Advances in hybrid detector development for synchrotrons and XFELs at PSI

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The Photon Science Detector Group at PSI

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A. Bergamaschi, HPXM2021
Motivation

Hard X-ray diffraction and imaging experiments
- Large dynamic range
- Large area
- Moderate spatial resolution

• Energy dispersive
• Soft X-rays
• Electron detection
• High resolution Imaging

Low noise
Sensor quantum efficiency
Small pixels

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Hybrid detectors

Sensor and readout electronics can be optimized separately

😊 Direct conversion in semiconductor
😊 Fast drifting of charge to the pixel
😊 Room temperature operation
😊 Fast highly parallelized readout

😊 Interconnection (bump bonding) limits the pixel pitch
😊 Input capacitance increases the electronic noise
Dynamic range at diffraction limited light sources

- **Photons**
  - High and low flux on the detector (>10MHz per pixel)
  - Large dynamic range
  - Fluorescence rejection
  - Pile-up at high fluxes
  - No energy information

- **Photon counter**
  - No flux limitation
  - Limited dynamic range
  - Needs fast readout

- **Charge Integrating**
  - Large dynamic range
  - No flux limitation
  - Needs fast readout

- **Charge Integrating with dynamic gain switching**
  - Large dynamic range
  - No flux limitation
  - Needs fast readout
  - Challenging calibration

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Dynamic range at XFELs

Log Photons

Photon counter

Charge Integrating

Charge Integrating with dynamic gain switching

Photons arrive simultaneously

️ Doesn’t work

️ Limited dynamic range

️ Large dynamic range

️ Challenging calibration
PSI detectors

Microstrips

50 µm

Pixels

25 µm

75 µm

> 150 µm

Single Photon Counting

MYTHEN

EIGER

PILATUS (172 µm)

Charge Integrating

GOTTHARD

MÖNCH

JUNGFRAU

AGIPD (200 µm)
“Noiseless”, stable, reliable, user friendly, rad-hard, fluorescence suppression, large area systems, fast frame rate, pump-probe…

15 years ago
Replaced CCDs/Flat panels for PX

10 years ago
Enabled ptychography (lensless imaging)

Future developments
• Count rate capability up to 20MHz/pixel
• Soft X-rays
  • LGADs
• Sub-pixel resolution

Thousands of protein structures solved using PIATUS/EIGER

Now few nanometers resolution can be achieved in 3D

Time resolved experiments
• In-situ analysis of the reaction runaway

Time resolution better than 50(15)µs (20(70)kHz) possible with EIGER

Hocine et al., Materials Today, 2020
Holler et al., Nature Electronics, 2019
Neuhauser et al., Acta Materialia 2020
• **JUNGFRAU @ SwissFEL**
  – 85 modules, >40Mpixels installed
  – Works also at the new beamline for soft X-rays (even without single photon resolution)

• **At synchrotron**
  – Improves data quality for protein diffraction
  – higher count rates, no corner effect
  – Enables pink beam serial crystallography
  – Large area systems require optimized data backend

Oct 2017 First diffraction

Nov 2017 First time resolved pilot experiment
Mariete et al., submitted

Jun 2019
First large bandwidth fs-crystallography

Aug 2018 First fs-crystallography
Nass et al., IUCrJ 2020.


Tolstikova et al., IUCrJ. 2019.
Single photon detection with charge integrators

Photons must be separated

Pixel pitch 25 µm
Area 1 cm²
Number of pixels 160k
Frame rate 1 kfps
Max flux per area 1E5 ph/s/mm²
Max total flux 1E7 ph/s

In time

Photons
fluorescence
readout

Fast readout
Clustering
Small pixels

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Charge sharing

- The charge diffuses while drifting to the electrodes
- The diffusion length depends on the drift time:
  - Charge mobility
  - Applied bias voltage
  - Absorption depth
    - Sensor thickness
    - X-ray energy
- The charge can be collected by several pixels
  - Partial signal collection
  - Inter-pixel correlation
  - Charge sharing region ca. 15-20 µm for 320 µm thick silicon at 120 V

Pilatus 172 µm  Eiger Jungfrau 75 µm  Mönch 25 µm
20% 42% >90%
Spectral analysis

- Exploit the information contained in the analogue readout
- The full charge can be retrieved by clustering
  - Photon counting –like performance
  - Preserves spectral information
  - Suppresses charge sharing
  - Noise is increased depending on the size of the cluster

Combined energy and spatial resolution

Intrinsic energy resolution
- 1x1 ⇒ 320 eV FWHM
- 2x2 ⇒ 740 eV FWHM
- 3x3 ⇒ 960 eV FWHM

Sample

Detector

Spatial resolution currently limited by pinhole size
Position interpolation

- Division of charge between pixels is strongly position dependent
- Can improve the spatial resolution
  - Pitch ≈ charge sharing distance
  - 320 µm thick Si, 120V ≈ 20 µm
- High SNR
  - Low noise
  - Hard X-rays
- Isolated photons
  - Fast frame rate
  - Low flux
Does it work?

- Acquired with MÖNCH 650 µm thick silicon with 300 V bias voltage at the TOMCAT beamline (SLS) @ 10 keV
- 2 µm thick Gold on 200 µm silicon sample
  - Fabricated at LMN (PSI) by M. Lebugle
  - Eiger, Mönch and Jungfrau mountains
  - The size of the flag is 25 µm
  - The width of the Swiss cross is 7 µm

The spatial resolution is enhanced of \( \approx \) one order of magnitude!

Courtesy S. Chiriotti
Fourier ptychography

SLS, cSAXS beamline, 8.7 keV

- Interpolation to 6.25µm to compare with 6µm pixel indirect detector
- The reconstruction didn’t work with the CCD
  - Single photon resolution is necessary!
- Fourier ptychography quantitatively reproduces results obtained with traditional methods
  - 47nm resolution after reconstruction
  - Robust reconstruction, insensitive to aberrations/misalignements
  - Significantly lower dose than TXMs
- Larger area faster detector desirable for users operation
Energy resolved imaging with X-ray tubes

A full spectrum with an energy resolution of about 750 eV FWHM is acquired for each pixel

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA
Edge subtraction imaging

Images can be binned in energy

Gold becomes “transparent” to X-rays below the L-edge

Below Au L-edge

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA
High resolution energy resolved imaging

Color imaging works also in combination with interpolation. Challenges due to polychromatic beam.

Siemens Star with spokes 60-0.5 µm gold on silicon with silicon microspheres
W-anode X-ray tube 40 kV 200 µA

Below Au L-edge
Interpolated to 1 µm bins
• Silicon is too light to achieve good QE above 20 keV
• High-Z materials under test (GaAs, CdTe, CdZnTe)
  – Material quality often challenging in terms of yield, uniformity, stability...
  – Thicker sensors give more charge sharing and interpolation is possible also with 75µm pixels
  – With small pixels and interpolation we can observe strange effects

Courtesy D. Greiffenberg
-500V sensor bias, 40kV W anode

Spectroscopic CZT (JF1.1 m401)

-300V GaAs, 300V Si bias, 10 keV
The Photon Science
detector group at PSI...
... delivers outstanding
detectors worldwide.
... strives to optimize
hybrid detectors in
every aspect.
Next challenges...
... soft X-ray detectors.
... new single photon
counting pixel detector
for diffraction limited
light sources.
... faster frame rates and
data backend.

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