Prospects for Energy Resolving X-Ray Imaging with Compound Semiconductor Pixel Detectors

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Outline

• GaAs and SiC X-Ray detectors
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• The achieved results
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• The achieved results
• Some related issues :
  – Leakage current
  – Electronic noise
  – Charge transport
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• GaAs and SiC X-Ray detectors

• The achieved results

• Some related issues:
  – Leakage current
  – Electronic noise
  – Charge transport

• Prospects with GaAs and SiC pixel detectors
GaAs Radiation Detectors:
30 years of a fascinating history

- **1971-72**: Eberhart et al. (NIM-94), Kobayashi et al. (NIM-98)

- **1992 -1998:**
  - **Europe**: Aachen, CERN, Freiburg, Glasgow, Imperial College, Lecce, Leicester, Milano, Modena, Pisa, Sheffield…
  - **USA**: Michigan Univ., Sandia; UCLA, Livermore, Naval, Berkeley, Wright Univ.
1996 – GaAs single pixel GaAs

Politecnico di Milano – KFA Julich Collaboration

MBE GaAs - 5 µm thick
p-i-n structure (3·10^14 cm^-3)
pixel: 170 x 320 µm

**Equivalent Noise Energies**

@ 20 °C: 532 eV FWHM (53 e- r.m.s.)

@ -30°C: 373 eV FWHM (37 e- r.m.s.)


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2002 - Pixel Array

A. Owen, M. Bavdaz, A. Peacock (ESA)
S. Nenomen, H. Anderson (Metorex)
G. Bertuccio, R. Casiraghi, D. Maiocchi (PoliMI)

CVD GaAs - 40 μm thick
p⁺n structure
Pixel size: 200 μm x 200 μm
Epitaxial Layer Characteristics

Equivalent to
20 X Silicon thickness (650 µm)

33 µm @ 100 V

1.5 \times 10^{14} \text{ cm}^{-3}
Junction Leakage Current

Reverse Current [A] vs. Reverse Voltage [V]

- T = +30°C
- T = 10°C
- T = -10°C
- T = -30°C

Reverse Current [A]

0 2 4 6 8 10

-15

-14

-13

-12

-11

-10

Reverse Voltage [V]

0 20 40 60 80 100

-10

-9

-8

-7

-6

-5

-4

-3

-2

-1

0

10

10

10

10

10
Junction Leakage Current

![Graph showing junction leakage current as a function of reverse voltage and temperature. The graph plots reverse current in pA on the y-axis and reverse voltage in V on the x-axis. The graph shows data for different temperatures: T = +30°C, T = -10°C, and T = -30°C. The graph indicates a junction leakage current density of 3-12 nA/cm² at these temperatures.](image)
Can this current (noise) be lowered?
Leakage Current densities

Current density \[ \text{[ A/cm}^2 \text{]} \]

Mean electric field \[ \text{[ kV/cm]} \]

Is the ultimate limit reached for \( J_{\text{GaAs}} \) ?
Investigation on

the leakage current origin

in junctions on GaAs
Leakage current origin in GaAs detectors

Schottky junction GaAs detectors

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Leakage current origin in GaAs detectors

Schottky junction GaAs detectors

\[ T = 300 \text{ K} \]

\[ \phi_B = 0.91 \text{ eV} \]

Thermionic emission

\[
I_R = S A T^2 e^{\frac{q \phi_B}{kT}} \left( 1 - e^{\frac{qV_R}{kT}} \right)
\]

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Leakage current origin in GaAs detectors

Schottky junction GaAs detectors

\[ T = 300 \text{ K} \]

\[ \phi_B = 0.91 \text{ eV} \]

Barrier lowering:

\[ \phi_B = \phi_{B0} - \sqrt{\frac{qE_m}{4\pi\varepsilon_s}} \]

Thermionic emission:

\[ I_R = S A^* T^2 e^{\frac{q\phi_B}{kT}} \left(1 - e^{\frac{qV_R}{kT}}\right) \]
Leakage current origin in GaAs detectors

Schottky junction GaAs detectors

Barrier lowering + static
\[ \phi_B = \phi_{B0} - \frac{qE_m}{4\pi\varepsilon_s} - \alpha E_m \]

Barrier lowering
\[ \phi_B = \phi_{B0} - \frac{qE_m}{4\pi\varepsilon_s} \]

Thermionic emission
\[ I_R = S A^* T^2 e^{\frac{q\phi_B}{kT}} \left( 1 - e^{\frac{qV_R}{kT}} \right) \]

\[ T = 300 \text{ K} \]

\[ \phi_B = 0.91 \text{ eV} \]
Leakage current origin in GaAs detectors

$p^+n$ junction GaAs detectors

![Graph showing reverse current vs. reverse voltage with a temperature of 291 K]
Leakage current origin in GaAs detectors

$p^+n$ junction GaAs detectors

Thermal Generation

$E_A = 0.7$ eV

$\tau_G = 1 \, \mu s$
Leakage current origin in GaAs detectors

p⁺n junction GaAs detectors

Thermal Generation

\[ E_A = 0.7 \text{ eV} \]
\[ \tau_G = 1\mu\text{s} \]

Poole Frenkel effect

Reverse Current [A]

Reverse Voltage [V]

291 K

x 3
Leakage current in GaAs: conclusions

• Current densities $\leq 10 \text{ nA/cm}^2$ @ 290 K
Leakage current in GaAs: conclusions

• Current densities $\leq 10\text{ nA/cm}^2$ @ 290 K

• Schottky junction:
  
  – Barrier height $\phi = 0.9\text{ eV}$
  
  – Significant barrier lowering effects
  
  – Higher barrier, lower doping (smaller $E_m$) required
Leakage current in GaAs: conclusions

• Current densities \( \leq 10 \text{ nA/cm}^2 \) @ 290 K

• Schottky junction:
  - Barrier height \( \phi = 0.9 \text{ eV} \)
  - Significant barrier lowering effects
  - Higher barrier, lower doping (smaller \( E_m \)) required

• p+n junction:
  - Generation current (\( \tau_G = 1\mu s; E_A = 0.7 \text{ eV} \))
  - Poole-Frenkel effect observed
  - Higher purity, lower doping (smaller \( E_m \)) required
Prototype GaAs pixel array

Test with discrete front-end electronics

16 electrons r.m.s. at +20°C
14 electrons r.m.s. at -30°C
Which are the limits?
Can we hope higher resolution?

Room temperature (20°C)
242 eV FWHM (24 e - r.m.s.)

Thermoelectric cooling (-30°C)
163 eV FWHM (16 e - r.m.s.)

Trans. Nucl. Sci. 50, 2003


Noise Components Analysis

![Graph showing ENC and FWHM vs. Shaping time for GaAs detector connected and front-end electronics at 20 °C.]

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Noise Components Analysis

![Graph showing ENC vs. Shaping time for GaAs detector connected and Front-end electronics.](image)

**GaAs detector connected**

**Front-end electronics**

20 °C

ENC [electrons r.m.s.]

Shaping time [µs]

FWHM [eV]

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Noise Components Analysis

GaAs detector connected

Front-end electronics

Series noise

Current noise

ENC [electrons r.m.s.]

Fano [eV]

20 °C

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Noise Components Analysis

ENC [electrons r.m.s.]

<table>
<thead>
<tr>
<th>Shaping time [µs]</th>
<th>ENC</th>
<th>FWHM [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>36</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>20</td>
<td>24</td>
<td>350</td>
</tr>
</tbody>
</table>

GaAs detector connected
Front-end electronics
Series noise
Dielectric noise
Current noise

20 °C

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X-\( \gamma \) Ray Spectroscopy
with epi-GaAs pixels detectors

Results
**X-γ Ray Spectroscopy with GaAs**

- **Energy Resolution**:
  - 204 eV FWHM @ 59.5 keV
  - (Fano limit: 410 eV FWHM)

- **Temperature and Voltage**:
  - T = -30°C
  - ENE = 204 eV FWHM
  - (20 e- r.m.s.)

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59.5 keV line analysis

- No significant charge trapping
- Fano factor: $F = 0.124 \pm 0.004$

$^{241}$Am 59.54 keV
- 501 ± 5 eV FWHM

Pulser
- 283 ± 1 eV FWHM

Is the Charge Collection Efficiency 100 % ?
Charge trapping in GaAs detectors

\[ CCE = \frac{Q_{\text{ind}}}{Q_{\text{gen}}} \]

\[ Q_{\text{gen}} = \frac{E_{\text{ph}}}{\varepsilon} \]

Accurate knowledge of the electron-hole pair generation energy required
Generation Energy in GaAs

\[ \varepsilon = 4.55 - 0.00122 \ T \ [\text{eV}] \]

\[ \varepsilon = 4.18 \pm 0.02 \text{ eV} \]

Bertuccio, Maiocchi, JAP 92, 2002
Charge Collection Efficiency

\[
CCE = \frac{\lambda_e + \lambda_h}{W} \left(1 - e^{-\frac{W}{\lambda_e + \lambda_h}}\right)
\]

\[\lambda_e + \lambda_h = 1400 \mu m @ 110 V\]

CCE \geq 99 %

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Conclusions on tested GaAs pixel

• High resolution with epi-GaAs pixels
  – 242 eV FWHM @ 20°C
  – 163 eV FWHM @ -30°C
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- Main noise component: dielectrics (with discrete electronics)
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- Leakage current density: \( \leq 10 \text{ nA/cm}^2 \) @ 20°C
Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
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- Main noise component: dielectrics (with discrete electronics)

- Leakage current density: \( \leq 10 \text{ nA/cm}^2 \) @ 20°C

- Mean drift length: up to 1.4 mm (CCE > 99% for 30 \( \mu \text{m} \))
Conclusions on tested GaAs pixel

- High resolution with epi-GaAs pixels
  - 242 eV FWHM @ 20°C
  - 163 eV FWHM @ -30°C

- Main noise component: dielectrics (with discrete electronics)

- Leakage current density: \( \leq 10 \text{ nA/cm}^2 @ 20°C \)

- Mean drift length: up to 1.4 mm (CCE>99 % for 30 µm)

- **Limits:** depletion layer depth (detection efficiency)
  - residual doping \( 10^{14} \text{ cm}^{-3} \)
  - Epi layer thickness: 40 µm
GaAs pixel detectors

Status

- Good Schottky and p⁺n junction detectors exists!
- Epitaxial thickness >300 µm has been grown (Poster: Glasgow-Paris)
GaAs pixel detectors

**Status**

- Good Schottky and p+n junction detectors exists!
- Epitaxial thickness >300 µm has been grown (Poster: Glasgow-Paris)

**Prospects**

- Energy resolution of 180 eV FWHM are reachable at 20°C
- Residual doping \( \leq 10^{13} \text{ cm}^{-3} \) required
- Integrated spectroscopic-grade front-end electronic required
GaAs pixel detectors

Status

• Good Schottky and p+n junction detectors exists!

• Epitaxial thickness $>300\ \mu m$ has been grown (Poster: Glasgow-Paris)

Prospects

• Energy resolution of 180 eV FWHM are reachable at 20°C

• Residual doping $\leq 10^{13}\ cm^{-3}$ required

Integrated spectroscopic-grade front-end electronic required
Large Format Detector Readout ASIC

D. Martin, A. Owens  
EUROPEAN SPACE AGENCY, ESA-ESTEC - Noordwijk (NL)

P. Bastia, I. Cappelluti, F. Ferrari, N. Ratti  
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“Prospects for Energy Resolving X-ray Imaging with Compound Semiconductor Pixel Detectors”
**LFDR ASIC (designed – in production)**

- 0.35 µm CMOS (AMS)
- 16 x 16, 32x32, 64x64 pixel channels
- 300 x 300 µm² channel size
- Complete: Preamplifier → ADC
- Spectroscopic grade - 500 µW/channel (simulated)
- 30 electrons r.m.s. @ 20°C (simulated)
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Silicon Carbide X-Ray Detectors
Silicon Carbide X-Ray Detectors

- Introduction on SiC
Silicon Carbide X-Ray Detectors

- Introduction on SiC
- Prototype detectors
Silicon Carbide X-Ray Detectors

- Introduction on SiC
- Prototype detectors
- X-ray spectroscopy at room temperature…and above
Silicon Carbide X-Ray Detectors

- Introduction on SiC
- Prototype detectors
- X-ray spectroscopy at room temperature…and above
- SiC Pixel detectors: a sub-electron electronic noise device
SiC politypes

3C-SiC
\( (E_G = 2.2 \text{ eV}) \)

4H-SiC
\( (E_G = 3.3 \text{ eV}) \)

6H-SiC
\( (E_G = 3 \text{ eV}) \)
SiC properties

- **Wide Bandgap**
  - $E_G = 3.2$ eV

- **Low thermally generated currents**

- **Room temperature operation**

- **High frequency/speed devices**
  - $v_s = 200 \, \mu$m/ns

- **Short transit time**

- **Low trapping probability**

- **High Critical Field**
  - $E_C = 2$ MV/cm

- **High Voltage devices**

- **High thermal conductivity**

- **High Power devices**

- **High Voltage devices**

SiC properties:

- **High saturation velocity**
  - $v_s = 200 \, \mu$m/ns

- **High frequency/speed devices**

- **Short transit time**

- **Low trapping probability**

- **High Voltage devices**

- **High Power devices**
SiC High Performance Electron Devices…
...a reality
SiC High Performance Electron Devices

The highest $V_B$ diode

Power MOSFET: $5 \text{ kV} - 88 \text{ m}\Omega \text{ cm}^2$

High Power X-Band MESFET

$V_B = 19 \text{ kV}$

$T=14.5 \text{ GHz}$, $f_{\text{MAX}}=38 \text{ GHz}$

$I_{\text{Dmax}} = 400 \text{ mA}$, $V_{\text{DSmax}} = 150 \text{V}$

Gain: $16 \text{ dB} @ 2 \text{ GHz}$
Would SiC be advantageous for X-Ray Spectroscopy and Imaging?
Can SiC compete with Si? (!)

\[ \lambda_{\text{SiC}} \leq \lambda_{\text{Si}} \]
**Electron-hole pairs : Signal !**

\[ Q = \frac{E_{ph}}{\varepsilon} \]

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>( E_{\text{GAP}} )</th>
<th>( \varepsilon )</th>
<th>e-h pairs @ 10 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>0.7</td>
<td>3.0</td>
<td>3.3 k</td>
</tr>
<tr>
<td>Si</td>
<td>1.1</td>
<td>3.7</td>
<td>2.7 k</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.4</td>
<td>4.2</td>
<td>2.4 k</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.5</td>
<td>4.5</td>
<td>2.2 k</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.3</td>
<td>7.8</td>
<td>1.3 k</td>
</tr>
</tbody>
</table>

**What about the SiC detector noise ?**
Detector noise sources

- Leakage current
- Carriers trapping phenomena
- Dielectric noise
- [Charge collection process (balistic deficit → signal reduction)]
Run of SiC X-Ray Detectors
(Technology: Alenia Marconi Systems - Rome)
(SiC wafers: CREE Inc., USA)

Array of pixels

Schottky contact - Au

- n - epilayer $5 \times 10^{14}$ - 70 $\mu$m
- n+ buffer 1 $\mu$m
- n+ substrate - 320 $\mu$m

ohmic contact - Ti/Pt/Au
I-V Characteristics

Forward bias

Reverse bias

Schottky Barrier Height: $\Phi_b = 1.16$ eV

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**Leakage Current Density**

State of the art detectors

- CdZnTe
- 4H-SiC (Epi)
- CdTe
- GaAs (VPE)
- GaAs (SI LEC)
- Silicon

**Current density** $[\text{A/cm}^2]$

**Mean electric field** $[\text{kV/cm}]$

- $1\ n\text{A/cm}^2$
- $5\ p\text{A/cm}^2$

- Room Temperature
- 200
- 4H-SiC (Epi)
Temperature effect: SiC vs. Si

![Graph showing current density vs. mean electric field for Silicon and 4H-SiC at different temperatures (67°C, 47°C, 27°C).]
Experimental Results on SiC Detectors

Tested devices

- Pixel detector: area=0.03 mm$^2$ ; capacitance: 0.17 pF
- Pad detector : area= 0.3 mm$^2$ ; capacitance : 1.7 pF
SiC detectors at 27 °C (300 K)

Pad: A=0.3 mm²

Pixel: A=0.03 mm²

Energy resolution
415 eV FWHM (22 e⁻ r.m.s.)

Energy resolution
315 eV FWHM (17 e⁻ r.m.s.)
SiC pixel at 27 °C (300 K)

Energy resolution: 315 eV FWHM (17 e⁻ r.m.s.)
Beyond Room Temperature...
Operation beyond room temperature?

E = 100 kV/cm, T = 27 °C → J_R = 14 pA/cm^2

T = 100 °C → J_R = 0.5 nA/cm^2
High temperature set-up

SiC Detector

Preamplifier

Termoresistance

Thermo-controller

Front-end
Energy resolution: 330 eV FWHM (18 e⁻ r.m.s.)
$63\,^\circ\text{C} \ (336\,\text{K} - 145\,\text{F})$

Energy resolution: $386\,\text{eV FWHM} \ (21\,\text{e}^-\,\text{r.m.s.})$
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Energy resolution: 522 eV FWHM (28 e⁻ r.m.s.)
100 °C (473 K - 212 F)

Energy resolution: 797 eV FWHM (43 e⁻ r.m.s.)

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SiC pixel detector: from 27 °C to 100°C

At high T the resolution is limited by the Front-end, NOT by the detector
Prototype of SiC Pixel Matrix

- 4 x 4 matrix
  - Pixel size: 400 \( \mu m \times 400 \mu m \)

- 6 x 6 matrix
  - Pixel size: 250 \( \mu m \times 250 \mu m \)
Pixel Forward Bias Characteristic

Saturation current

\[ I_s = 3.5 \cdot 10^{-18} \text{A} \]

Ideality factor

\[ n = 1.06 \]

Absolute Current [A] vs Voltage [V] for Pixel MM-W5-400-11 at T = 28°C.

Saturation current \( I_s \) = 3.5 \cdot 10^{-18} \text{A}

Ideality factor \( n \) = 1.06
Measurement of the Pixel Leakage Current

The problem…

SiC Pad detectors: \( J_{\text{SiC}} = 5 - 15 \text{ pA/cm}^2 \)

Current density of a pixel?

\( J = 5 - 100 \text{ pA/cm}^2 \), Area = 400 x 400 \( \mu \text{m}^2 \)

\[ \text{I}_{\text{REV}} = 8 \text{ fA} - 160 \text{ fA} !!!! \]
Instrumentation and device noise

Electrometer noise

Test-fixture /device

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Pixel Reverse Bias Characteristic

Room Temperature

Reverse Current [fA] vs. Reverse Voltage [V]

Current Density [pA/cm²]

27 °C

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SiC Pixel
Reverse Bias Characteristic

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Reverse Current Map

Leakage Current E.N.C.

@ 27 °C @ 10µs

I = 274 fA : 1 pixel = 5.8 e-
I = 98 fA : 1 pixel = 3.5 e-
I = 36 fA : 1 pixel = 2 e-
I < 10 fA : 12 pixel < 1 e- r.m.s.
Summary

- SiC has the same absorption length as Si
Summary

• SiC has the same absorption length as Si

• SiC can give superior resolution at certain T and Areas
Summary

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• SiC can give superior resolution at certain T and Areas

• Pixel and pad detectors have been fabricated and tested
Summary

- SiC has the same absorption length as Si
- SiC can give superior resolution at certain T and Areas
- Pixel and pad detectors have been fabricated and tested

- Leakage currents: 5 - 14 pA/cm² @ 27 °C
  500 pA/cm² @ 100°C
Summary

• SiC has the same absorption length as Si

• SiC can give superior resolution at certain T and Areas

• Pixel and pad detectors have been fabricated

• Leakage currents: 5 - 14 pA/cm² @ 27 °C
  500 pA/cm² @ 100°C

• SiC pixel detector: 315 eV FWHM @ 27 °C
  797 eV FWHM @ 100 °C
Summary

• SiC has the same absorption length as Si

• SiC can give superior resolution at certain T and Areas

• Pixel and pad detectors have been fabricated

• Leakage currents: 5 - 14 pA/cm² @ 27 °C
  500 pA/cm² @ 100°C

• SiC pixel detector: 315 eV FWHM @ 27 °C
  797 eV FWHM @ 100 °C

• SiC pixel: toward sub-electron (Fano limited) noise
Prospects for SiC detectors: Limits and needed...

• Thicker epi-SiC layers: $t > 100 \, \mu\text{m}$ (now: 50-70 $\mu\text{m}$)

• Ultra-low doping and pure SiC: $N \leq 10^{13} \, \text{cm}^{-3}$ (now: $> 5 \times 10^{13}$)

• High purity semi-insulating SiC (?)

• Ultra low noise front-end at room and high temperature
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Dr. Marco Mandena – Politecnico di Milano