GHz hard X-ray imaging

Challenges in efficiency, timing and rates

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P-25, Los Alamos National Lab

(Collaboration discussion with MIT/LL, LLNL)

LANL Collaborators (growing):
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A. V. Klimenko, S.-N. Luo and C. L. Morris

(May. 16, 2013)
No solution exists today.

Very exciting time for detector/instrument developers
MaRIE XFEL

12 GeV

5 - 42 keV

80 - 100 m

Shadow/contact imaging
Phase contrast
Holography/CXDI

(1) Spontaneous emission
(2) Modulation, exponential gain
(3) Bunching, coherent emission
(4) Overbunching, saturation

Beam dump

10^6 - 10^9

Input: Rich Sheffield, Richard Sandberg

A. Snigirev et al, RSI (1995)
**Experimental time scales for MPDH**

\[ \tau_1 \sim 1 \text{ ps (laser pulse/gating)} \]

\[ \tau_2 \sim 300 \text{ ps (3 GHz or faster)} \]

\[ \tau_3 \sim 1 \mu\text{s} \]

\[ \tau_4 \sim 10 \text{ ms} \]

Light source

Detector Technology

Detector Technology / cost

Source/Facility cost

Input: C. W. Barnes
R&D Challenges for MPDH HX imaging

- **The “efficiency + ps challenge”**
  - High-efficiency (>50%) for 42 keV X-rays
  - Fast time response (300 ps or less)

- **The “GHz challenge”**
  - Sub-ns (~3 GHz or faster) frame rate X-ray cameras
  - Movie length, 10 to 10,000 frames

- **The “GB challenge”**
  - High data rate, $6 \times 10^{16}$ bit of data per second = $3 \times 10^9$ (frame per second) $\times 10^6$ (number of pixels) $\times 20$ bit.
  - Large amount of data, up to 10 GB per 1 µs event.
Energy resolution desirable

Separation of coherent from incoherent photons, background reduction

Compton continuum (incoherent scattered photon)

Coherent photon peak

- 0.38 keV (10 keV)
- 8.2 keV (50 keV)
Outline

- MPDH/MaRIE HX imaging requirements
  - The efficiency challenge for HX (42 keV)
  - The ps (“sub-ns”) challenge
  - The GHz challenge
  - The GB challenge

- Detectors today

- Paths forward
Commercial X-ray detectors (Si dominance)

- CCD
  - Fiber optics coupled CCD
  - Front illuminated CCD
  - Back-illuminated deep depletion CCD
  - Back-illuminated CCD with AR coating

- CMOS

X-Ray Energy (eV)

State-of-the-art hybrid CMOS-based detection (Si dominance)

The Crab Nebula (M1)  NGC2683 Spiral Galaxy  The Hercules Cluster (M13)

1Kx1K H1RG-18 HyViSI  2Kx2K H2RG-18 HyViSI  4Kx4K H4RG-10 HyViSI

(too slow for MPDH)
Small group R&D, industrial activities  *(many more)*

- New scintillators  
  *(Zhu et al.)*

- SNSPD  
  *(Gol’tsman et al.)*

- Molecular detectors  
  *(Kemtko et al.; Tahara et al.)*

- Frequency-Resolved Optical Gating  
  *(Trebino et al.)*

- Delayline detectors  
  *(http://www.surface-concept.de/)*
Source-specific development

CS-PAD
Synchrotron/XFEL

pnCCD
Synchrotron/XFEL/Astronomy

DEPFET
Astronomy/Synchrotron/XFEL

CZT detector
NIF

Large-area ps photodetector
HEP

CsI(Tl) array
Commercial (RMD)
Paths forward

• Peer groups
• Sensor development strategies
  – Si
  – High-Z semiconductors
  – Scintillators
Major US X-ray detector R&D groups ↔ major sources

Map produced by Cartographic Res. Lab
Univ. Alabama

UC Berkeley/Astronomy
LBL/ALS,NGLS
LLNL/NIF
SLAC/LCLS
UC Irvine (pRad)
LANL/pRad, NIF, MaRIE
ANL/APS
FNL/HEP
Cornell/CHESS
MIT/LL
BNL/NSLS,NSLS2

0.1  1.0  10  100  keV
42 keV (MPDH)
Beyond CS-PAD: Mixed Mode PAD

<table>
<thead>
<tr>
<th>PAD Tile Format</th>
<th>6 modules, each 128 x 128 pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel Size</td>
<td>150 μm x 150 μm</td>
</tr>
<tr>
<td>Max Frame Rate</td>
<td>1,000 Hz</td>
</tr>
<tr>
<td>Data Rate</td>
<td>400 MB/s</td>
</tr>
<tr>
<td>Read Noise (rms)</td>
<td>0.15 X-ray [8 keV] / pix</td>
</tr>
<tr>
<td>Sensor</td>
<td>300 um silicon, fully depleted</td>
</tr>
<tr>
<td>Well Capacity</td>
<td>&gt; 3 x 10^7 X-rays/pix/frame</td>
</tr>
</tbody>
</table>

*Chip development: collaboration with Area Detector Systems Corp.

Credit: Sol M. Gruner
Cornell Univ.
Tremsin’s team (Space Sci. lab/UC Berkeley)

Synchrotron beamline detectors:
- ARPES – angular resolved photoelectron emission spectroscopy

COS detector installed on last Hubble repair mission

Thermal neut. radiography
ANL and collaborators– MCP technologies

Phosphor screen image of a 33mm diameter borosilicate/ALD MCP with 20µm holes

512x512 of 55 um pixels (2x2 Timepix ASIC)

- MCP technology
- ASIC’s (Timepix, U. Hawaii)
- ALD and other processes

Credit: A. Tremsin, UC Berkeley.
European detector R&D \leftarrow ESRF, XFEL

Si
- HPAD -> AGIPD (DESY)
- DEPFET-APS -> DSSC (DESY)
- LPD (UK group)
- LAMBDA (Medipix-based)

High-Z
- Germanium
- Galapad (GaAs)
- HiZPAD (CdTTe)
- XNAP

European XFEL @ DESY
## European XFEL Si imagers

<table>
<thead>
<tr>
<th></th>
<th>DSSC</th>
<th>LPD</th>
<th>AGIPD</th>
</tr>
</thead>
<tbody>
<tr>
<td># Pixels</td>
<td>$1k \times 1k$</td>
<td>$1k \times 1k$</td>
<td>$1k \times 1k$</td>
</tr>
<tr>
<td>Pixel size</td>
<td>$200\mu m \times 200\mu m$</td>
<td>$500\mu m \times 500\mu m$</td>
<td>$200\mu m \times 200\mu m$</td>
</tr>
<tr>
<td>Sensor</td>
<td>DEPFET array</td>
<td>Si-pixel</td>
<td>Si-pixel</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>$&gt;10^4$ ph</td>
<td>$2 \times 10^4$ ph $(10^5$ ph)</td>
<td>$2 \times 10^4$ ph</td>
</tr>
<tr>
<td>Noise</td>
<td>$\sim 15 \times 10^{-3}$ ph</td>
<td>$0.21$ ph (0.93ph)</td>
<td>$\sim 45 \times 10^{-3}$ ph</td>
</tr>
<tr>
<td></td>
<td>$\sim 50$ e</td>
<td>$700$ e (3100e)</td>
<td>$\sim 150$ e</td>
</tr>
<tr>
<td>Concept</td>
<td>DEPFET nonlinear gain compression Per-pixel ADC</td>
<td>Multiple gain paths On-chip ADC</td>
<td>Adaptive gain switching (preset gain option)</td>
</tr>
<tr>
<td>Storage</td>
<td>8-bit DRAM</td>
<td>3-fold analogue</td>
<td>2-bit digital + analogue</td>
</tr>
<tr>
<td>Storage depth</td>
<td>$\geq 256$</td>
<td>512</td>
<td>$&gt;200$</td>
</tr>
<tr>
<td>Challenges</td>
<td>Linearity &amp; calibration In-pixel ADC DRAM refresh Power budget Pixel area</td>
<td>Preamplifier: noise, dynamic range &amp; PSRR Feedback discharge Analogue storage</td>
<td>Dynamic gain switching Charge injection Analogue storage Pixel area</td>
</tr>
</tbody>
</table>

Radiation hardness
Hybrid CMOS: Flexible, Fast, bright Future

Sensor layer (diode)

Bump bonding

ASIC (CMOS)

X Ray
ASIC architectures

C1-C8: 130 fF

ASIC Fabrication: *shares* CMOS technology

- IBM cmrf8sf DM (130nm CMOS)
- Chosen by DSSC, AGIPD, LPD
- De-facto standard for LHC upgrades
- Advanced over cmos6sf (0.24 um)
- Well established for layout based radiation hardening
- Permits sufficiently high integration density
- (dual) MIMCAPS can be employed as a (fallback) solution for storage caps.
- Long-term availability
- Uncertainties do exist (*IBM, threshold $50 M*)

*U. Trunk, ASICs for XFEL Detectors, CMOS ET Workshop (2009)*
Fast electronics & data storage challenges: it takes time

From: ITRS 2011 report

MPU/ high performance ASIC half pitch and gate length trends
Sensor challenges

- **Materials**
  - *Standard (Si, Ge)*
  - High impurities (charge trapping)
  - Defect densities
  - Stoichiometric imbalances
  - Radiation damage

- **Structures**
  - Natural
    - Crystalline
    - Amorphous
  - Fabrication technologies
  - Signal transport
  - Integration
  - Testing

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1 yr. ago...

- Maximizing electron mobility
- Lower temperature
- Higher electrical bias
- Ultimate “drift” limit
  $\sim 10^8$ cm/s?

Wang et al, RSI (2012)
Efficient absorption thickness ⇐ High Z

![Graph showing attenuation of different materials at various energies](image)

- Si
- CdTe
- Ge (GaAs)
- C

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>42</td>
</tr>
<tr>
<td>C</td>
<td>20</td>
</tr>
<tr>
<td>CdTe</td>
<td>100</td>
</tr>
<tr>
<td>Ge (GaAs)</td>
<td>80</td>
</tr>
</tbody>
</table>

1 mm thick
Response time ↔ electron drift time

\[ 10^5 \text{ m/s} \times 1 \text{ ns} = 100 \text{ um} \]
\[ 10^5 \text{ m/s} \times 50 \text{ ps} = 5 \text{ um} \]
\[ E_e = 0.03 \text{ eV} \]
\[ 3 \times 10^8 \text{ m/s} \times 1 \text{ ns} = 300 \text{ mm} \]

Semiconductor down-selection

- Elemental: C, Si, Ge
- Binary (IV-IV): SiGe
- Binary (III-V): InP, GaAs
- Binary (II-VI): CdTe, HgTe
- Binary (I-VII): AgCl
- Ternary: HgCdTe, CZT
- Quarternary: InGaAsP

- Si
- GaAs, Ge
- InP
3D structures ↔ reducing charge collection time

150 - 300 ns $\rightarrow$ 5 - 30 ns $\rightarrow$ 300 ps

D. Eckstein, DPG spring meeting, Munich (2009).

Scintillators ... the list is growing

Credit: R-Y Zhu, Caltech
Columnar structures for efficient light guide

- R & D
- Reduction to practice


RMD (Scintillator injection technology)
Capillary diameter: 25 – 2000 um

http://www.scint-x.com
Summary

- Requirements of MPDH HX imaging unprecedented
  - Efficiency, ps, GHz, GB

- No technology comes close in overall performance
  - Efficiency < 10% for HX @ 42 keV
  - Time/frame rate off by ~ x 300

- Phased development approach
  - ~ 100 ns (today) → 5 - 30 ns → 300 ps

- Multi-pronged approach for sensor material & 3D structure
  - Si
  - High-Z semiconductors
  - Fast scintillators

Very exciting time for detector/instrument developers