>
<td>&lt;1x10$^5$</td>
<td>1.2x10$^8$</td>
<td>5770</td>
<td>51</td>
<td>25</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;2x10$^5$</td>
<td>9.65x10$^6$</td>
<td>7517</td>
<td>57</td>
<td>no photopeak detected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;6x10$^4$</td>
<td>2.6x10$^7$</td>
<td>6915</td>
<td>72</td>
<td>12.5</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>LEC</td>
<td>Non</td>
<td>&lt;8x10$^5$</td>
<td>1.4x10$^8$</td>
<td>4830</td>
<td>32</td>
<td>no photopeak detected</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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EBIC: SI GaAs

SE

Bias voltage: 0 -30 V -60 V

F: M/A COM LP LEC SI GaAs

Detector contact: 2 mm diameter
Base thickness: 200 µm

E: M/A COM HP LEC SI GaAs

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I-V characteristic of SI GaAs detector with the Schottky barrier

?? Explanation of the second current saturation region observed at the reverse I-V characteristics

\[ I = I_S \left[ e^{\frac{q(V - I_R S)}{nkT}} - 1 \right] \]

**Thermiionic emission current via Schottky barrier**

\[ I_S = AA^{**} T^2 e^{-\frac{q\phi_B}{kT}} \]

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I-V characteristics of SI GaAs detectors with the Schottky barrier (2 mm diameter)

Fig. 1. Room-temperature $I-V$ characteristics versus reverse bias voltage for SI LEC GaAs detectors at different acceptor dopant concentrations, $N_a$, as reported in Table 1.

Fig. 2. A detailed reverse current behaviour from low voltages, $1 \times 10^{-3}$ V, to 200 V, with the saturation current, $I_s$, range indicated.

Pulse-height spectra of $^{241}$Am and $^{57}$Co detected by “dedicated” SI GaAs PAD detector

![Graph showing pulse-height spectra of $^{241}$Am and $^{57}$Co detected by a SI GaAs PAD detector. Peaks are labeled with energies and types of radiation.]


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Optimization of the ohmic and blocking SI GaAs detector contacts


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Conclusions

• **Bulk SI GaAs:** Radiation detector-grade material is available on the market!

• **Key material characteristics:**
  - preferable VGF, low dislocation density
  - high chemical purity (GDMS)
  - RT Hall mobility > 6500 cm²/Vs
  - RT resistivity (0.8 – 3)e7 ohm cm

• Following material evaluation tools: X-ray topography, LST, PL, ...

• Detector evaluation tools: I-V, C-V, EBIC, pulse height spectra,...

• Detector electrodes: Must be optimized for required performance

• Schottky back-to-back electrode technology: Potential improvement must be investigated in more details!!

• **PERSPECTIVE APPLICATIONS:** Quantum X-RAY IMAGING, Quantum X-CT,...

• **BASIC & SPACE RESEARCH:** PLASMA DIAGNOSTIC IN NUCLEAR FUSSION
THANK YOU
FOR YOUR ATTENTION!!!