Development of high-Z sensors for pixel array detectors

David Pennicard, DESY

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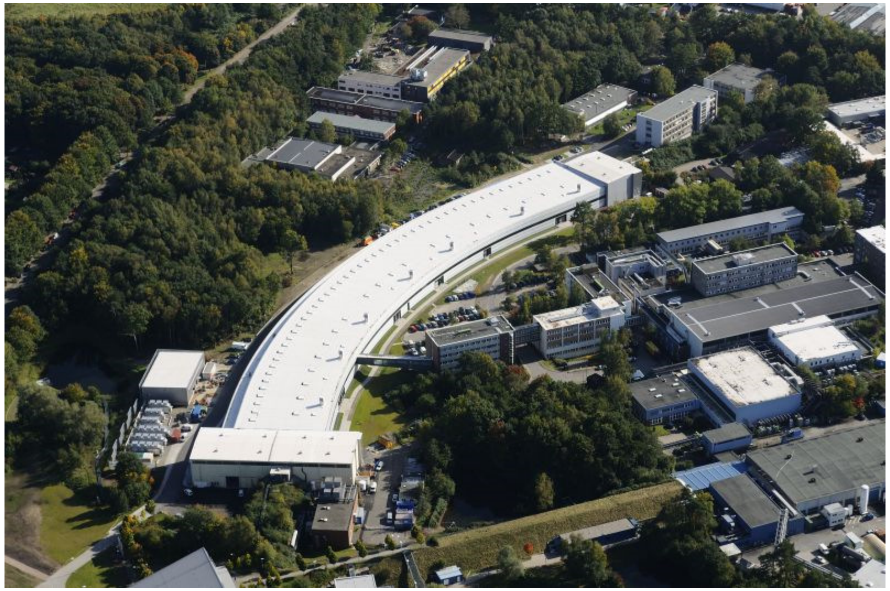
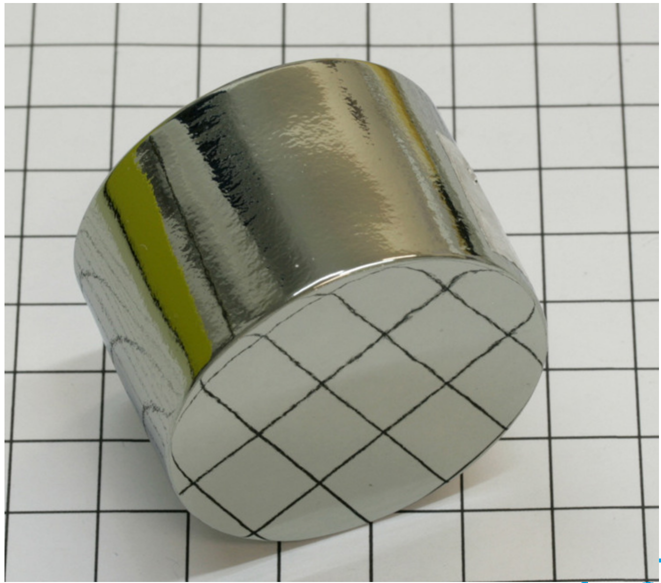
Vertex 2010, Loch Lomond, 6-11 June 2010





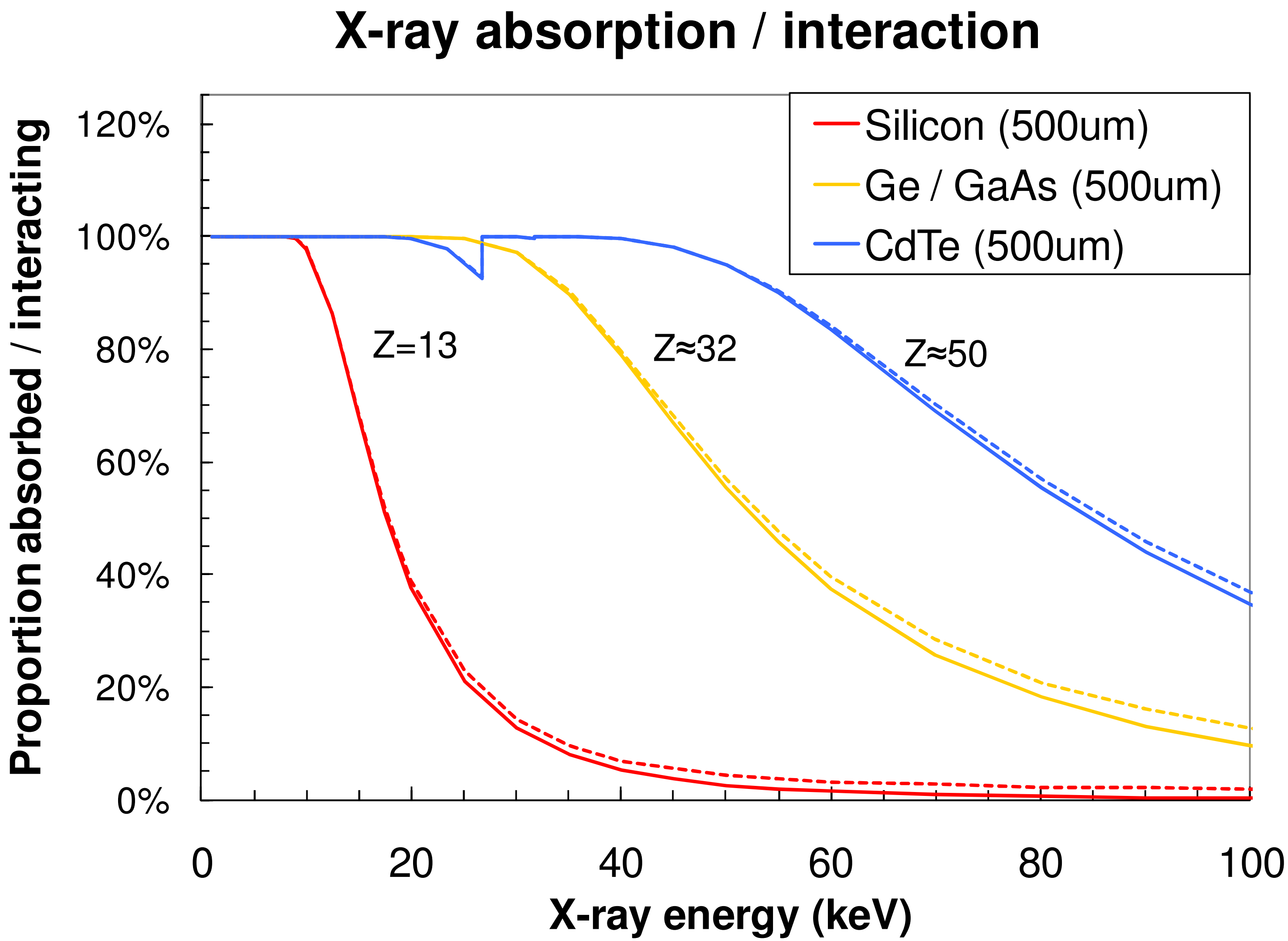
HELMHOLTZ | ASSOCIATION

DESY

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



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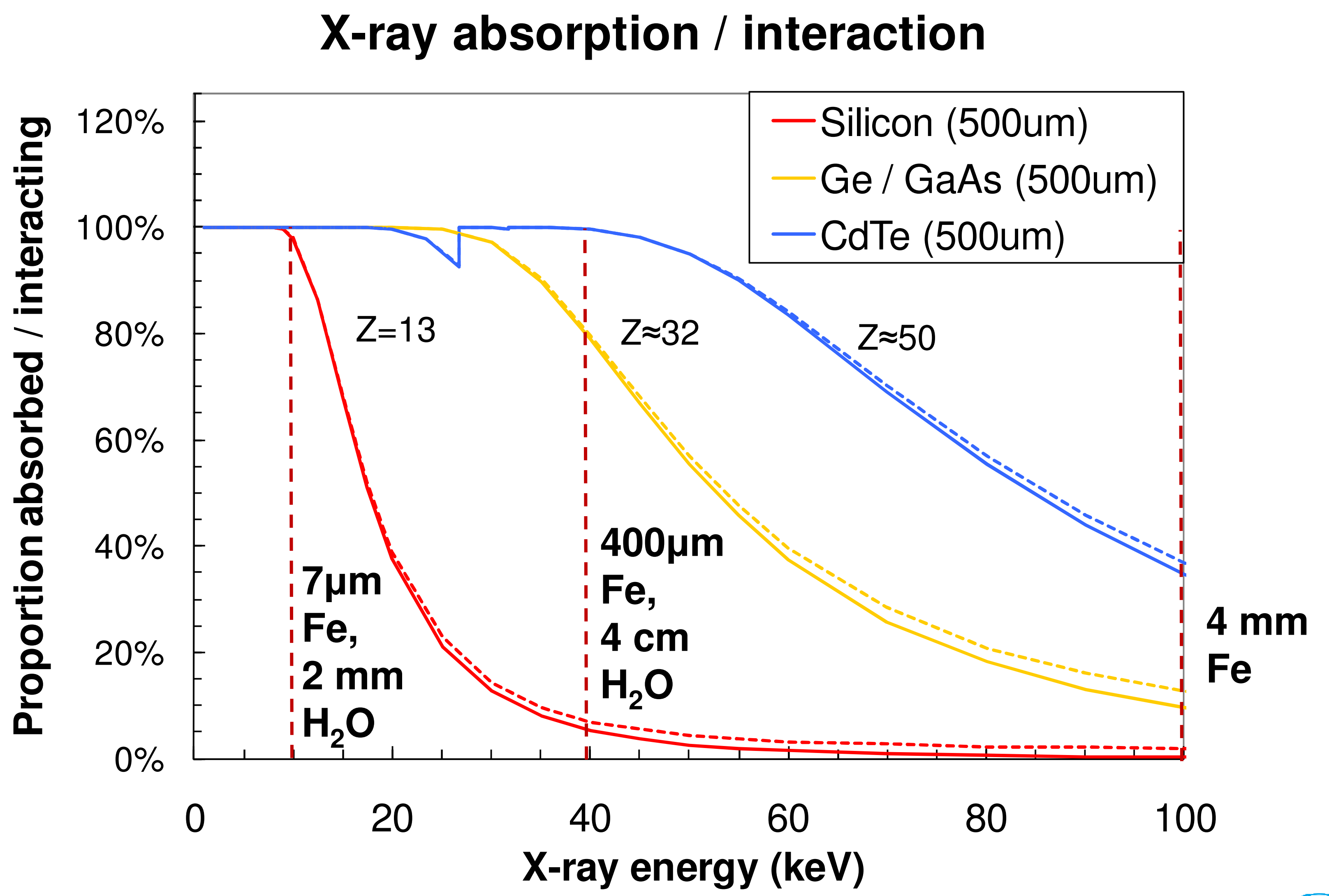
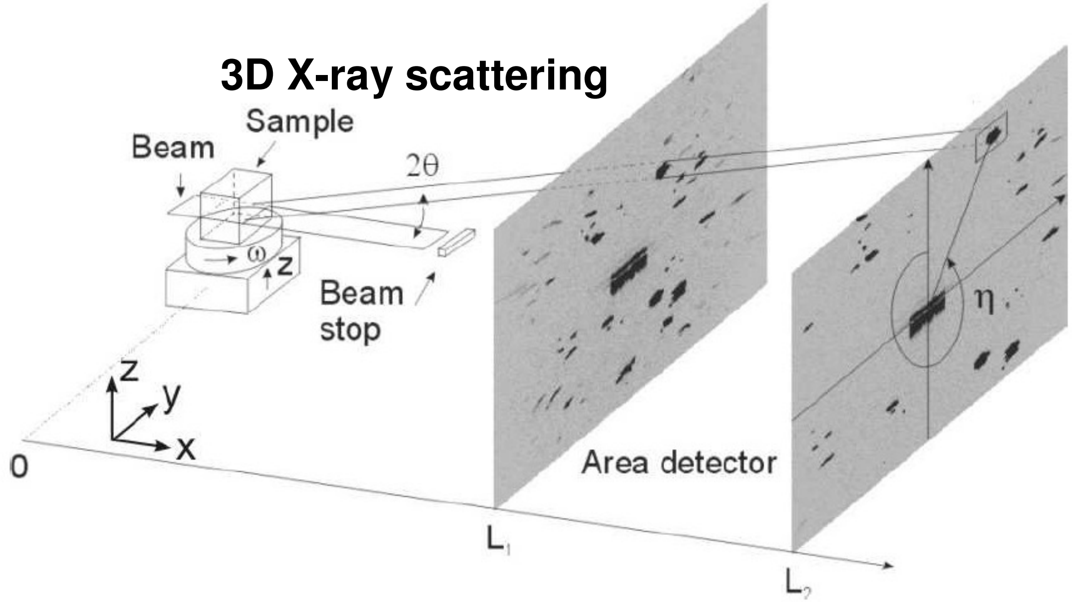


Synchrotron applications

> PETRA-III at DESY

- Beamline energies to 150keV (mostly 50keV)
- Materials science apps

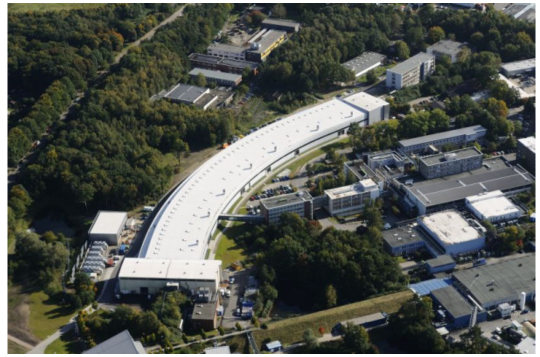


> High-E scattering and tomography

- Structure at buried interfaces, grain mapping...

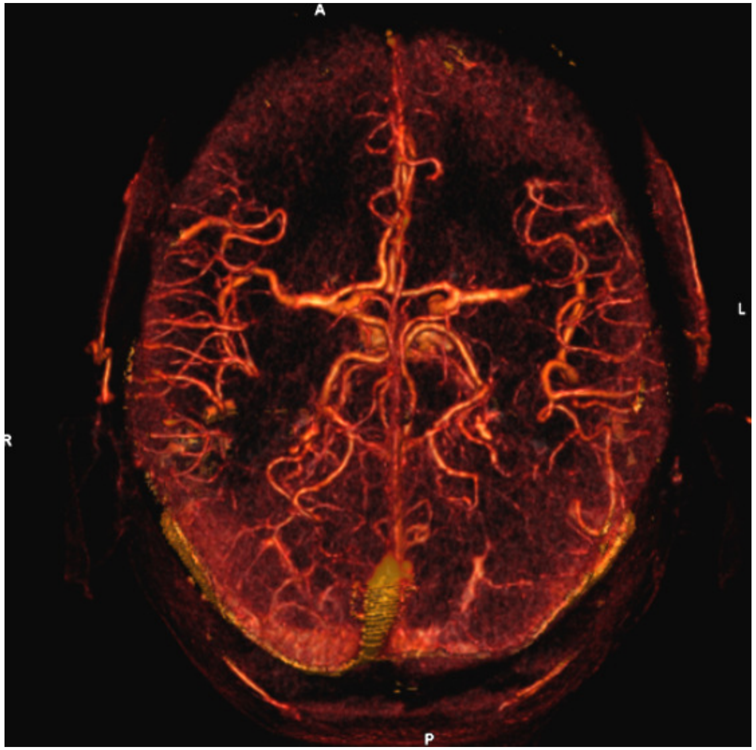
> Most promising application

- Si pixels already successful
- Tolerance of expense and infrastructure



Medical and small animal imaging / CT

- 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**
  - **CdTe / CZT**
  - **GaAs**
- > Work on pixellated Ge sensors at DESY
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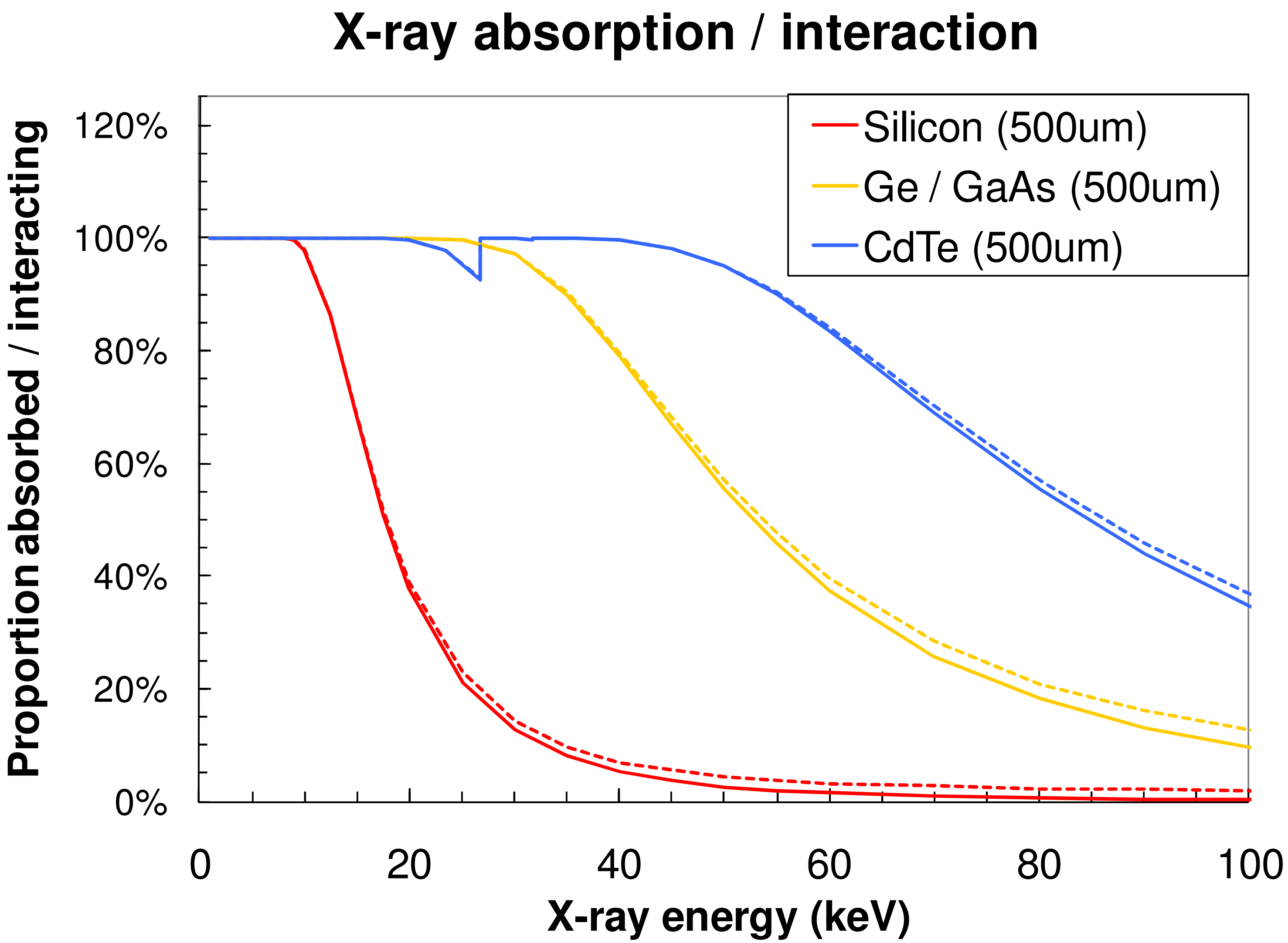
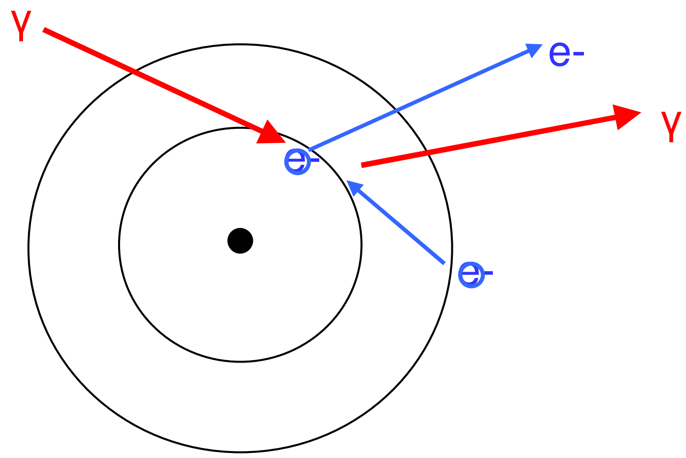
Which high-Z material to use?

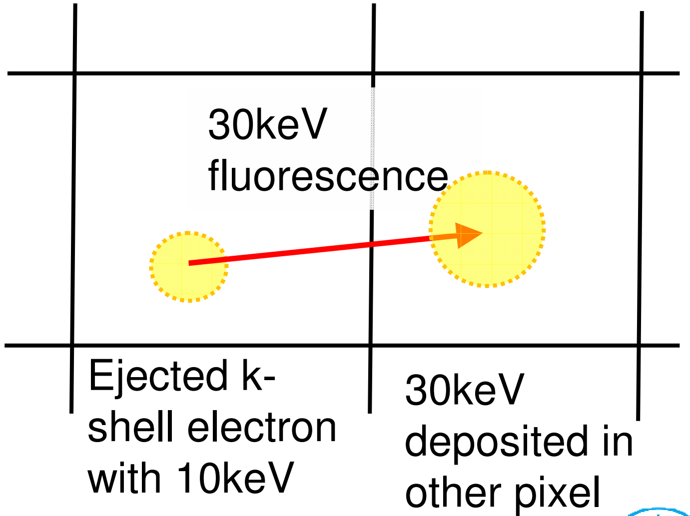


Fluorescence effects

- 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



40keV photon in CdTe



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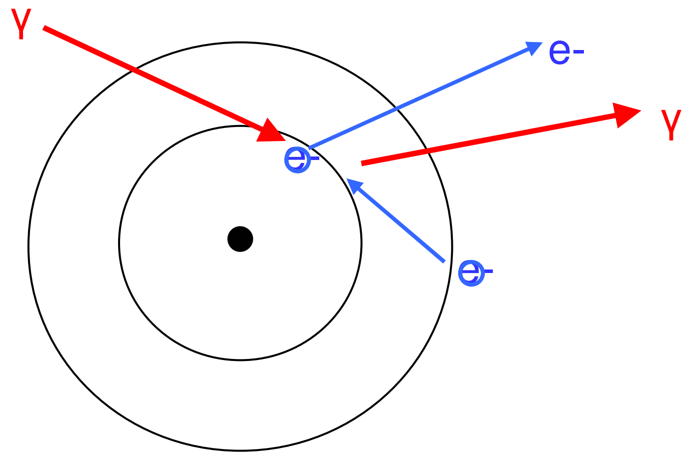

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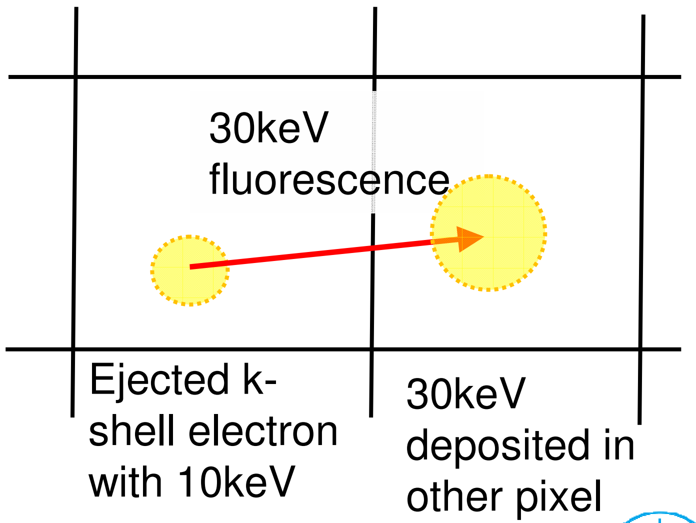
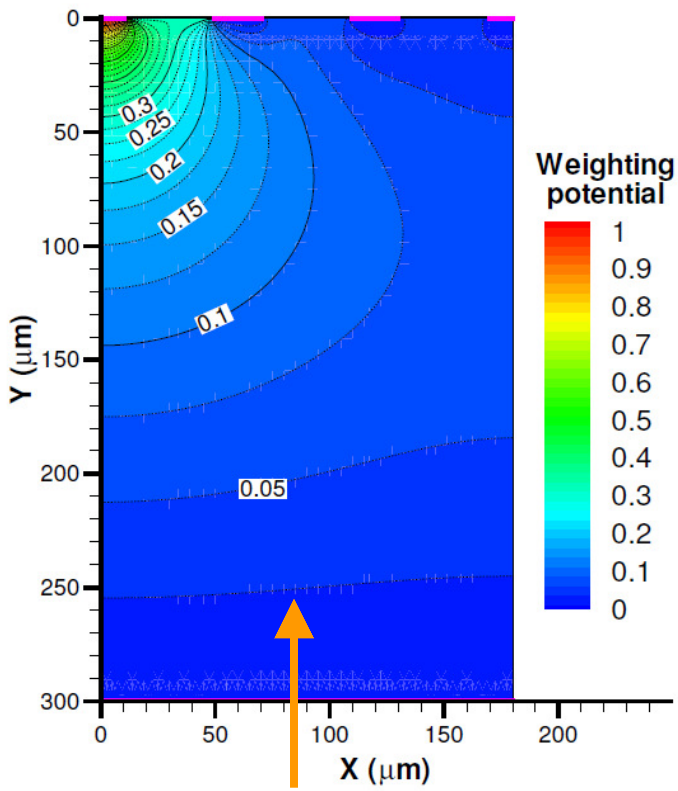


General issues with high-Z sensors

- (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

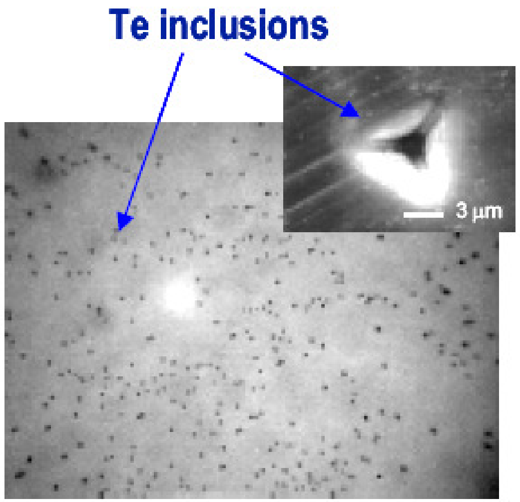
"Small pixel" effect

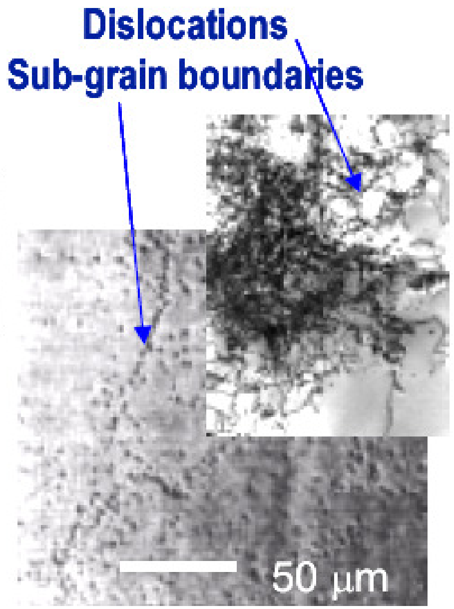


Irradiation from back surface

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
  - $\mu_e T_e \sim 3*10^{-3}$ cm^2/V
    - Mean drift distance of cm
    - *Use electron readout!*
  - $\mu_h T_h \sim 2*10^{-4}$ cm^2/V
    - Mean drift distance of mm





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

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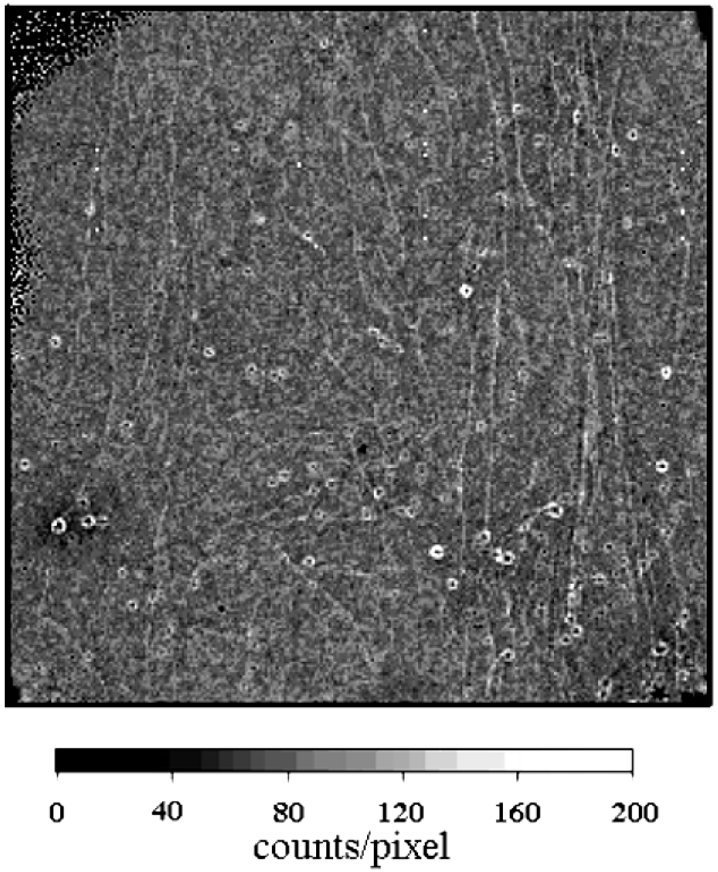
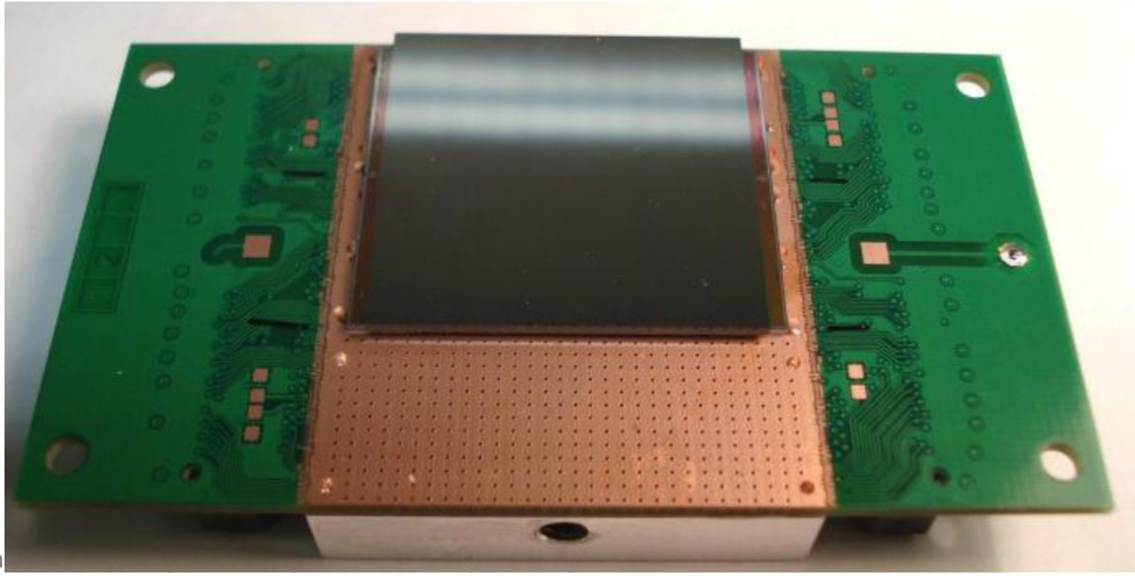


M. Chmeissani et al. 2004, "First Experimental Tests With a CdTe Photon Counting Pixel Detector Hybridized With a Medipix2 Readout Chip"

Cadmium Telluride

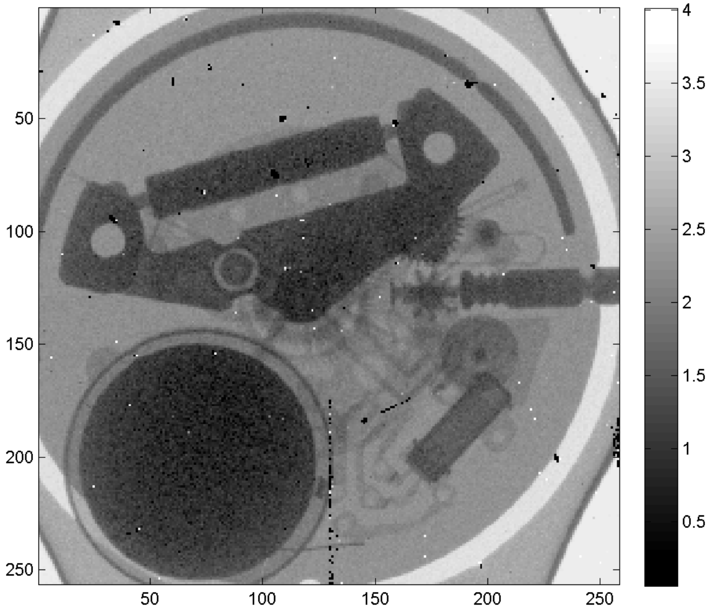
- Typically use Schottky or ohmic contacts (Pt, Au, In)
- Temperatures above 200℃ degrade transport properties
  - Low temp sputtering / electroless deposition of contacts
- Low-temp bump bonding (Pb/Sn, In)
  - CdTe relatively fragile
- Demonstrated with Medipix2, XPAD3



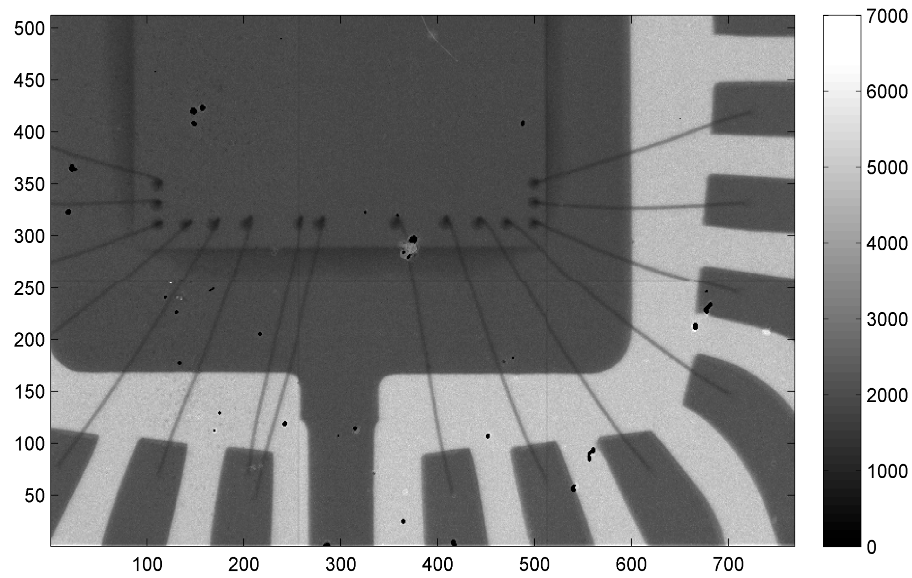
Medipix2 quad
(FMF)

CdTe Medipix2 Assemblies

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



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

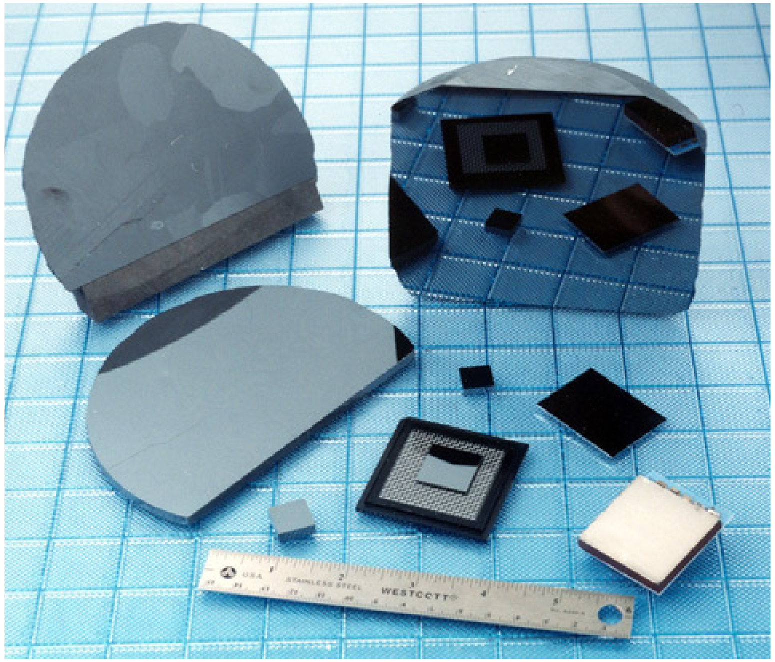


>Hexa (2x3) 55 µm pixel pitch
28x43 mm^2 active area,390,000 pixels
>Flat field & filter

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 I)
- > $\mu_e >> \mu_h$
  - Short hole mean drift distance (100’s of µm)
  - 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

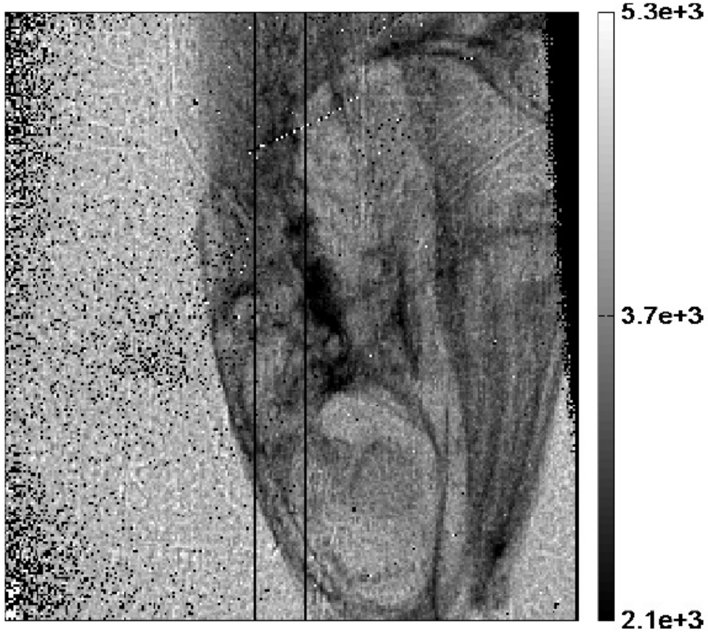
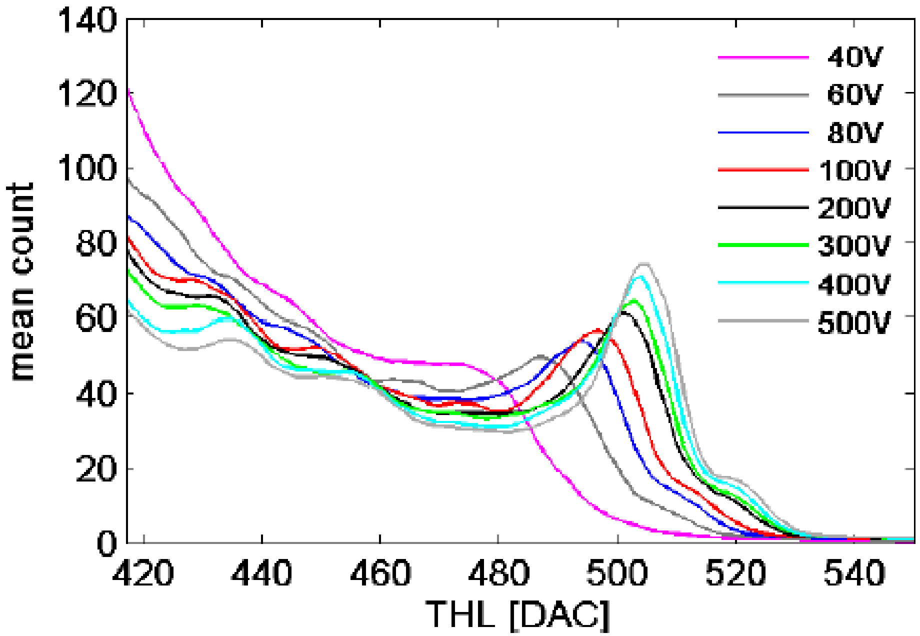


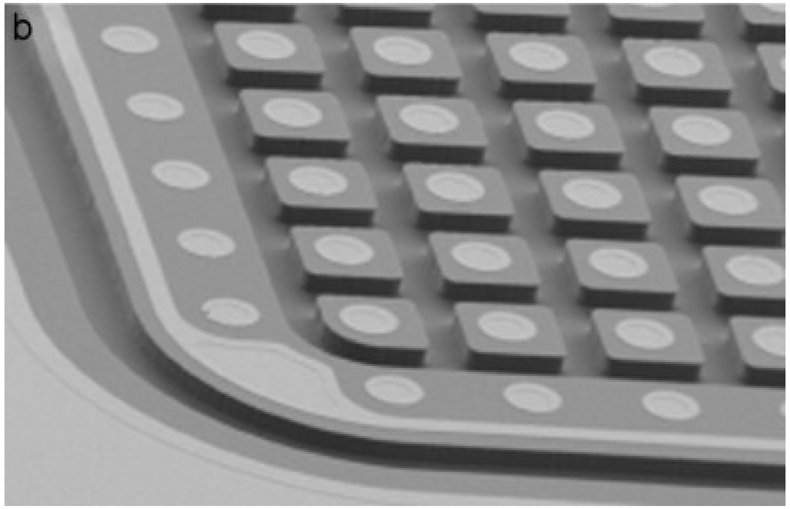
Figure 8: Flatfield corrected image of the head of an anchovy.



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



Kostamo 2008, “GaAs Medipix2 hybrid pixel detector”

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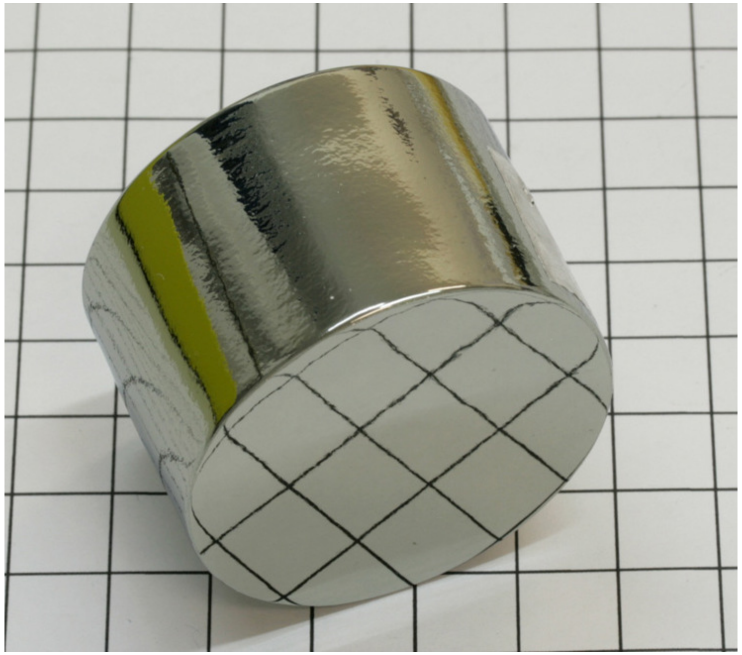
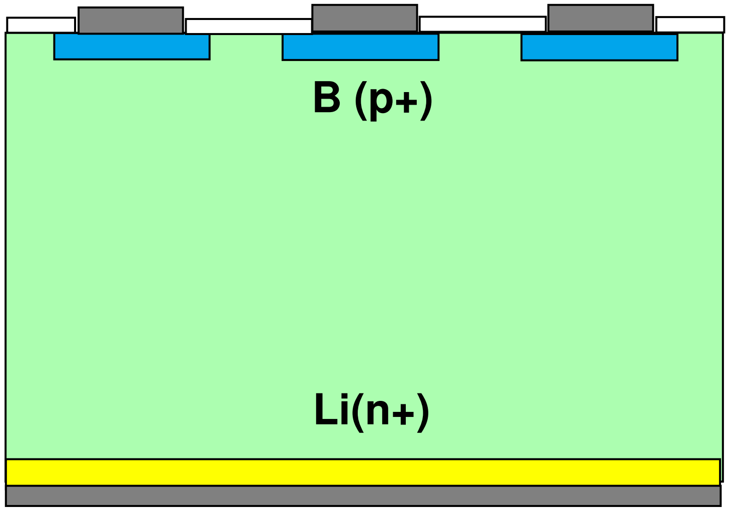
Germanium pixels

- 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℃ 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*14mm^2), 500µm
  - Second run 2*3 (28*42mm^2)
    - Option of thicker Ge



M Lampert, M Zuvic, J Beau

CANBERRA

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 LN_2!
- Indium bump bonding
  - Bumps on ASIC and sensor
  - Thermosonic compression at low T
  - *Possible* reflow above 156℃
- Currently performing tests on Ge diodes

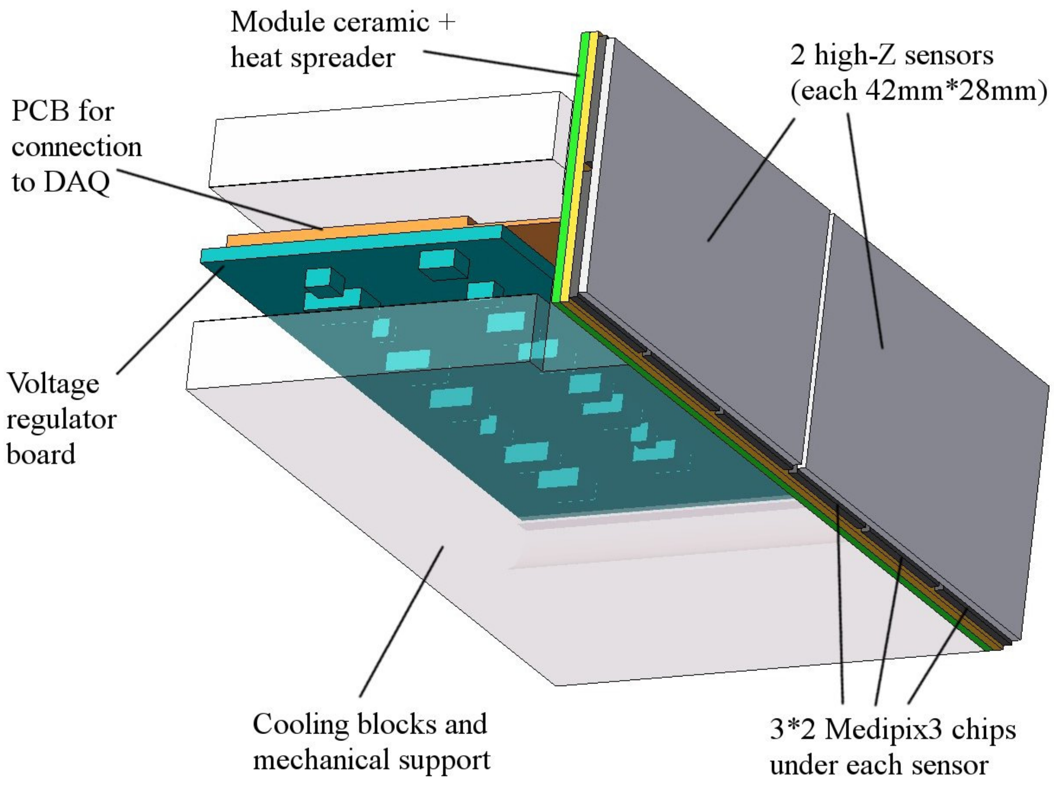
Sputter coat TiW
↓
Photoresist mask
↓
Electroplate In
↓
Dissolve excess TiW
↓
Wafer dicing
↓
Flip chip assembly
↓
Optional reflow

T Fritzsch, H Oppermann, O Ehrmann, R Jordan

Fraunhofer IZM

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



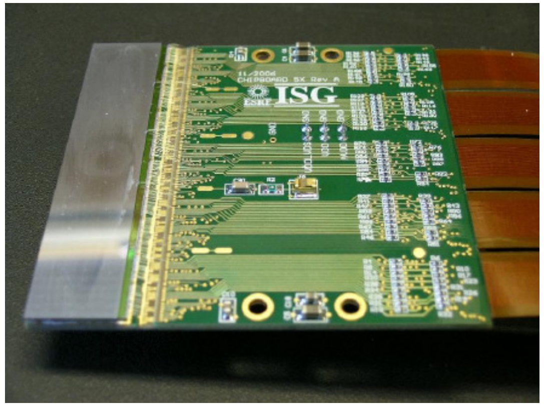
Conclusions

- 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

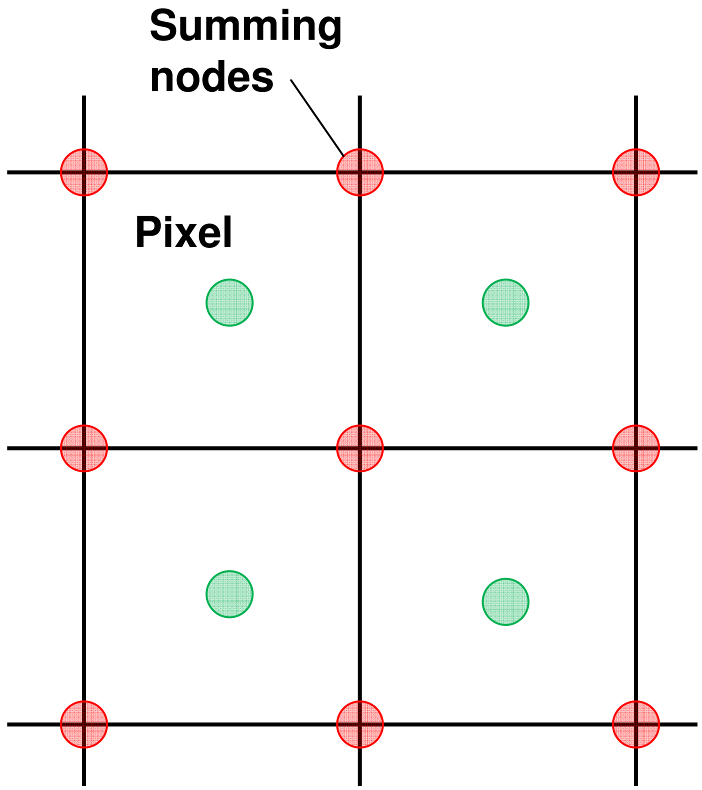
What do hybrid pixels offer?

- 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)



Medipix3

- 256 * 256 pixels, 55µm pitch
  - 14.1 * 14.1 mm^2 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



Signal summing at nodes:
Node with highest signal "wins"

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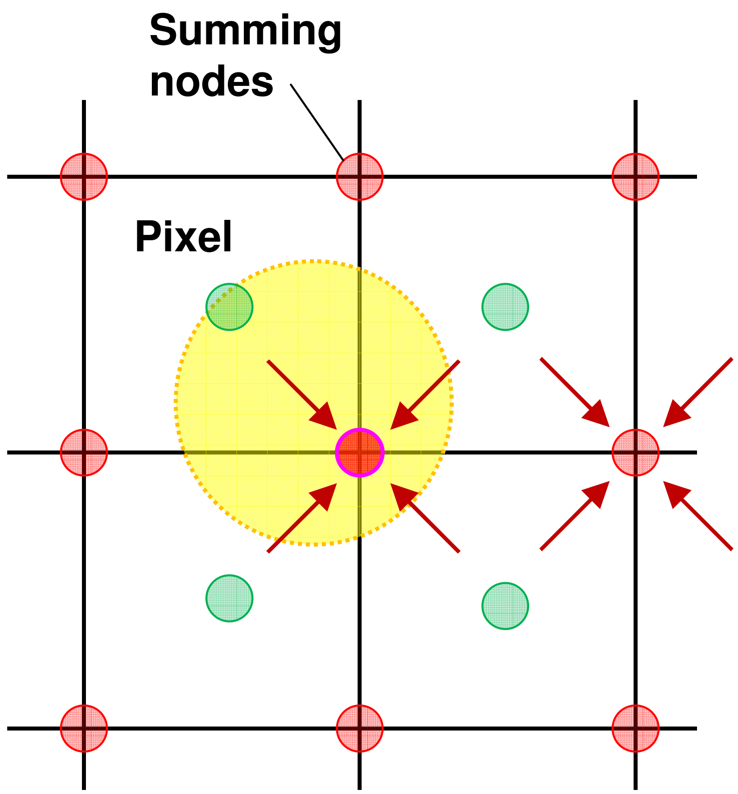
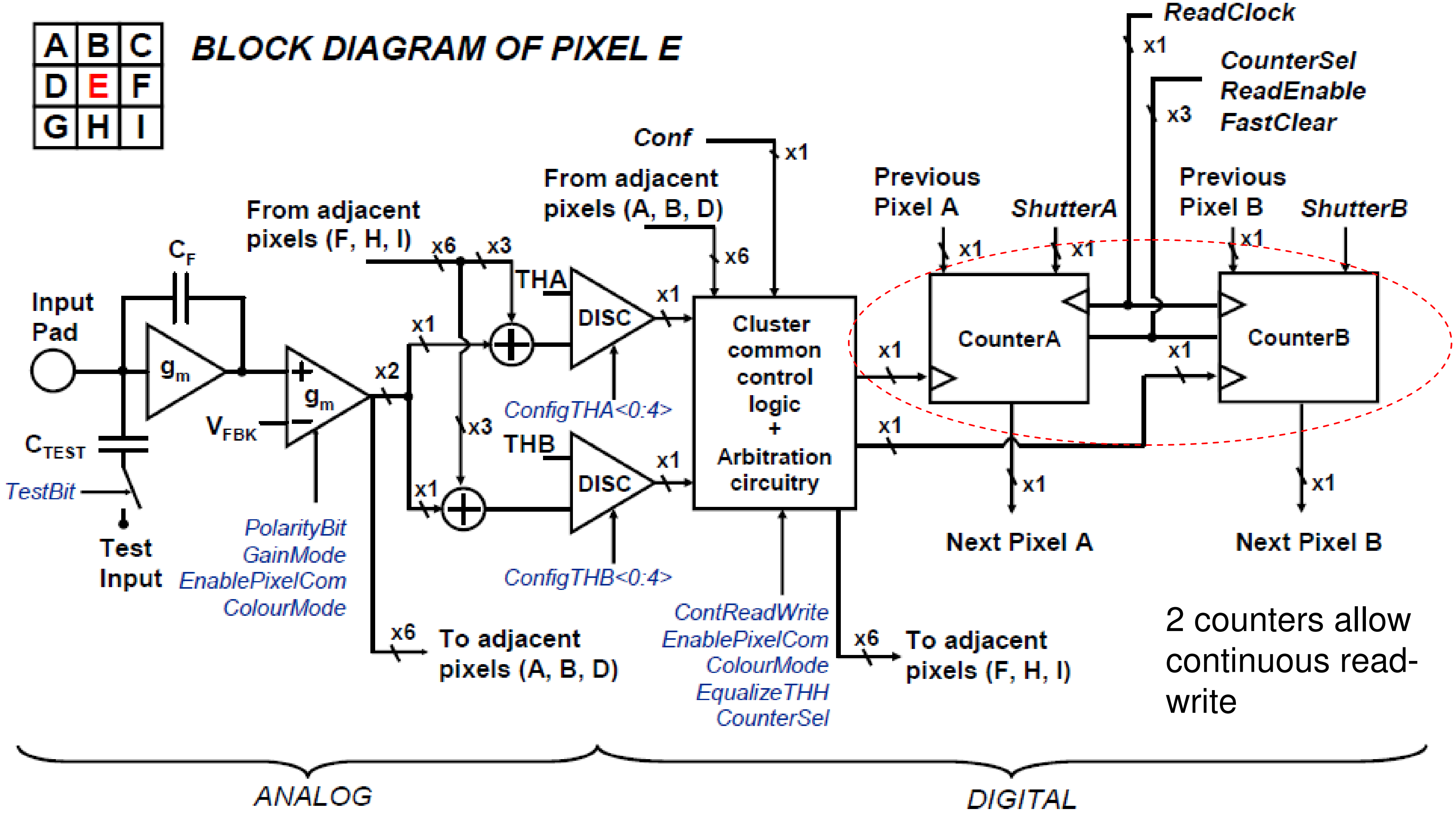


Signal summing at nodes:
Node with highest signal "wins"

Medipix3 circuitry

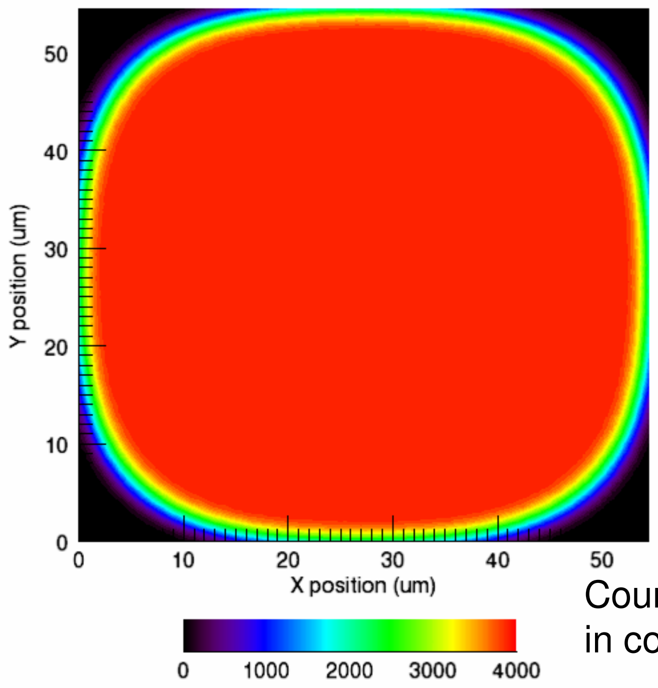


2 counters allow continuous read-write

Effects of charge sharing

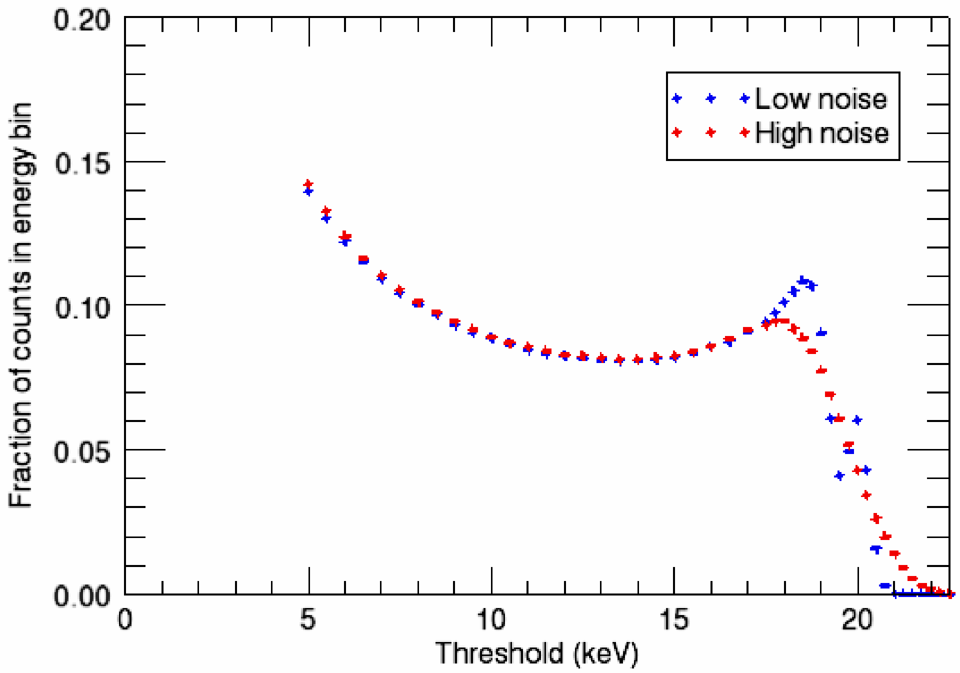
- Loss of efficiency at pixel corners
  - Typically, set threshold to E/2 with mono beam
- Loss of energy resolution

Simulated pixel scan (500µm Ge)



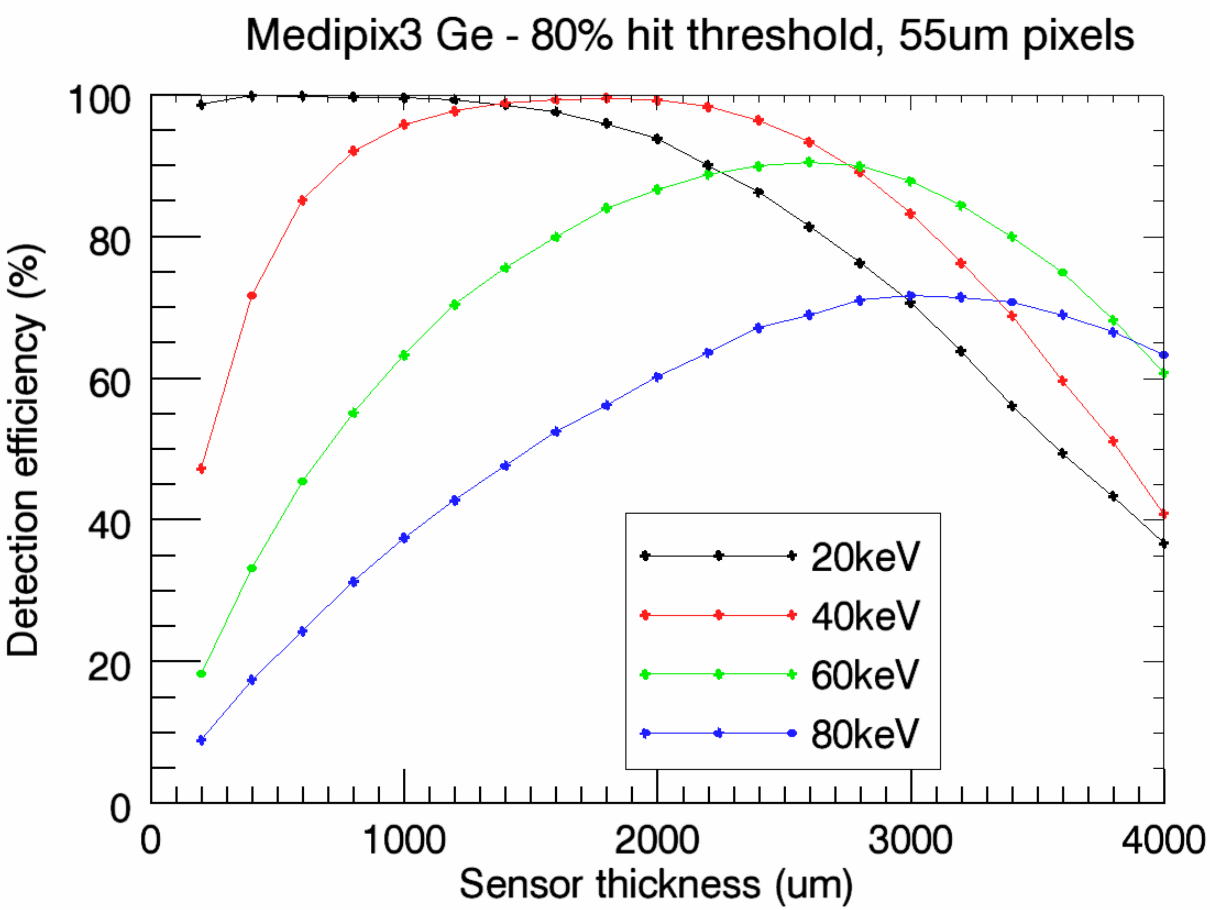
Counts lost in corner

Simulated spectrum (500µm Ge)



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