LAMBDA, High-Z sensors and the HORUS simulation tool

David Pennicard - DESY
Overview

> LAMBDAA (Large Area Medipix3-Based Detector Array)
  - Photon-counting detector for PETRA-III
  - Basis for high-Z sensor development

> High-Z pixel detector development
  - Germanium
  - Gallium arsenide
  - Cadmium telluride

> HORUS simulation tool
  - Medipix and high-Z sensor example
Large Area Medipix3-Based Detector Array (LAMBDA)

> David Pennicard, Sergej Smoljanin, Sabine Lange, Bernd Struth, Helmut Hirsemann, Milija Sarajilic, Heinz Graafsma – DESY

> Michael Epple – Technical University of Munich

> Thanks to the Medipix3 collaboration
Large Area Medipix3-Based Detector Array (LAMBDA)

- Photon-counting hybrid pixel detector based on Medipix3 chip
- 55µm pixel size, tileable layout 1536 x 512 pixels (85mm x 28 mm)
- High-speed readout up to 2000 frames per second (in progress)
- Compatible with high-Z sensor materials
Medipix3 readout chip

> CERN-led collaboration (20 institutes)
  - Flexible design
  - 256 by 256 array of 55µm pixels

2 photon-counting thresholds available

Interpixel communication

2-stage amplifier

2 x 12-bit counters per pixel
Medipix3 readout chip

> Synchrotron use – 2 counters for deadtime-free operation
  - 2000 frames per second with 200MHz readout & 12-bit depth
  - 4000 frames per second (+?) with 6-bit depth

> But also possible to have 24 bit counter depth, multiple energy bins …

> Charge summing compensates charge sharing (more later in simulation part)
Detector head

- 6 by 2 chips (1536 by 512 pixels)
  - Large Si sensor
    - 300µm Si sensor here
  - 2 x “Hexa” high-Z sensors

- Ceramic circuit board (LTCC)
  - Good match to semiconductor CTE
  - Cooling through thermal vias

- 500-pin connector on board
  - Full parallel readout (8 LVDS data outputs per chip)
High-speed electronics

- DESY high-speed readout card (also used for AGIPD and PERCIVAL)
  - Virtex-5 FPGA with PowerPC
  - Up to 4 * 10 Gigabit Ethernet links
  - DDR2 RAM (8GB)

- “Signal distribution” board connects to det. head
  - Space for vacuum barrier with germanium detector
High-speed electronics

> Firmware development
  - 1 GE link for control and monitoring
  - Currently 1 x 10G readout
    - Recently tested at 750 fps
  - Plan 3 x 10G readout for 2000 fps

> Data rate challenge!
  - Get ~1GB/s with one 10GE link
  - Rely on server PC with 256GB RAM
  - Limited run period before writing data to disk at lower speed
Test results with Si module
Work with LAMBDA detector

➢ Rheology experiments at PETRA P10
  ▪ Taking advantage of small pixel size
➢ Plan to use in XPCS (P10) and SAXS (P03) experiments
  ▪ Small pixel size and high frame rate
➢ Tests with high-Z sensors also planned
➢ Currently working on more modules, and multimodule systems
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High-Z pixel detectors

- **Aim:** replace silicon sensor in LAMBDA with high-Z semiconductor
  - Combine high QE with hard X-rays, high frame rate, high signal-to-noise
- **Investigating different materials in collaboration with other institutes and industry**
  - Germanium
  - Gallium arsenide
  - Cadmium telluride
Germanium pixel development

Canberra France (Lingolsheim): M Lampert, M Zuvic, J Beau

Fraunhofer IZM (Berlin): T Fritzsch, R Jordan, M Rothermund

- High-purity, high uniformity 90 mm Ge wafers available
- Cooled operation needed to reduce leakage current and allow depletion
  - Small pixel and photon counting mean LN$_2$ temp not necessary
    - Canberra reported -80°C needed for good depletion
  - However, cooling power relatively high (~1W per chip)
  - Lambda module designed to be cooled

- Fine pixellation and bump-bonding needed to be developed
Pixelated Ge detector production

- Sensors produced by Canberra France based on existing strip technology

- 2 high purity Ge wafers produced
  - 16 Medipix3 singles per 90mm wafer
  - 55µm pixel size
  - ~700µm thick
  - Electron readout

- Indium bump bonding at Fraunhofer IZM (Berlin)
  - Low-temperature process necessary to avoid damage to Ge
  - Ductility of indium prevents cracking of bonds during cooling
Testing of germanium sensors

- Batches bonded to Medipix3.0 and Medipix3RX chips
  - Results from most Medipix3RX shown (very recent!)
- Mounted on standard LAMBDA ceramic board
- Full system mounted in vacuum chamber
- Cryotiger cooling
- Tested with miniature X-ray tube (Ag target)
Recent tests with Medipix3RX chips

- Tested around -100°C to -110°C, 100V bias
- High pixel yield, generally uniform response
  - Edge pixels nonfunctional due to excessive leakage current

Flat illumination, Ag tube
Next steps with germanium

- Mechanics with high-speed readout outside vacuum
  - Vacuum barrier on signal distribution board

- Production of hexa sensors (3 x 2 chip, 768 x 512 pixel)
  - 2 per 90mm wafer
  - Requires overhaul of cooling system
Gallium arsenide

- GaAs already widely-used semiconductor
- Standard crystal growth can’t produce detector-grade material
  - Either low resistivity or very short carrier lifetime
  - Various solutions tried
- Chromium compensation method at RID Ltd, Tomsk

Technological cycle of manufacturing GaAs compensated with Cr

As a result the experimental values of resistivity are \((0.5-1) \times 10^9 \, \Omega\cdot\text{cm}\), which are more than an order higher as compared to the resistivity of structures on the basis of traditional LEC Si-GaAs.
Galapad project (GaAs LArge Pixel Array Detector)

> German-Russian partnership project

- RID Ltd (Tomsk) and JINR (Dubna) produce sensors
  - O Tolbanov, A Tyazhev, G Shelkov
- FMF (University of Freiburg) bump-bond to Medipix
  - A Zwerger, A Fauler, T Baumbach, S Procz, M Fiederle
- KIT (Karlsruhe) and DESY characterize and build readout system
  - E Hamann, A Cecilia
GaAs sensor production

> Single-chip devices
  - 256 x 256 pixels, 55\(\mu\)m pixel size
  - 500\(\mu\)m thickness, linear I-V response to -400V
  - Timepix or Medipix3.0 readout so far (Medipix3RX on the way)

> Hexa (3 x 2 chip) devices on 3” wafers in production
Test results with GaAs

- High pixel yield
- Poor uniformity in original image
  - Cell structure reflects growth process
  - (Probably) varying mobility-lifetime product
- Non-uniformities are stable and can be flat-field corrected reliably

Thanks to Simon Procz, Alex Fauler and Michael Fiederle (FMF / University of Freiburg)
Test results with GaAs

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Cadmium Telluride

- Longer-established technology for high-Z hybrid pixel detectors
  - Resistivity and carrier transport properties quite good
  - Still room for improvement in sensor uniformity

- Acrorad CdTe wafers
  - 3” wafers available

- Sensor production and bonding at FMF, Freiburg
  - Previously produced Medipix2, Timepix with CdTe
  - Ohmic contacts used to improve stability
    - Schottky junctions prone to polarization
Cadmium telluride sensor

- “Hexa” (3 x 2 chip) module with Medipix3RX received
  - 55µm pixels, 768 x 512 array
- Tested with LAMBDA readout system
Cadmium telluride sensor results

- Various nonuniformities: boundaries (correctable) and blobs of dead pixels
- Some change in nonuniformities over time – not fully tested

Flat image response with 40kV Mo tube
Cadmium telluride sensor results

- Various nonuniformities: boundaries (correctable) and blobs of dead pixels
- Some change in nonuniformities over time – not fully tested

Flat-field corrected image of USB stick
High-Z sensors

- All materials could be used for experiments
- Each material has strengths and weaknesses
  - Germanium technology now works – but high cooling power for large systems
  - GaAs – widespread but correctable nonuniformity – what results will we get with monochromatic beam?
  - CdTe – most well-established, still some problems with uniformity and stability

![Ge](image1.png)  ![GaAs](image2.png)  ![CdTe](image3.png)
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HORUS detector simulation toolkit

> HORUS – HPAD Output Response fUnction Simulator
  - Originally developed by Guillaume Potdevin for AGIPD (XFEL) detector
  - Expanded by Julian Becker and me for general purpose use

> Aim: Fast and flexible simulation of detector and experiment
  - Evaluate different detector designs
  - Determine which aspects of detector have biggest impact on performance
  - Hopefully uncover surprises

> Written using IDL (Interactive Data Language – Matlab-like)
  - Monte Carlo approach
  - Relatively simple models
    - Not finite-element physics model of sensor behaviour
    - Not aimed at maximum precision (though results generally good)
Typical simulation flow (photon counting detector)

Incoming photons (as image or list)

Detector geometry

Module tiling → Detector properties → Photon absorption → Charge collection → Noise, dispersion → Hit assignment

Sensor response

Fluorescence → Trapping

ASIC response

Loop over all photons in image

Output image from detector
Absorption of photon in sensor

Photoelectric absorption, fluorescence, Compton scattering

40keV photon

Absorption by Te, fluorescence

Absorption by Cd, fluorescence

CdTe
Charge collection model

- Collection time calculated (based 1-D field model)
- Gaussian charge cloud (diffusion from a point)
- Charge distribution integrated over pixels
- Charge trapping effects based on simple analytical weighting field
Good agreement with experiment using reported material properties and readout chip performance (e.g. 10ns electron lifetime)

Charge sharing & fluorescence peaks

23 keV photons, ~90% collection

Will charge summing improve our performance

> Feature of Medipix3RX chip

- Medipix3.0 charge summing had bug (reproducible in HORUS)

> 2 thresholds

> A low threshold is applied to each individual pixel

> If more than one is above threshold, the highest signal suppresses the others

> Then, a hit is registered if at least one neighbouring summing node is above its threshold

Single-pixel response used to perform arbitration
> Feature of Medipix3RX chip

- Medipix3.0 charge summing had bug (reproducible in HORUS)

> 2 thresholds

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Then, hit registered if at least one summing node over threshold
GaAs detector plus charge summing

![Graph showing the fraction of counts in energy bin versus threshold (keV) with different pixel locations.

- All pixels
- Centre pixel
- Neighbour pixel
- Other pixel

10ns electron lifetime]
GaAs detector plus charge summing

> Variation in trapping time should have less effect on count rate
GaAs detector plus charge summing

> Variation in trapping time should have less effect on count rate
Summary

- Monte Carlo detector simulation using relatively simple models
  - Aimed at flexible simulation of full detector systems
  - Not detailed finite element physics models

- Our code is available for use
  - Already used with Medipix, AGIPD, CSPAD (Cornell), LPD (RAL, UK)
  - david.pennicard@desy.de, julian.becker@desy.de
Thanks for listening