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 (Unv. of Tsukuba)
- Private Sector
  - Lapis Semiconductor, A-R-Tec Corp., Brookman Technology, Kyocera Corp.
- 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

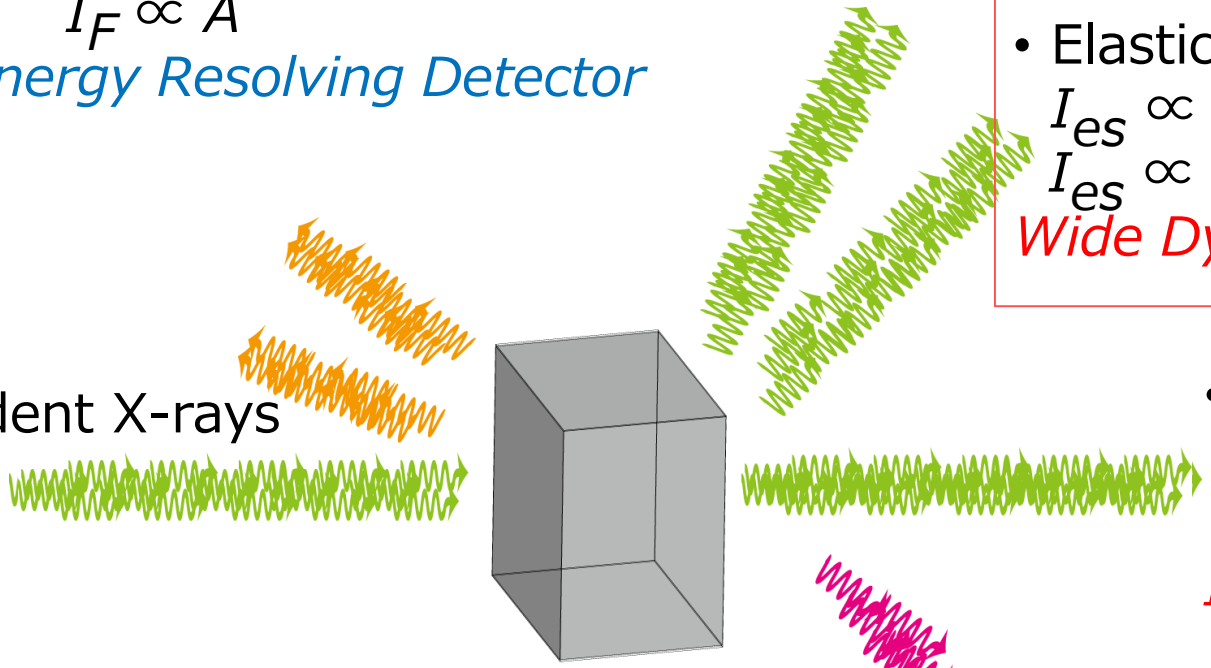
X-ray Matter Interaction

- X-ray Fluorescence
  $I_F \propto A$
  Energy Resolving Detector

This talk

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

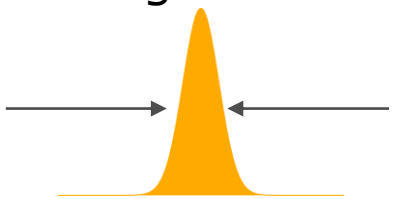
Incident X-rays



- Absorption
  $A = -\log(I/I_0)$
  Wide Dynamic Range Imager

- Compton Scattering
  Vector Measurement
  Photon Energy Measurement

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
  T. Ishikawa et.al., Nature Photonics(2012)
  - Operating at **60 pulses/s**
  - Two accelerators, Three BLs

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

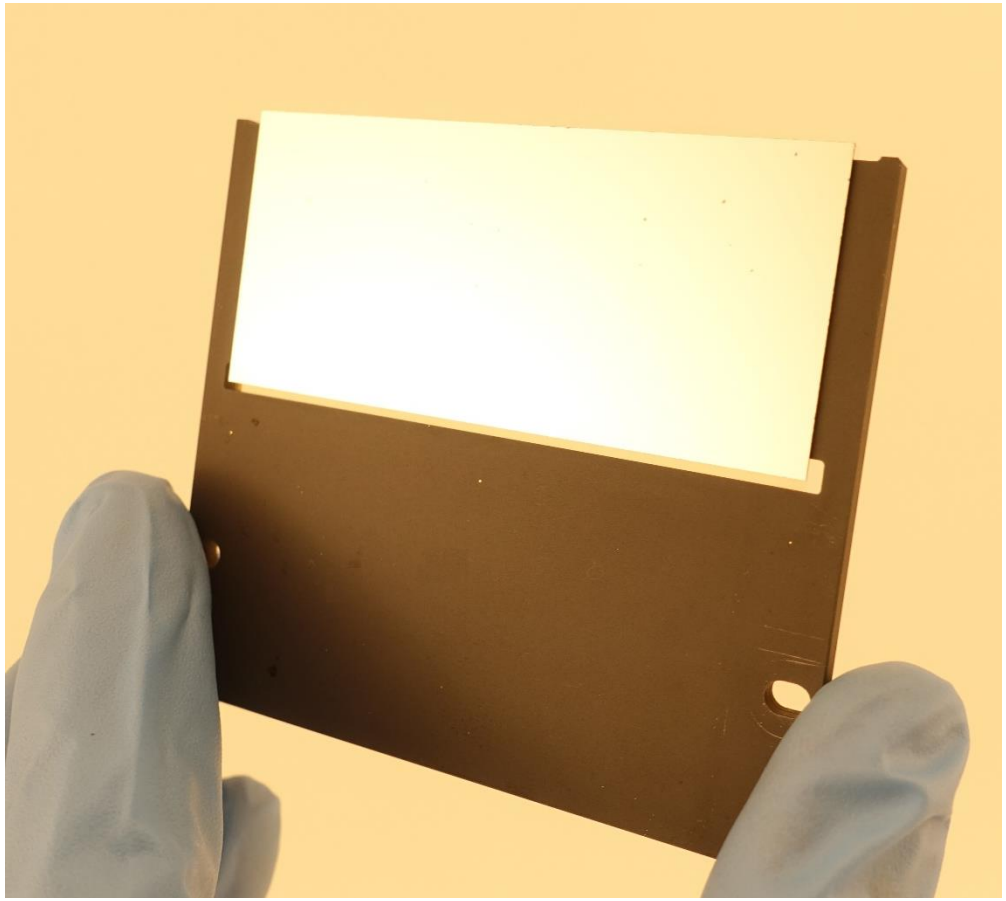
- Workhorse Detector: **Multport CCDs**
  - Dev. 2007-2012
  - upgrade projects until 2018
  - Operational system
    - 43.5 Mpixels, 0.11 m^2
    - 28 systems

- Workhorse detector: **CITIUS**
  - Development 2013-2021
  - Upgrade projects until ～2024
  - First installation (2021-2023)
    - 1000 chips, 450 Mpixels, 2.2 m^2
      + other facilities

SOPHIAS (2007-2018)
for small pixel, high-peak-signal-hungry experiments
- Production 50 chips including spares, 95 Mpixels, 0.09 m^2

SOPHIAS Sensor

Ping Grid Array Package
(Silicon nitride)

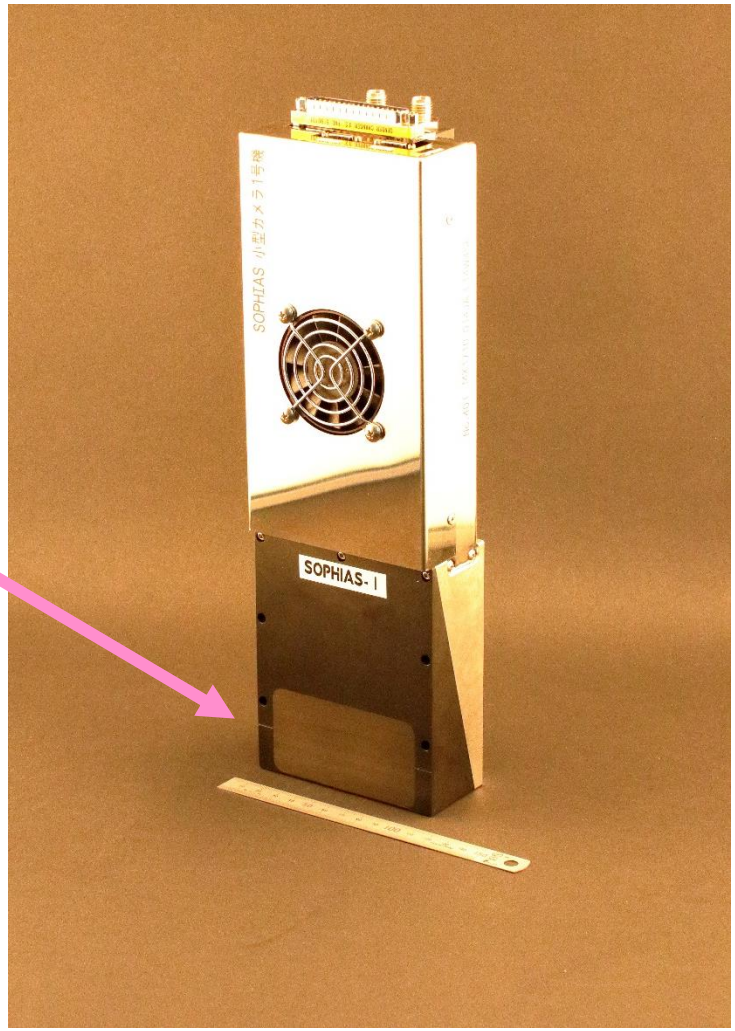


Major Feature

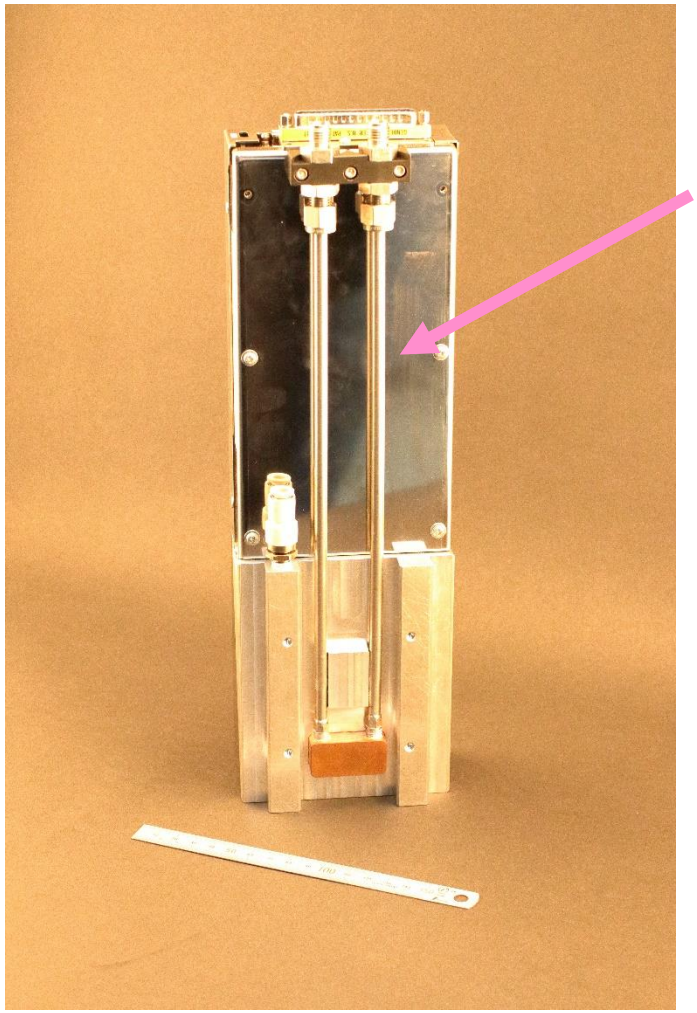
- Peak signal 18.7 Me-/pixel
- Noise 160 e-
- Imaging Area: 64.77 x 26.73 mm^2

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

Camera Head



Sensor

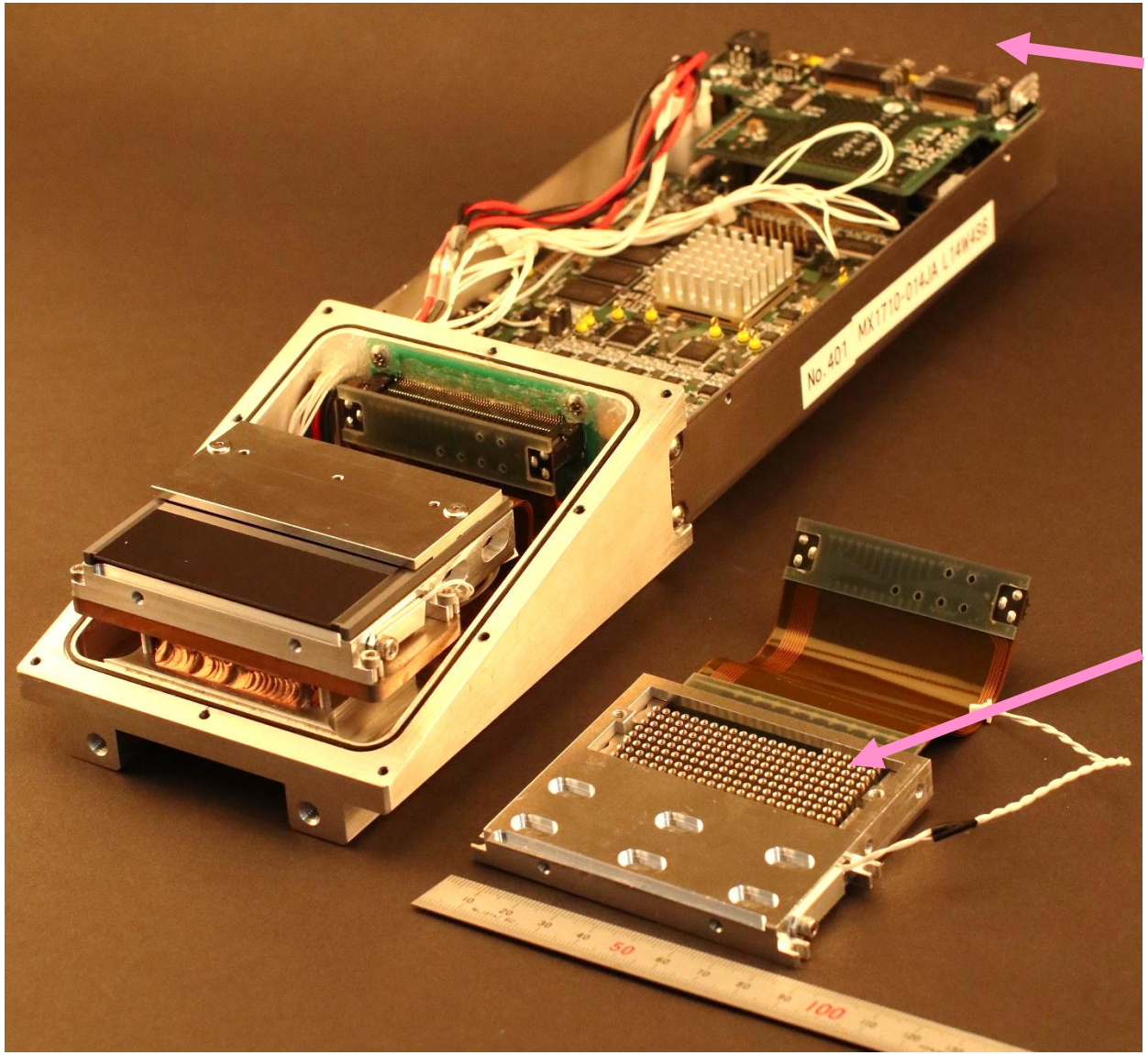


Water Tubing

Cooling by a thermoelectric cooler with water circulation
Sensor operation at -20 ℃

Single-Sensor Camera

3rd generation of the camera system



Camera Link Full Config. Interface

Pin Grid Array Socket

SOPHIAS: Sensor Performance

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

1) Max. signal satisfying analog raw linearity of 3 %

1) T. Hatsui, et.al, Proc. of Int. Image Sensor Workshop, 2013 Art. 3.05.
2) M. Okihara, et.al., Proc. IEEE NSS, 2012 p. 471.

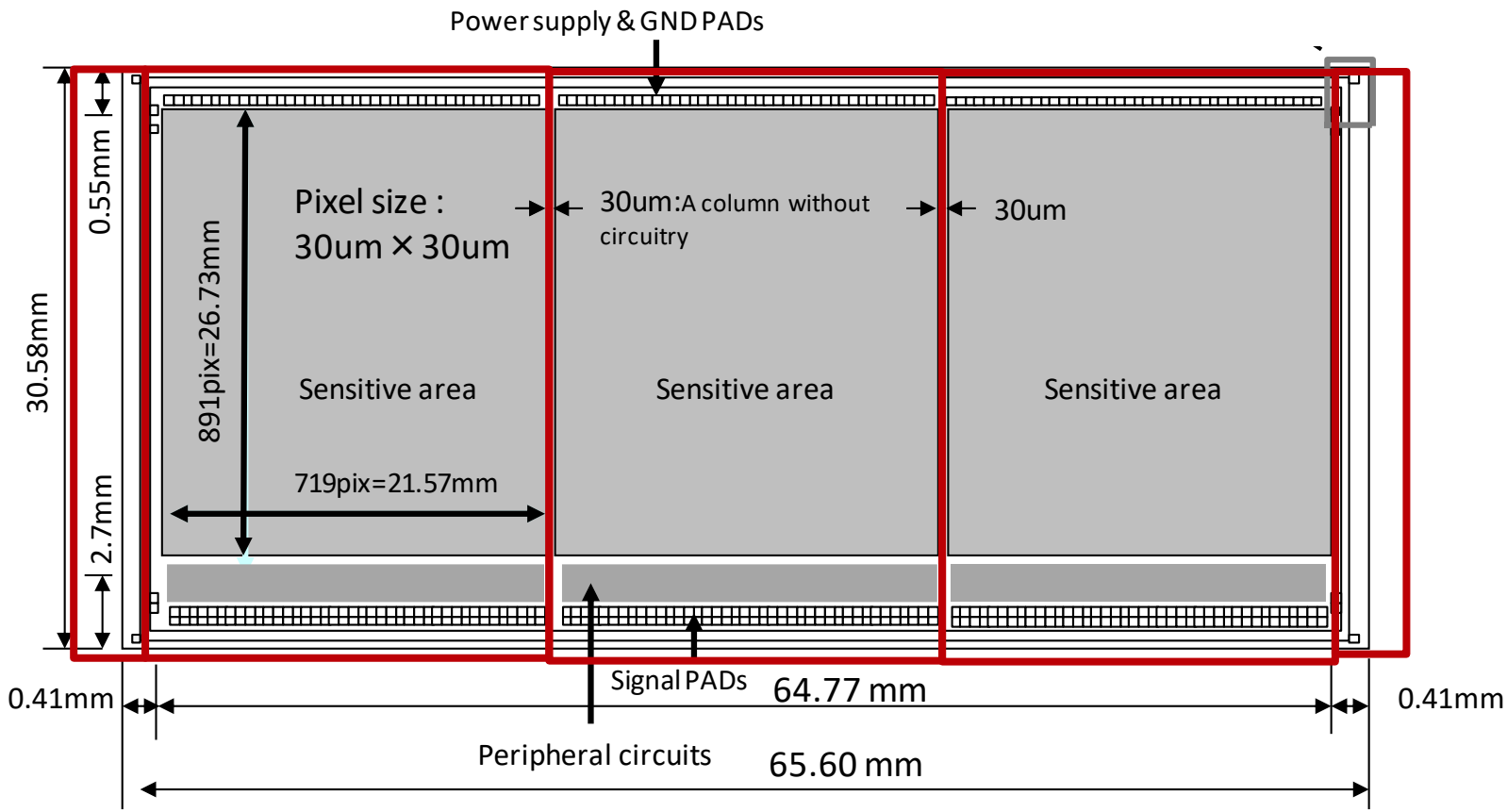
Sensor Power Dissipation

Parameters		Value
On-sensor power dissipation	pixel	0.5 μW/pixel 0.95 W/sensor
	Column Amp.	3.4 W/sensor
	Others	0.35 W/sensor
	Total	4.7 W/sensor
Camera	Sensors	1

Camera Specifications

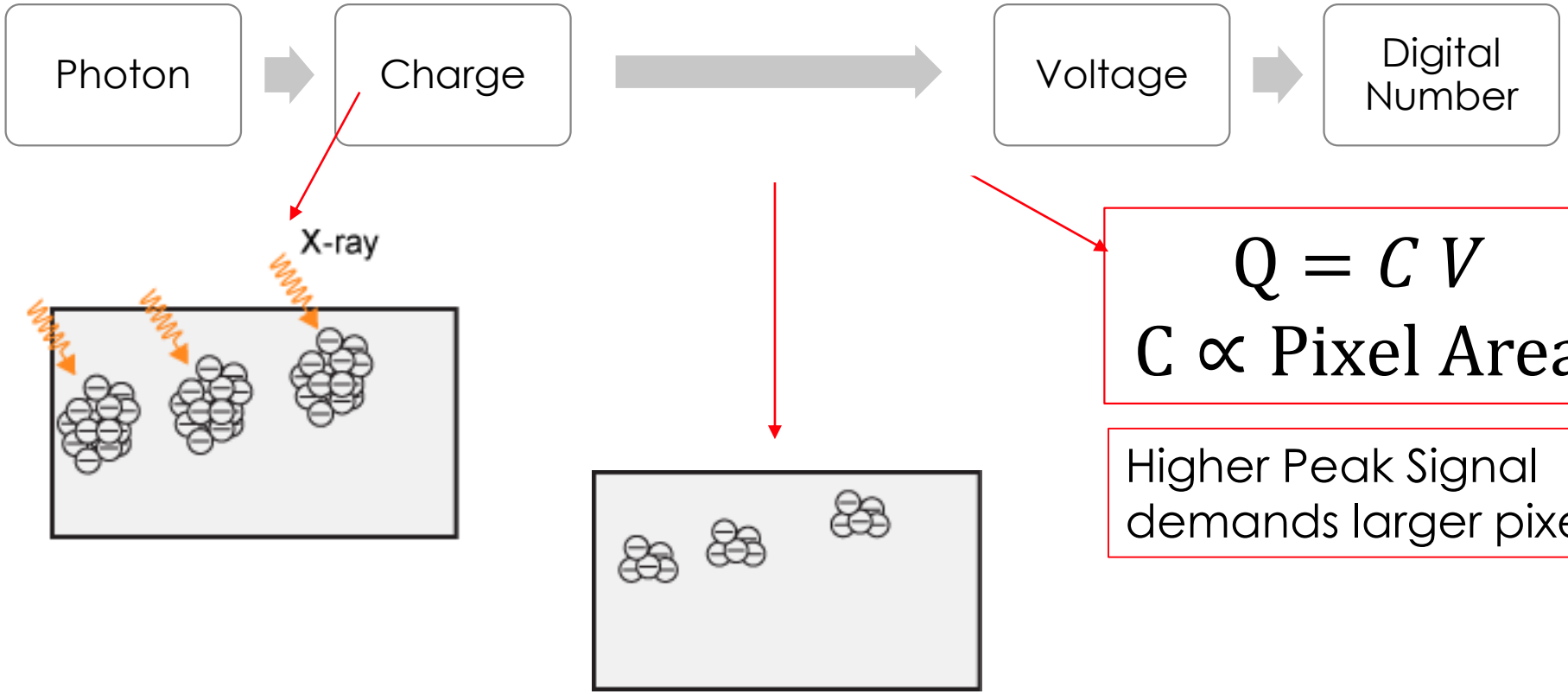
Parameters		Value
Camera	Sensors	1
	Pixel Number	1.9 M
	Format	891 x 2157
	Pixel-by-pixel calibration	On-the-fly
	Data Rate	3.7 Gbps

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

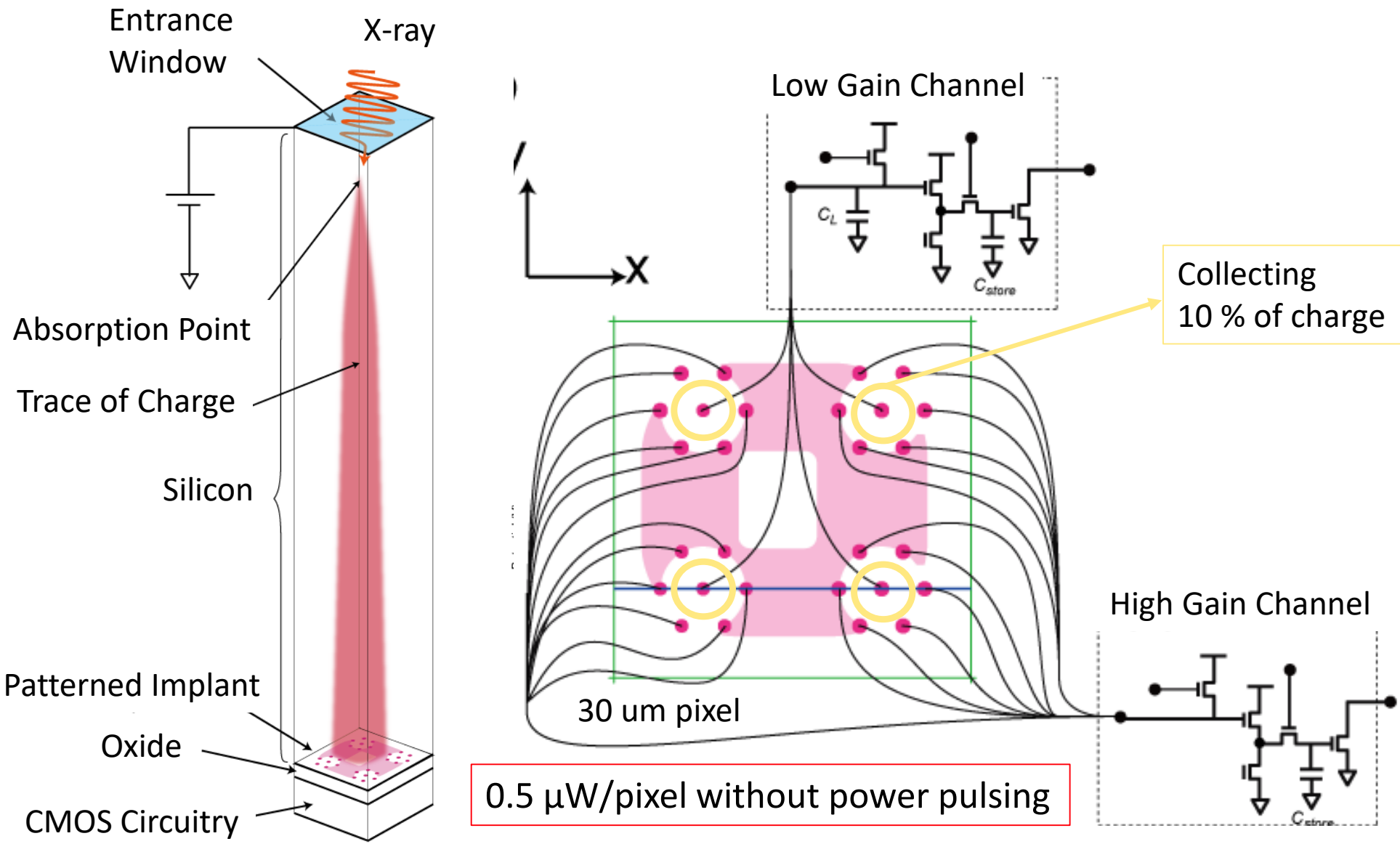


$$Q = C\,V$$
$$C \propto \text{Pixel Area}$$

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

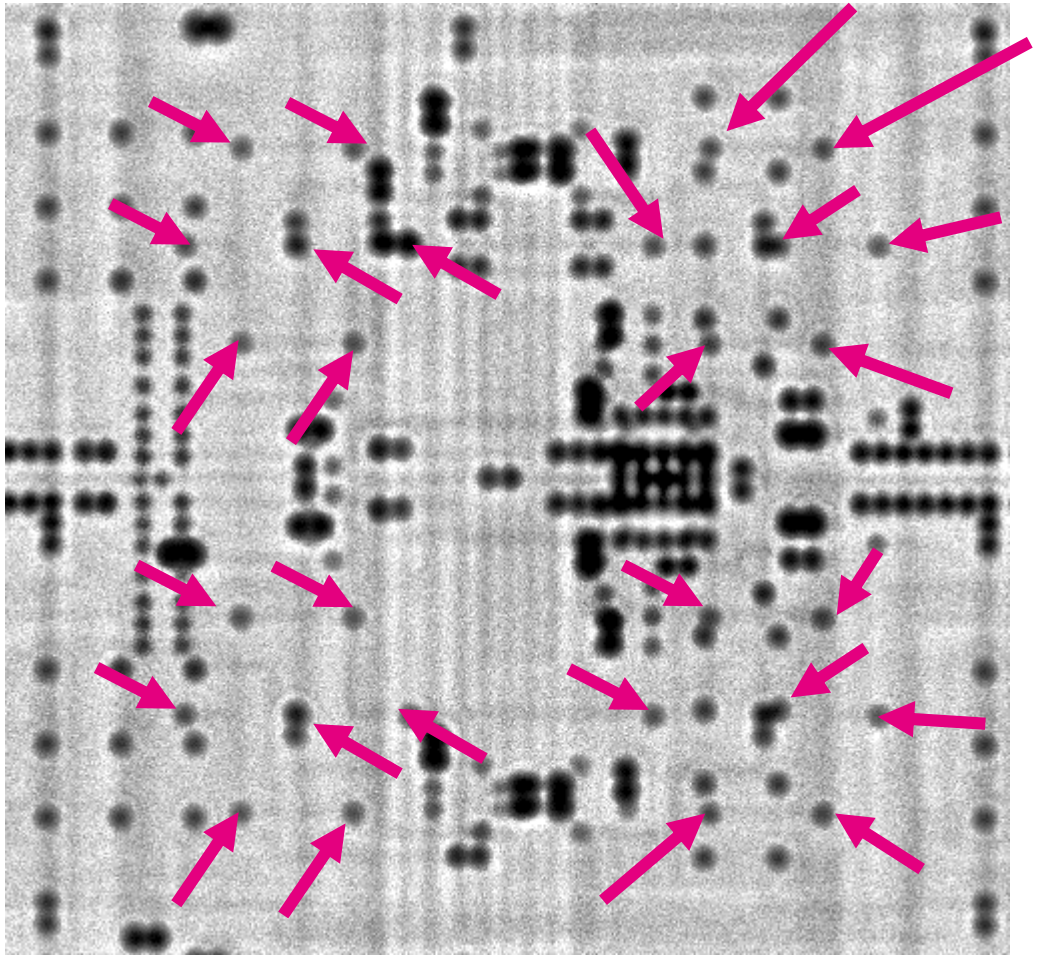
Implementation: Charge Collection



0.5 μW/pixel without power pulsing

Pixel “Portrait”

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.,

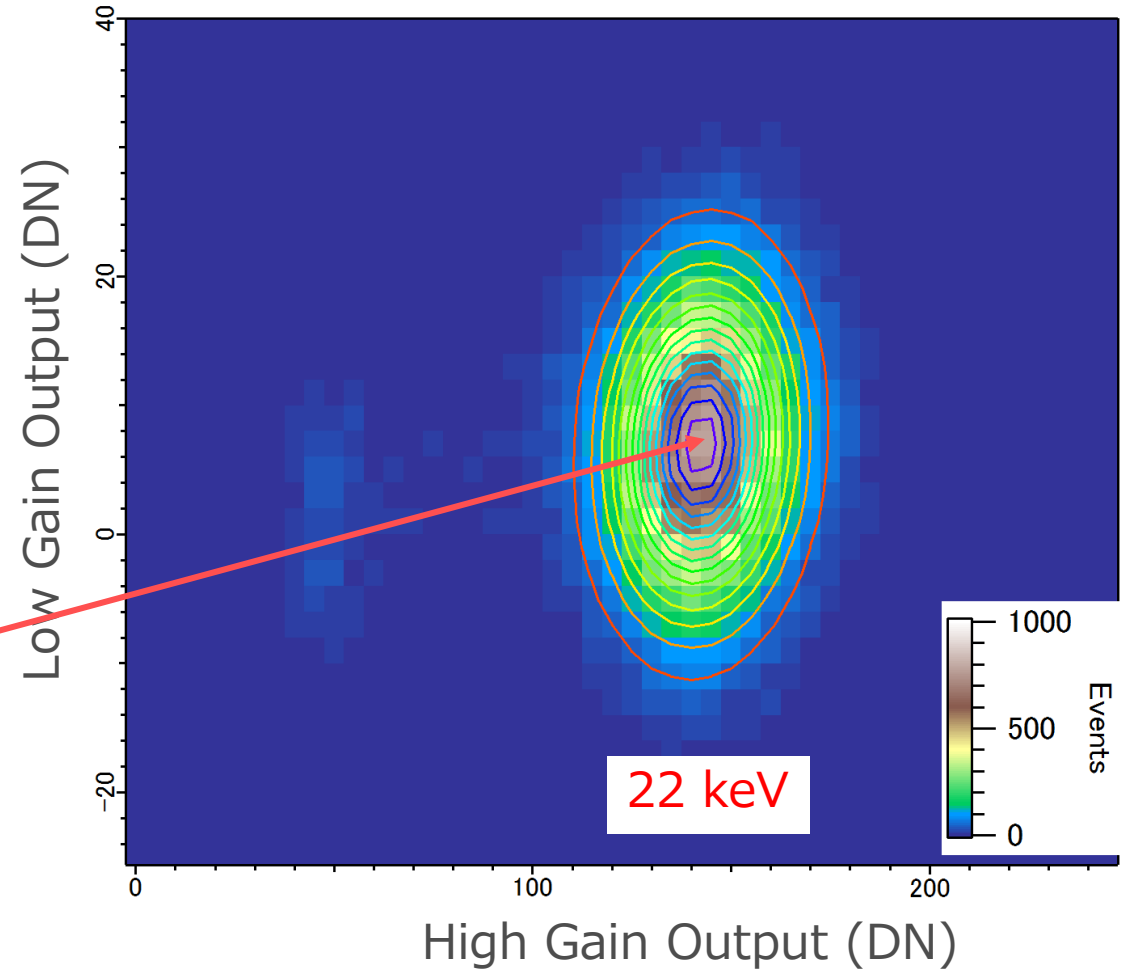
Preliminary

K. Ozaki et.al.,

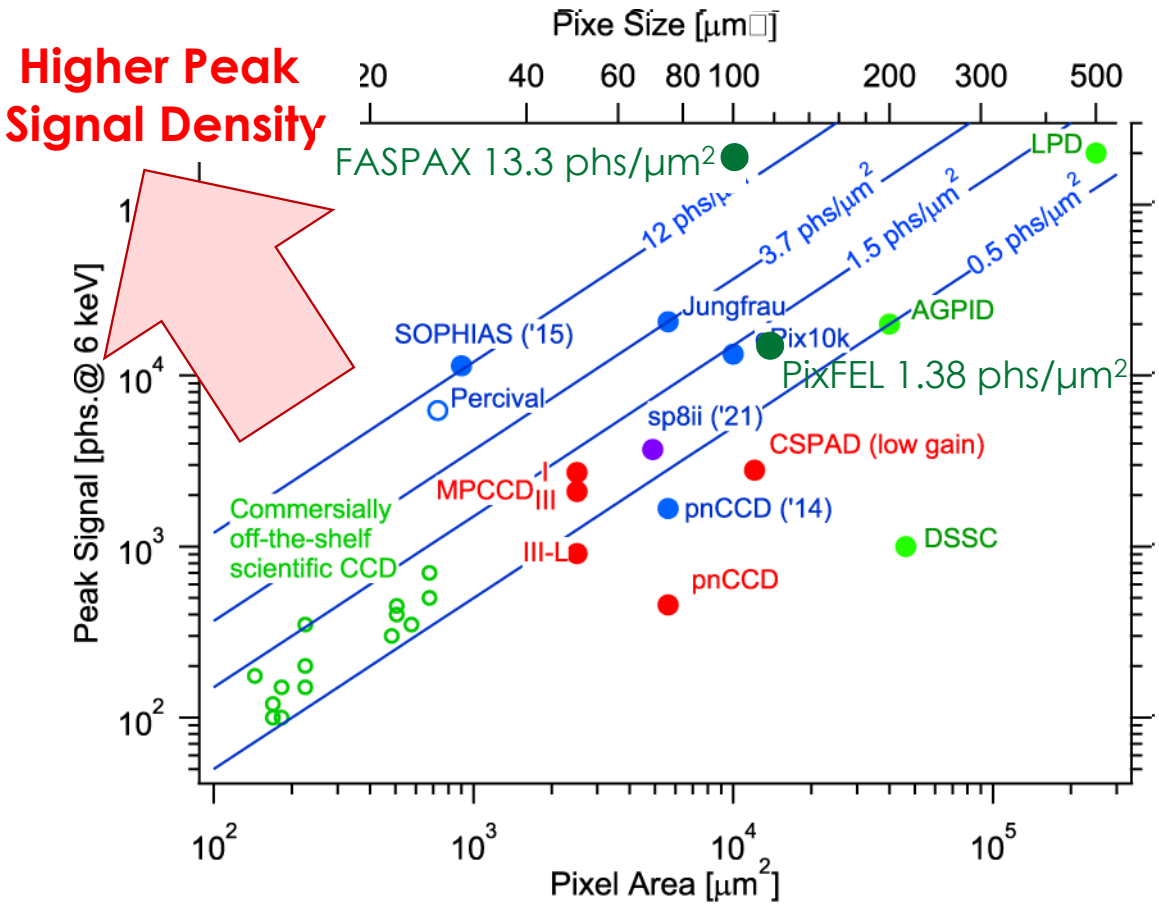
Experiments: Is Charge Division Principle Working?

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

Peak
High: 142.36 ± 0.050 (2σ)
Low: 6.953 ± 0.014(2σ)
(cf) w/o charge division
→ Low = 0 DN



Peak Signal vs. Pixel Area



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

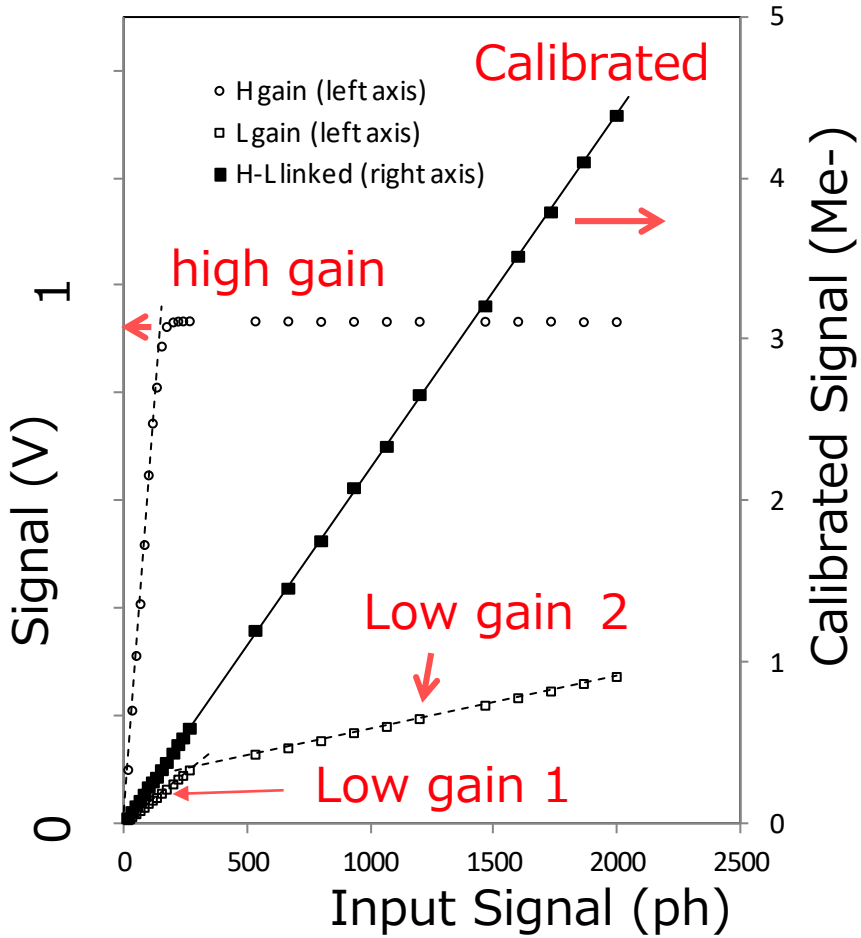
$$N_{ph,max} = \frac{Q_{max}}{(E_{photon}/W)}$$

$$Q_{max} = C\,V_{max} = \boxed{S}\,(C_{density}\,V_{max})$$

Pixel Size **F.o.M.**

Detectors for European XFELs (LPD, AGPID, DSSC, PixFEL), spectroscopic imagers (pnCCD, MPCCD phase III-L) are not targeting high peak signal density.

Pixel-by-Pixel Calibration (Update)

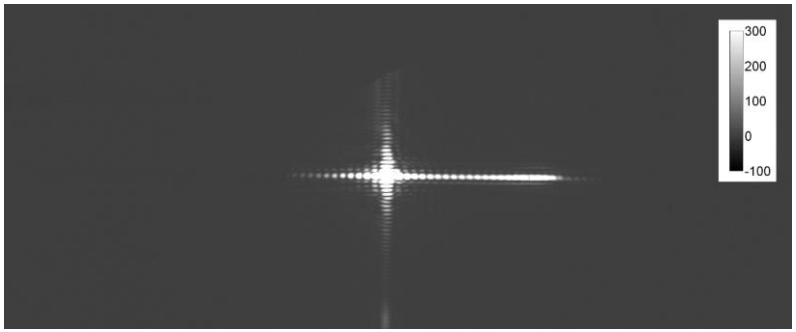


Low gain has a knee behavior.

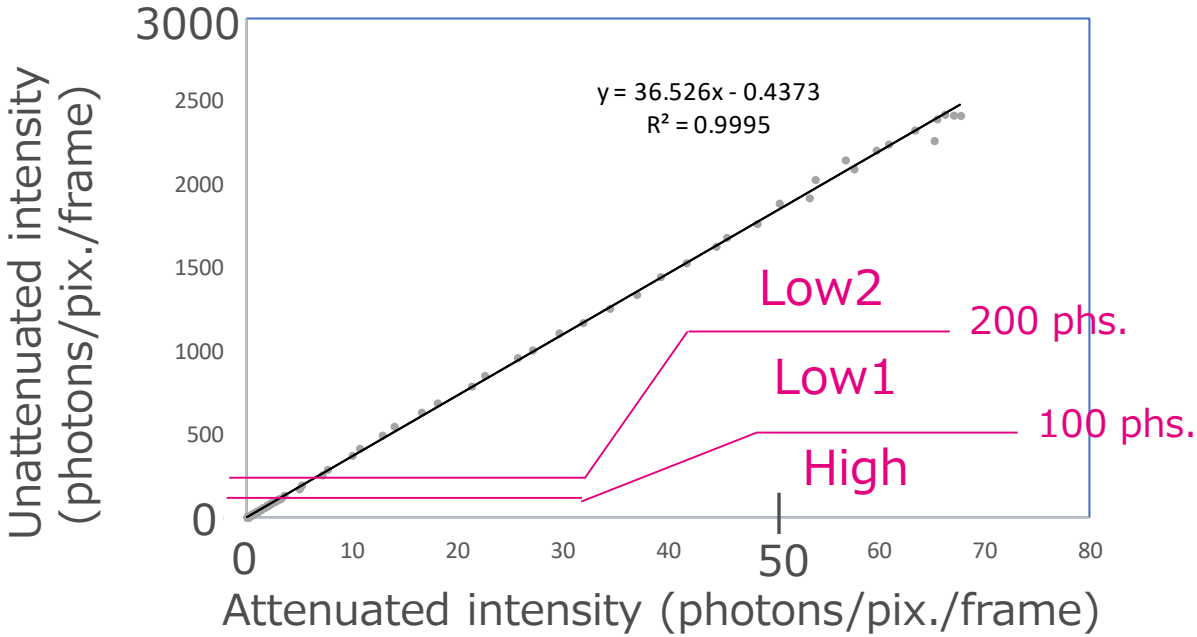
- An updated calibration method for SOPHIAS was established
- Calibration Data collection
  - Around 40 images with varied exposure time
  - Illuminated by optical light instead of X-rays
- Sensor
  - Optical blocking aluminum coating was not impletemted.
- 8 Parameters for a pixel
  - Gain:
    - High, Low1, Low2
  - Offset:
    - High, Low1, Low2
  - Switching points:
    - High->Low1, Low1-> Low2

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.



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

SOPHIAS-L

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

$1/\sqrt{2}$

24 ports with High gain
24 channel ADCs
14 bit depth @12.5 MSPS

$1/\sqrt{2}$

SOPHIAS-L: Design vs. Experiments

Specifications

	Noise [e-]	Sensor Resposivity [uV/e-]
Project Target	< 80	
Design Target	< 60	> 5

Results

	Noise [e-]		Sensor Resposivity [uV/e-]	
	Design	Experiment	Design	Experiment
Pixel L	63	76	4.7	6.3
Pixel M	58	72	5.3	6.6
Pixel S	55	83	5.8	5.8

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

Now

- 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.

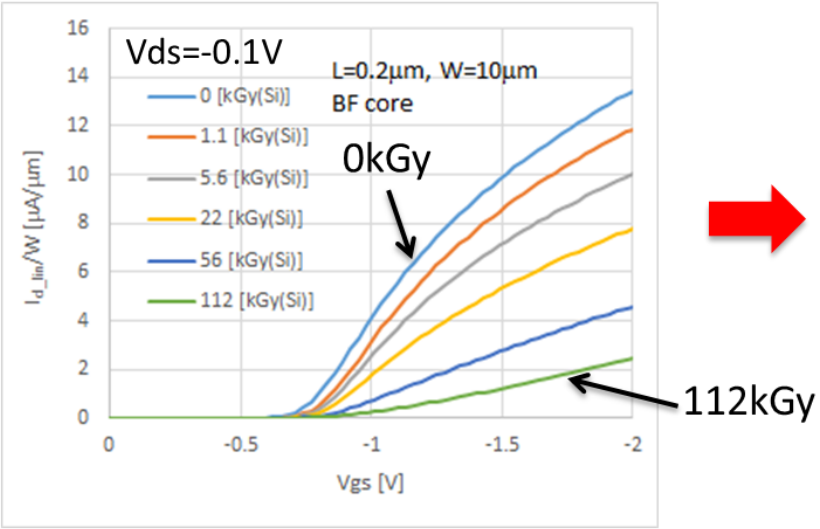
Future project possibility for XFEL/SR?
A step forward

I. Kurachi, "Analysis of Effective Gate Length Modulation by X-Ray Irradiation for Fully Depleted SOI p-MOSFETs, IEEE Trans. on Elec. Dev. Vol. 62, Aug. 2015, pp. 2371-2376

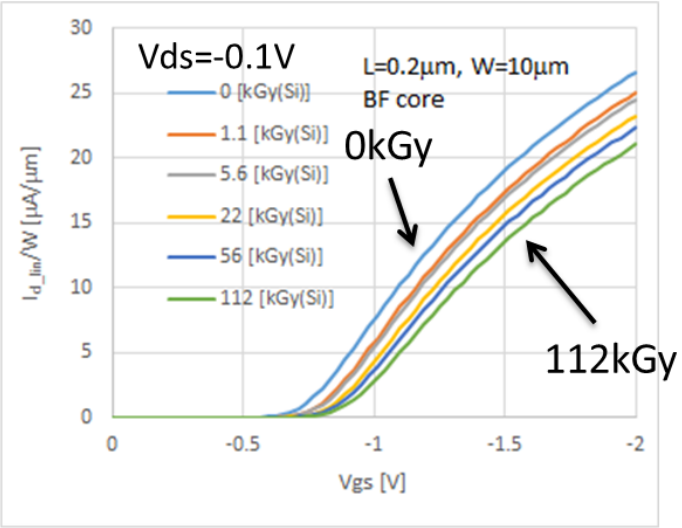
Id-Vg Characteristics in Triode Region

Linear Id

Previous Process



LDD Dose x 6



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

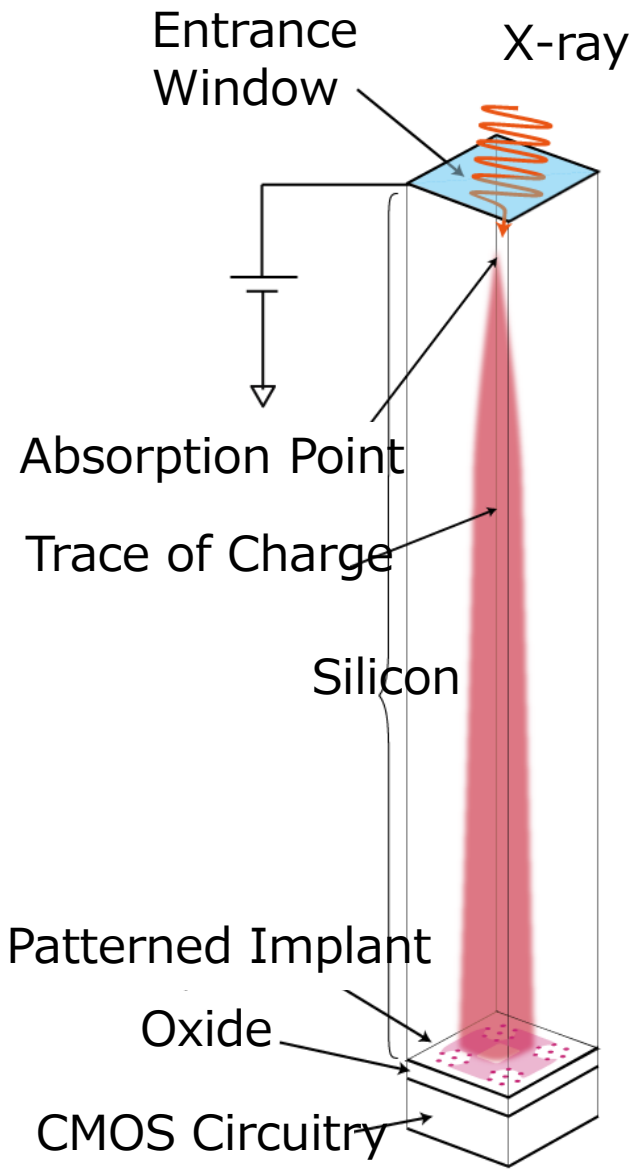
- Implemented with parallel CPU calculation code within a desktop PC
  - Intel Xeon CPU E5-1650 v4 3.6 GHz

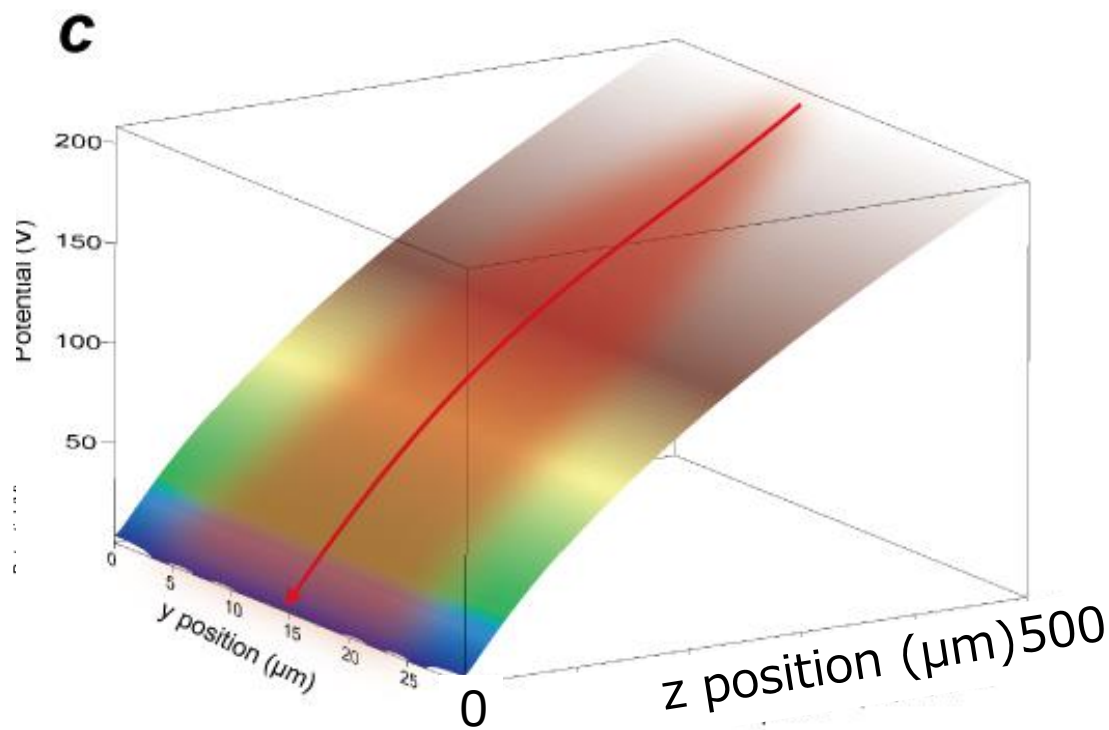
- Method
  - Memory Access Pattern was optimized
  - SIMD vectorization within Intel® Xeon® Processor

- 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)*

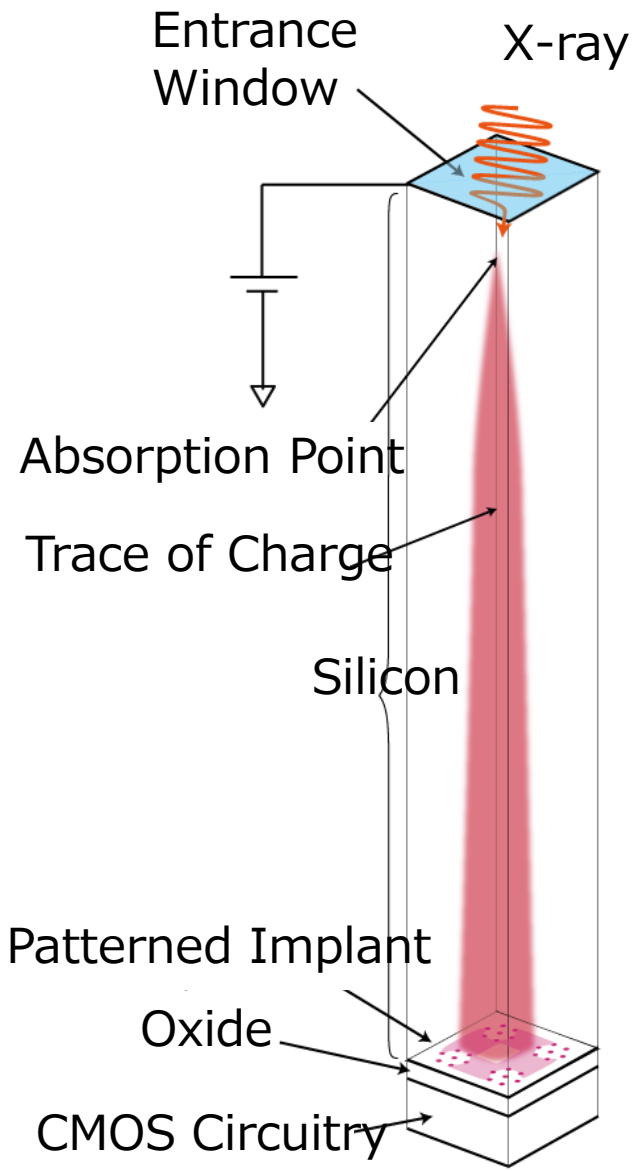
Implementation: Charge Dynamics

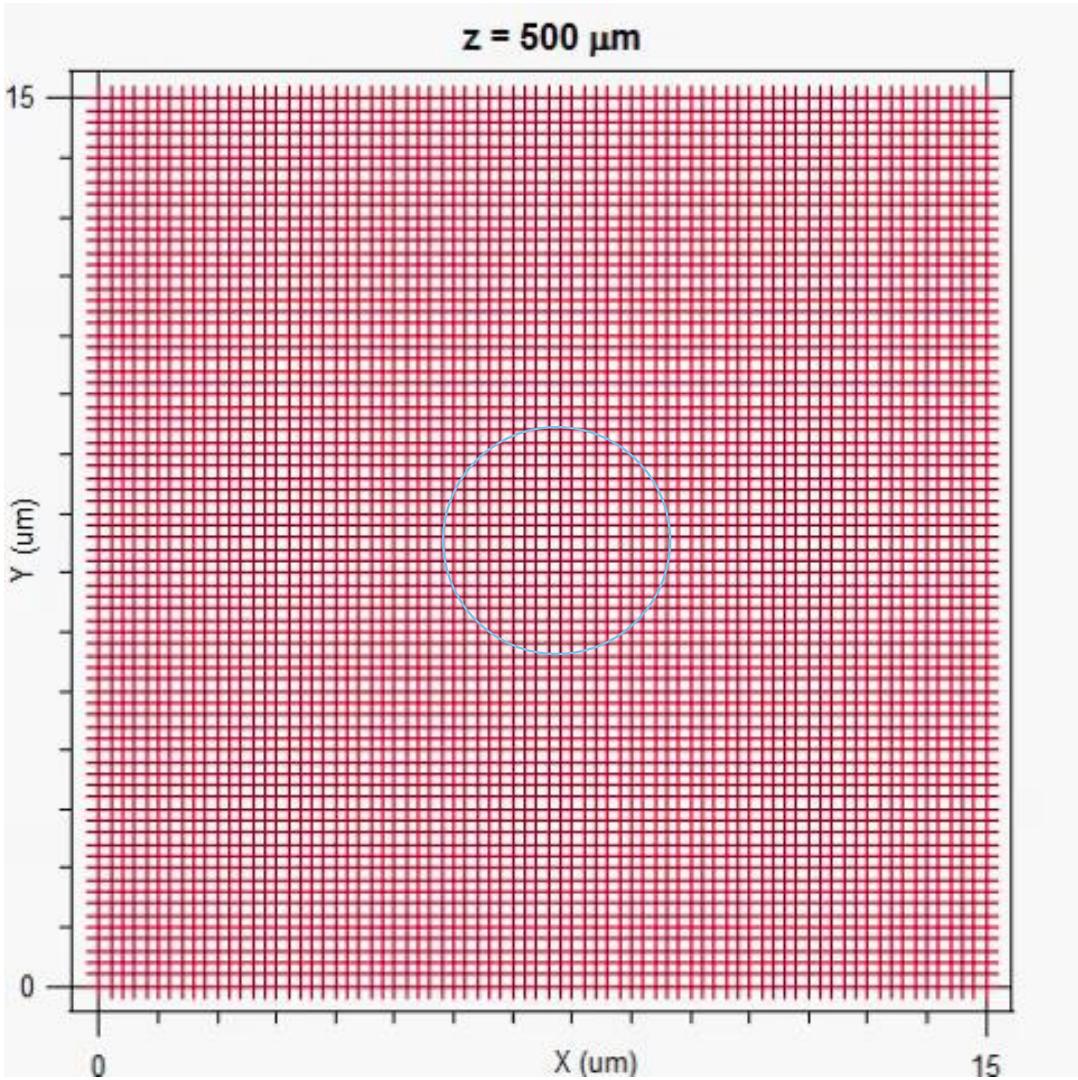




Implementation: Charge Division

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





Implementation: Charge Division

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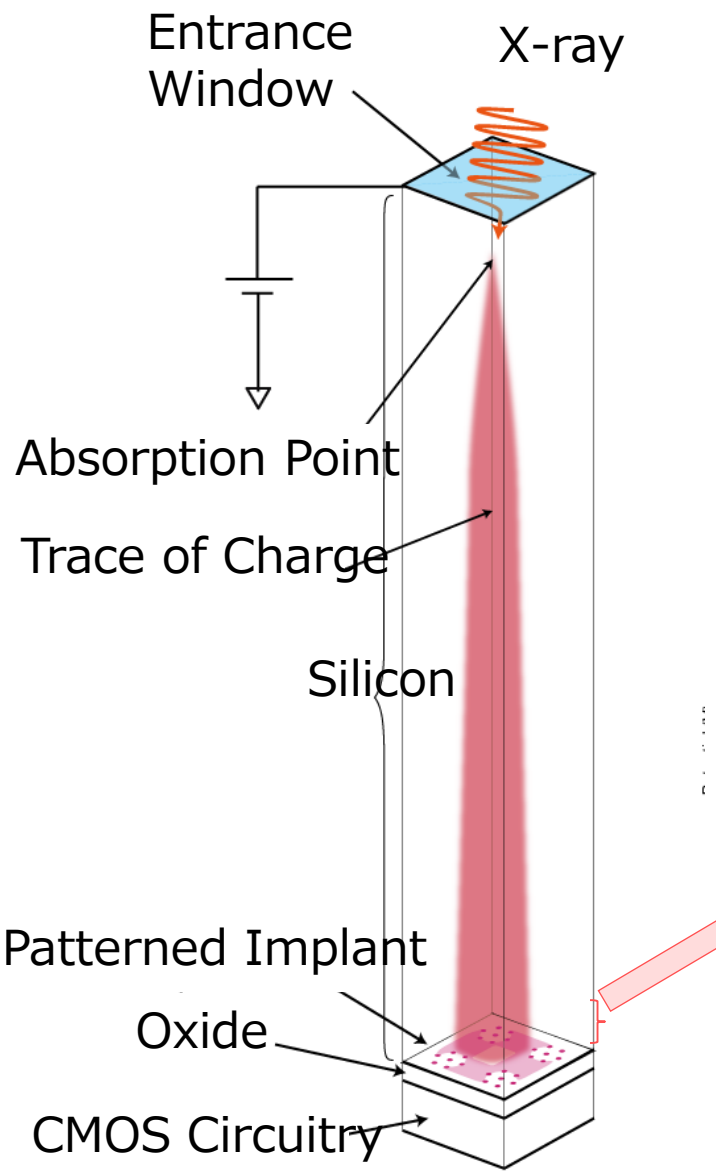
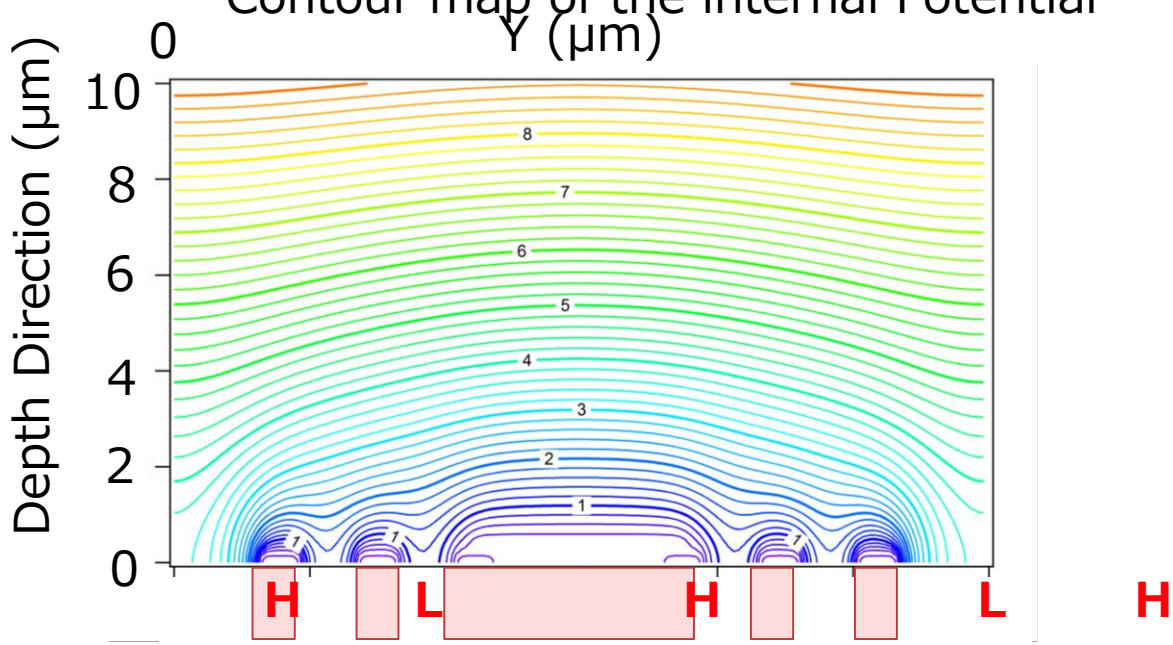


Contour map of the internal Potential



- 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.