SOPHIAS Detectors for X-ray Free-Electron Laser (XFEL) Experiments and Synchrotron Radiation (SR)

Takaki Hatsui, Togo Kudo on behalf of SOPHIAS collab.

RIKEN
Collaborators

- RIKEN, JASRI
  *All members of SACLA members, especially,*
  - N. Teranishi, T. Tosue, K. Ozaki, K. Kobayashi, T. Kameshima, M. Omodani, S. Ono,

- Univ. of Hyogo
  - Takeo Watanabe, Hiroo Kinoshita

- SOIPIX collaboration
  *esp. Yasuo Arai (KEK), Ikuo Kurachi (KEK), Jiro Ida (Kanazawa Inst. of Technology), Takeshi Tsuru (Kyoto Univ.), Kazuhiko Hara (Univ. of Tsukuba)*

- Private Sector

- SACLA Detector Advisory Committee
  - Peter Denes (chair, LBNL), Andrew Holland (The Open Univ.), Grzegorz Deputch (Fermilab), Yasuo Arai (KEK), Bernd Schmitt (PSI)
Outline

- Detector needs at SPring-8 site
- SOPHIAS Sensor
  - Camera system
  - Charge division concept
  - Pixel design
    - Validation of the charge division principle
    - Calibration accuracy
- Future project possibility for XFEL/SR
- Summary
X-ray Matter Interaction

- X-ray Fluorescence
  \[ I_F \propto A \]
  
  *Energy Resolving Detector*

- Absorption
  \[ A = - \log \left( \frac{I}{I_0} \right) \]
  
  *Wide Dynamic Range Imager*

- Compton Scattering
  
  *Vector Measurement Photon Energy Measurement*

- Elastic Scattering
  \[ I_{es} \propto q^{-4} \text{ (uniform material)} \]
  \[ I_{es} \propto E_{ph}^{-2} \]
  
  *Wide Dynamic Range Imager*

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  *Wide Dynamic Range Imager*

Pulse Nature of XFEL/SR X-rays
→ Integrating pixel for intense signal recording

a few fs – 40 ps
XFEL facility, SACLA (Since 2012-)
8 GeV 700 m long

SR facility, SPring-8 (Since 1997-)
8 GeV circumference 1.5 km

- Operation for users from March 2012
  - Operating at 60 pulses/s
  - Two accelerators, Three BLs

- Workhorse Detector: Multport CCDs
  - Dev. 2007-2012
  - Upgrade projects until 2018
  - Operational system
    - 43.5 Mpixels, 0.11 m²
    - 28 systems

- SOPHIAS (2007-2018)
  - for small pixel, high-peak-signal-hungry experiments
  - Production 50 chips including spares, 95 Mpixels, 0.09 m²

- Upgrade to SPring-8 II proposed.
  SPring-8-II Conceptual Design Report (2014)
  - Max 500 Mpulses/s
  - Simultaneous operation for 56 BLs

- Workhorse detector: CITIUS
  - Development 2013-2021
  - Upgrade projects until ~2024
  - First installation (2021-2023)
    - 1000 chips, 450 Mpixels, 2.2 m²
    - + other facilities
Ping Grid Array Package
(Silicon nitride)

Major Feature
- Peak signal 18.7 Me-/pixel
- Noise 160 e-
- Imaging Area: 64.77 x 26.73 mm$^2$

Largest Sensor chip as monolithic active pixel sensor (MAPS) for radiation detection.
Camera Head

Cooling by a thermoelectric cooler with water circulation
Sensor operation at -20 °C
Single-Sensor Camera

3rd generation of the camera system

Camera Link Full Config. Interface

Pin Grid Array Socket
# SOPHIAS: Sensor Performance

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>5M 0.2 um FD-SOI with 500 um FZ(n-type)</td>
</tr>
<tr>
<td>Photodiode</td>
<td>P+ in n with laser annealing on the back side. Thickness of 500 µm</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>30 µm</td>
</tr>
<tr>
<td>Pixel Number</td>
<td>1.9 M</td>
</tr>
<tr>
<td>Format</td>
<td>891 x 2157</td>
</tr>
<tr>
<td>Readout Noise</td>
<td>163 e-rms, 3 uV/e-</td>
</tr>
<tr>
<td>Sensor Resposivity</td>
<td>18.7 Me- (11400 phs.@6 keV)</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>4.7 W/sensor</td>
</tr>
<tr>
<td>Rad. Hardness</td>
<td>10 MGy @ 7 keV, 1 kGy for Transistors</td>
</tr>
</tbody>
</table>

1) T. Hatsui, et.al, Proc. of Int. Image Sensor Workshop, 2013 Art. 3.05.
## Sensor Power Dissipation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-sensor power dissipation</td>
<td></td>
</tr>
<tr>
<td>pixel</td>
<td>0.5 μW/pixel</td>
</tr>
<tr>
<td></td>
<td>0.95 W/sensor</td>
</tr>
<tr>
<td>Column Amp.</td>
<td>3.4 W/sensor</td>
</tr>
<tr>
<td>Others</td>
<td>0.35 W/sensor</td>
</tr>
<tr>
<td>Total</td>
<td>4.7 W/sensor</td>
</tr>
<tr>
<td>Camera</td>
<td>Sensors 1</td>
</tr>
</tbody>
</table>

## Camera Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tr>
<td>Camera</td>
<td>Sensors 1</td>
</tr>
<tr>
<td>Pixel Number</td>
<td>1.9 M</td>
</tr>
<tr>
<td>Format</td>
<td>891 x 2157</td>
</tr>
<tr>
<td>Pixel-by-pixel calibration</td>
<td>On-the-fly</td>
</tr>
<tr>
<td>Data Rate</td>
<td>3.7 Gbps</td>
</tr>
</tbody>
</table>
Sensor Floor plan

Stitched by 5 regions (2 mask regions within a mask set)
Output: High-gain port 12
       Low-gain port 12
       Total 24 (each port consists of a quasi-differential output pair)
Principle

\[ Q = C \cdot V \]
\[ C \propto \text{Pixel Area} \]

Higher Peak Signal demands larger pixel

Approach in this work
Reduce the charge/photon ratio
SOPHIAS: 10\% of charge is collected for low gain channel
→ x10 improvement in Peak Signal
Implementation: Charge Collection

Entrance Window
Absorption Point
Trace of Charge
Silicon
Patterned Implant
Oxide
CMOS Circuitry

X-ray

Low Gain Channel
Collecting 10% of charge

High Gain Channel

30 μm pixel

0.5 μW/pixel without power pulsing
X-ray Transmission Image (*)

28 connections/pixel Between
- transistor
- the charge collection anodes

(*) X-ray image was taken by using a solid-state diffusion bonded scintillator camera
T. Kameshima et.al.,
Experiments: Is Charge Division Principle Working?

- Experiment
  - Cd-109 source
- Analysis
  - Correlation between High/low outputs was found.

Peak
High: $142.36 \pm 0.050 \text{ (2}\sigma\text{)}$
Low: $6.953 \pm 0.014\text{ (2}\sigma\text{)}$

(cf) w/o charge division → Low = 0 DN

May 21, 2018
Peak Signal vs. Pixel Area

Higher Peak Signal Density

- Peak Signal, $N_{ph,max}$

$$N_{ph,max} = \frac{Q_{max}}{E_{photon}/W}$$

$$Q_{max} = C V_{max} = S \left( C_{density} V_{max} \right)$$

Detectors for European XFELs (LPD, AGPID, DSSC, PixFEL), spectroscopic imagers (pnCCD, MPCCD phase III-L) are not targeting high peak signal density.
An updated calibration method for SOPHIAS was established.

Calibration Data collection:
- Around 40 images with varied exposure time
- Illuminated by optical light instead of X-rays

Sensor:
- Optical blocking aluminum coating was not implemented.

8 Parameters for a pixel:
- Gain:
  - High, Low1, Low2
- Offset:
  - High, Low1, Low2
- Switching points:
  - High->Low1, Low1-> Low2

Low gain has a knee behavior.
Calibration Verification

Tested pattern
- 7.2 keV SPring-8 BL29XU
- diffraction pattern of a rectangular slit

- **Approach**
  - Obtain ratio of unattenuated vs. attenuated (~1/36) intensities
  - Linear across all the gain regions.

![Graph showing unattenuated vs. attenuated intensities](image)

- **Graph Details**
  - **Equation:** $y = 36.526x - 0.4373$
  - $R^2 = 0.9995$
  - Low1: 100 phs.
  - Low2: 200 phs.
  - High: Photon counts for different gain regions.
SOPHIAS Deployment status

9 systems are under deployment

- SPring-8
  - 4 systems
- Photon Factory
  - 1 system
- Osaka University
  - 1 system
- Gunma University
  - 1 system
- Collaboration study for the other applications
  - 2 system

May 21, 2018
**Goal**
- Lowering photon energy limit well below 4 keV
- False positive rate lower for low intensity measurements

**Project Target**
- Noise of 80 e-rms while keeping the sensor interface

**SOPHIAS**
- Noise 163 e-rms
- High and Low gain channels
- 12 ports with High and Low gains
- 24 channel ADCs
- 14 bit depth @25 MSPS

**SOPHIAS-L**
- 80 e-rms
- High gain only
- 24 ports with High gain
- 24 channel ADCs
- 14 bit depth @12.5 MSPS

\[
\frac{1}{\sqrt{2}} \quad \text{and} \quad \frac{1}{\sqrt{2}}
\]
## SOPHIAS-L: Design vs. Experiments

### Specifications

<table>
<thead>
<tr>
<th></th>
<th>Noise [e-]</th>
<th>Sensor Responsivity [uV/e-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Target</td>
<td>&lt; 80</td>
<td></td>
</tr>
<tr>
<td>Design Target</td>
<td>&lt; 60</td>
<td>&gt; 5</td>
</tr>
</tbody>
</table>

### Results

<table>
<thead>
<tr>
<th></th>
<th>Noise [e-]</th>
<th>Sensor Responsivity [uV/e-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>Experiment</td>
</tr>
<tr>
<td>Pixel L</td>
<td>63</td>
<td>76</td>
</tr>
<tr>
<td>Pixel M</td>
<td>58</td>
<td>72</td>
</tr>
<tr>
<td>Pixel S</td>
<td>55</td>
<td>83</td>
</tr>
</tbody>
</table>

### Discrepancy
- Origin of the difference is under investigation.

### Project decision
- Produce SOPHIAS-L with one of the three pixel design.
- Design completed. Production start in Oct. 2018
Development history/Schedule

- Sept. 2015: SOPHIAS-L target performance approved
- Jan 2016: Noise re-analysis of SOPHIAS
  - May 2016: Tape out, 1st production
  - Dec 2016: chip delivered
    - Characterization
    - Noise analysis completed
  - July 2017: 2nd Production
    - In-pixel: doping condition was varied.
    - Process delayed ~2 months
  - March 2018: chip delivered
    - Characterization
- Oct 2018: Final design fixed
- March 2019: chip delivered
  - Assembly
  - Verification
- Summer 2019: production completed

Pros.
- A Project will be completed within 4 years
  - shorter considering the SOIPIX history, but not satisfactory at least for x-ray applications
- Delay of about 1 year from the original plan
- Circuit level performance was achieved by single run.

Cons.
- Pixel re-design took 1.5 years extra.

Future
- Better and established pixel design will boost rapid development.
Future project possibility for XFEL/SR? 
A step forward


**Id-Vg Characteristics in Triode Region**

**Previous Process**
- V\textsubscript{ds}=-0.1V
- L=0.2μm, W=10μm
- BF core
- 0kGy
- 112kGy

**LDD Dose x 6**
- V\textsubscript{ds}=-0.1V
- L=0.2μm, W=10μm
- BF core
- 0kGy
- 112kGy

With increasing Implantation dose of PLDD region 6 times higher than present value, the degradation is reduced from 80% to 20% at 112 kGy(Si).
Summary

- **SOPHIAS**
  - Charge division concept is used to achieve high peak signal of 18.7 Me-/pixel
  - Charge division principle to be demonstrated by experiments
  - Final production will be completed in 2019

- **SOPHIAS-L**
  - Lower noise version
  - Production will be completed in 2019
  - 4 years of developments
    - Long, but showing progress of our understanding of SOIPIX

- Future possibility of SOIPIX in XFEL/SR applications
  - Radiation hardness possibly reach 100 kGy range.
    - XFEL/SR applications generally require 1 MGy.
    - Some will be compatible with 50-100 kGy hardness
SPARE SLIDES
Calibration Calculations

- Implemented with parallel CPU calculation code within a desktop PC
  - Intel Xeon CPU E5-1650 v4 3.6 GHz

- Method
  - Memory Access Pattern was optimized
  - SIMD vectorization within Intel® Xeon® Processor

- Performance
  - Target 16.6 ms/frame for 60 Hz operation
  - Results 12 ms/frame

- Discussion
  - SIMD within the CPU was more effective than
    - GPGPU
    - Parallel computation
  - Probably because of many condition branches (if)
Implementation: Charge Dynamics

Entrance Window

X-ray

Absorption Point

Trace of Charge

Silicon

Patterned Implant

Oxide

CMOS Circuitry

Potential (V)

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200

z position (µm)

500
Implementation: Charge Division

Entrance Window

Absorption Point

Trace of Charge

Silicon

Patterned Implant

Oxide

CMOS Circuitry

X-ray

T. Hatsui, M. Nagase, N. Teranishi et.al., in preparation

FEE2018
Implementation: Charge Division

Charge Division occurs nearby Charge Collection Node
Less than 2 μm (<< sensor thickness of 500 μm)

Dependence of charge division ratio to the X-ray absorption depth is negligible.