Development of high-Z sensors for pixel array detectors

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Vertex 2010, Loch Lomond, 6-11 June 2010
Development of high-Z sensors for pixel array detectors

- Applications of high-Z pixel arrays
- Overview of high-Z sensors
  - CdTe / CZT
  - GaAs
- Work on pixellated Ge sensors at DESY
- Summary
High-Z materials for X-ray absorption

X-ray absorption / interaction

Proportion absorbed / interacting

- Silicon (500um)
- Ge / GaAs (500um)
- CdTe (500um)

X-ray energy (keV)

Z=13
Z≈32
Z≈50
High-Z materials for X-ray absorption

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- Z=13
- Z≈32
- Z≈50

- 7μm Fe, 2 mm H₂O
- 400μm Fe, 4 cm H₂O
- 4 mm Fe
PETRA-III at DESY
- Beamline energies to 150keV (mostly 50keV)
- Materials science apps

High-E scattering and tomography
- Structure at buried interfaces, grain mapping...

Most promising application
- Si pixels already successful
- Tolerance of expense and infrastructure
Imaging with a high-E, broad spectrum source

- 15-25 keV mammography
- 30-120 keV torso

Hybrid pixels allow energy measurement

- Distinguish tissue, bone, contrast

Biological research (small animal)

Medical imaging

- Cost / infrastructure
- Tiling of large areas

Johnson 2007 - Material differentiation by dual energy CT: initial experience
Collaborations

> **HiZPAD (Hi-Z sensors for Pixel Array Detectors)**
  - ESRF (coordinator), CNRS/D2AM, DESY, DLS, ELETTRA, PSI/SLS, SOLEIL
  - CPPM, RAL, University of Freiburg FMF, University of Surrey, DECTRIS
  - Predominantly processing / bonding / testing of commercial CdTe, CZT

> **Medipix3**
  - See Richard Plackett’s talk
  - *Inter-pixel communication* allows thick high-Z sensors
Development of high-Z sensors for pixel array detectors

- Applications of high-Z pixel arrays
- **Overview of high-Z sensors**
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Which high-Z material to use?

X-ray absorption / interaction

Proportion absorbed / interacting

X-ray energy (keV)

- Red: Silicon (500um)
- Yellow: Ge / GaAs (500um)
- Blue: CdTe (500um)
Fluorescence effects

> Absorption by k-shell can produce high-E fluorescence photons
  - >~30keV for CdTe
  - >~10keV for GaAs and Ge

> Degrades performance above k-shell E

> Effect greater in higher-Z material
  - Higher fluorescence yield
  - Longer absorption lengths

> Inter-pixel communication could compensate

![Diagram of 40keV photon in CdTe](image-url)
Fluorescence effects

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General issues with high-Z sensors

> (Mostly) compound semiconductors
> Material quality
  - Charge trapping – one carrier produces most of signal
  - Leakage current, resistivity
> Material homogeneity and area
  - Grain boundaries – want single crystal
  - Dislocations, inclusions
> Pixellation
  - Diode, Schottky, resistive...
> Bump bonding
  - Temperature tolerance
Cadmium Telluride

> Used for γ-ray spectroscopy
> Commercially-grown wafers:
  - Single-crystal now 3”, 1mm-thick
  - Defects affect uniformity
> Properties
  - 1.44eV bandgap (room T)
  - High resistivity
  - \( \mu_e T_e \approx 3 \times 10^{-3} \text{ cm}^2/\text{V} \)
    - Mean drift distance of cm
    - Use electron readout!
  - \( \mu_h T_h \approx 2 \times 10^{-4} \text{ cm}^2/\text{V} \)
    - Mean drift distance of mm

Szeles 2003, CdZnTe and CdTe materials for X-ray and gamma ray radiation detector applications
Cadmium Telluride

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Cadmium Telluride

- Typically use Schottky or ohmic contacts (Pt, Au, In)
- Temperatures above 200°C degrade transport properties
  - Low temp sputtering / electroless deposition of contacts
- Low-temp bump bonding (Pb/Sn, In)
  - CdTe relatively fragile
- Demonstrated with Medipix2, XPAD3
CdTe Medipix2 Assemblies

1mm CdTe (Acrorad, 3”)
- Ohmic pixel contacts

QUAD (2x2) 110 µm pixel pitch
28x28 mm² active area
Flat field corrected

Hexa (2x3) 55 µm pixel pitch
28x43 mm² active area, 390,000 pixels
Flat field & filter

Produced by
A. Fauler, A. Zwerger, M. Fiederle
Freiburger Materialforschungszentrum FMF
Albert-Ludwigs-Universität Freiburg
CdZnTe

> Typically Cd$_{0.9}$Zn$_{0.1}$Te
  - Increased bandgap (1.57eV) – lower current
  - Better single-element spectroscopic performance

> Produced in large polycrystalline ingots
  - Crystal properties vary between grains
  - Good single-crystal segments up to 20*20mm$^2$
Gallium Arsenide

- Better single-crystal production (6”)
- 1.43eV bandgap (low leakage)
- $\mu_e >> \mu_h$
  - Short hole mean drift distance (100’s of $\mu$m)
  - Rely on electron readout
- Problem: Shallow defects – low resistivity
- Semi-insulating GaAs
  - Compensation of shallow defects
  - Operated as photoconductor / Schottky
- Epitaxial GaAs
  - Growth with fewer shallow defects
  - Operated as diode
Gallium Arsenide – Semi insulating

> As-rich growth produces deep defects (EL2)
  - Compensate shallow traps
  - But reduce electron lifetime (~1ns)

> **Cr** compensation promising
  - Dope n-type during growth, then overcompensate p-type with Cr diffusion

> Metallised contacts
  - Au for photoconductor (right)
  - Pt-Ti-Au for Schottky

> Moderate temp tolerance, physically fragile
  - Bonding at low temp
  - Indium / low T solder

JINR Dubna, Tomsk State University
Chromium-compensated GaAs

> Medipix2
> 300µm thick (1mm possible)
  - Photoconductive sensor
  - Operated at 500V here
> Full active volume, 90% CCE

L. Tlustos (CERN), Georgy Shekov (JINR Dubna), Oleg P. Tolbanov (Tomsk State University)
“Characterisation of a GaAs(Cr) Medipix2 hybrid pixel detector”, IWorld 2009
Epitaxial GaAs

> VPE growth of GaAs substrate
  - P-i-n structure grown
  - Etching of mesa to form pixels
  - Thinning of material before bonding

> Thickness limited
  - 140μm sensor required cooling to -20°C

Kostamo 2008, “GaAs Medipix2 hybrid pixel detector”
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Germanium pixels

- High-purity, high uniformity 95mm Ge wafers available
  - Negligible trapping
  - Low doping
- Narrow bandgap means cooled operation needed
  - *Per pixel* current must be within ROC limits (order of nA)
  - Est. -50°C operation with Medipix3 (55μm)
  - Need to consider thermal contraction, etc.
  - "Engineering problems"
- Fine pixellation and bump-bonding must be developed
Pixel detector production at Canberra (Lingolsheim)

> Diodes produced by lithography (p-on-n)
  - Thinned germanium wafer (0.5-1.5mm)
  - Li diffused ohmic back contact
  - Boron implanted pixels
  - Passivation, Al metallisation

> Plan 55μm, 110μm and 165μm Medipix3
  - First run singles (14*14mm²), 500μm
  - Second run 2*3 (28*42mm²)
    - Option of thicker Ge

M Lampert, M Zivic, J Beau
Bump bonding at Fraunhofer IZM (Berlin)

- Low temp bonding required
- Bonds must tolerate thermal contraction
  - 3.5μm max displacement for ΔT=100K
  - In remains ductile at LN₂!
- Indium bump bonding
  - Bumps on ASIC and sensor
  - Thermosonic compression at low T
  - Possible reflow above 156°C
- Currently performing tests on Ge diodes
Medipix3 module readout

> 2*6 chip module (28*85mm)
  - Tilable
  - Full-parallel readout (2000fps)
> Cooling through thermal vias
  - Ceramic and heat spreader match Ge CTE
> Readout FPGA board
  - 10 GBE for high-speed readout
  - Improved infrastructure needed
Conclusions

> Demand for high-Z hybrid pixels
  - Material science, biology / medicine, astronomy...

> Promising results from CdTe / CZT, GaAs
  - Commercial CdTe / CZT improving
  - Improved GaAs compensation

> Ge pixels could provide high-uniformity sensors (albeit without room-temp operation)
Thanks for listening
What do hybrid pixels offer?

> Current generation (Pilatus, Medipix2, XPAD2/3)
  - Noise rejection (photon counting)
  - High speed
  - Direct detection for small PSF

> Future detectors (Eiger, Medipix3, XPAD3+)
  - Deadtime-free readout
  - Inter-pixel communication (Medipix3)
    • Correct for charge sharing
    • Allows use of thick sensors
  - Energy measurement
    • Medipix3 provides 2 or 8 bins (55μm or 110μm)
> 256 * 256 pixels, 55µm pitch
  ▪ 14.1 * 14.1 mm² area
> Photon counting
> 2 counters / pixel (12bit)
  ▪ Continuous R/W
  ▪ or 2 energy bins
> Charge summing mode
> Optional 110µm pixels
  ▪ 8 energy bins
> 2000fps
  ▪ More with reduced counter depth
Medipix3

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Signal summing at nodes:
Node with highest signal “wins”
Medipix3 circuitry

2 counters allow continuous read-write
Effects of charge sharing

- Loss of efficiency at pixel corners
  - Typically, set threshold to E/2 with mono beam
- Loss of energy resolution
Medipix3 charge summing mode

> Allows large sensor thickness while maintaining energy resolution
  
  - No efficiency loss unless charge cloud > pixel size
Alternative methods of processing Ge

- Mechanical segmentation of contacts
  - Frequently used for large sensors
  - Limits on pitch
- Amorphous Ge contacts (e.g. LBNL, LLNL)
  - Similar to Schottky
  - Higher leakage current
  - *but* allows double-sided strips