Silicon-On-Insulator Pixel Detector Project

Imaging Devices Laboratory

Performance Improvement of the Event-Driven SOI Pixel Detectors for X-ray Astronomy

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Outline

- Introduction for X-ray Astronomy
- XRPIX Series
- Improvement of energy resolution for event-driven mode
  -> XRPIX6D / XRPIX6E
- Summary

Detector for X-ray Astronomy

Standard imaging spectrometer of modern X-ray astronomical satellites ...

-> X-ray CCD : Wide and fine imaging with the sensor size of ~20 – 30 mm, pixel size of ~30 μm sq.
Fano limited spectroscopy with the readout noise ~3 e^- (rms).

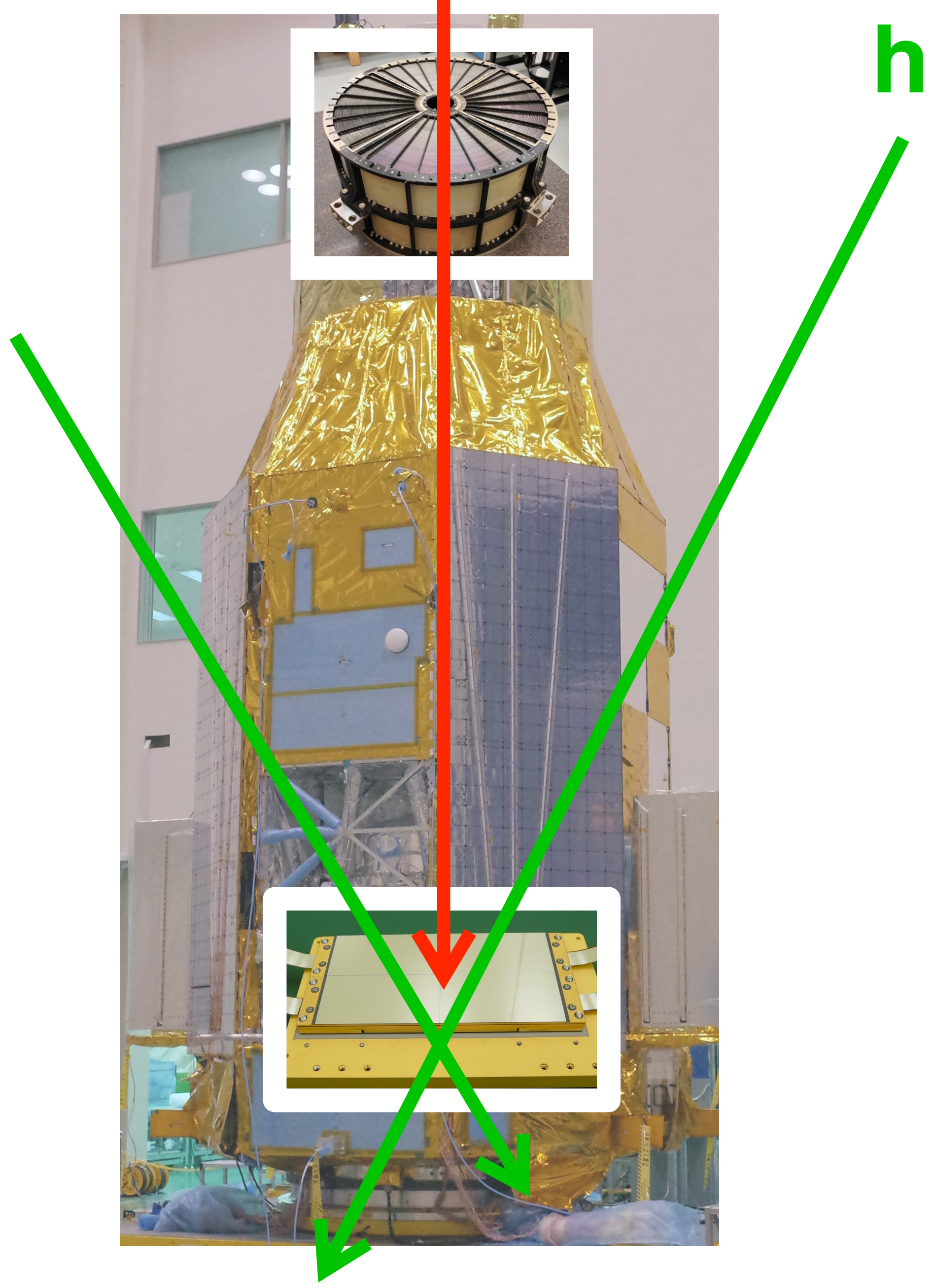
However ...

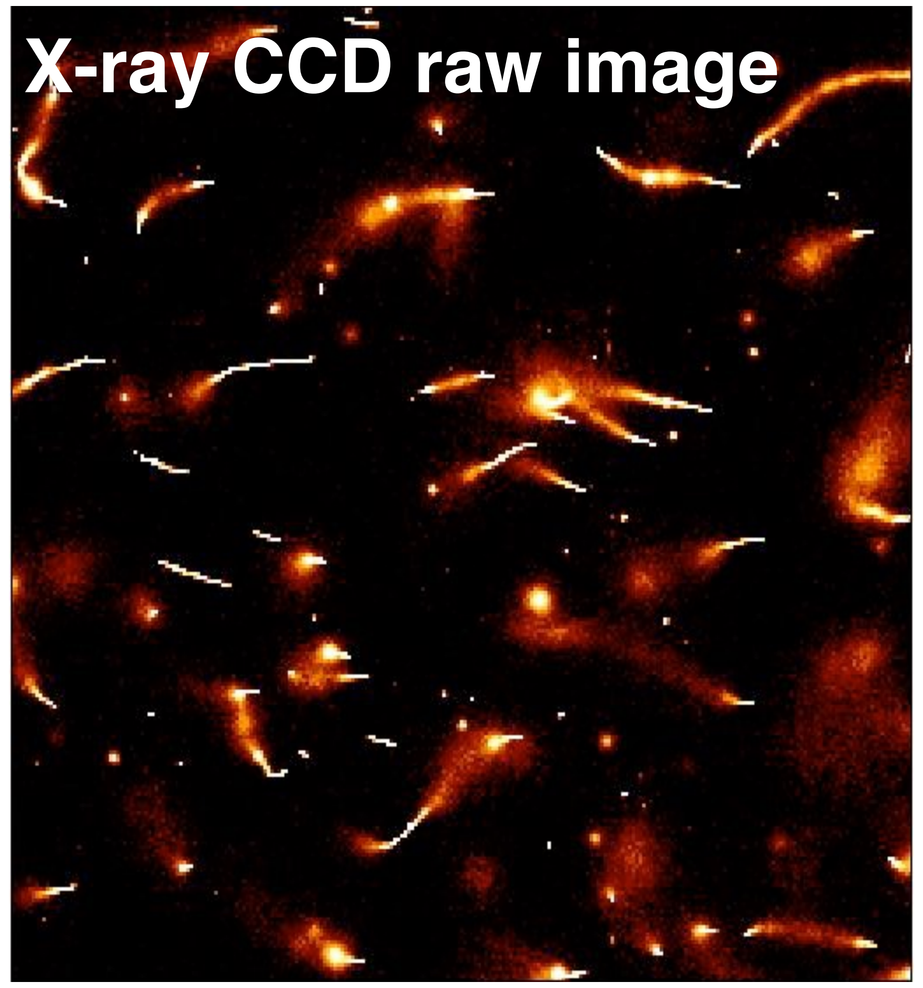
-> **Non X-ray background** (NXB) above 10 keV is too high to study faint sources.

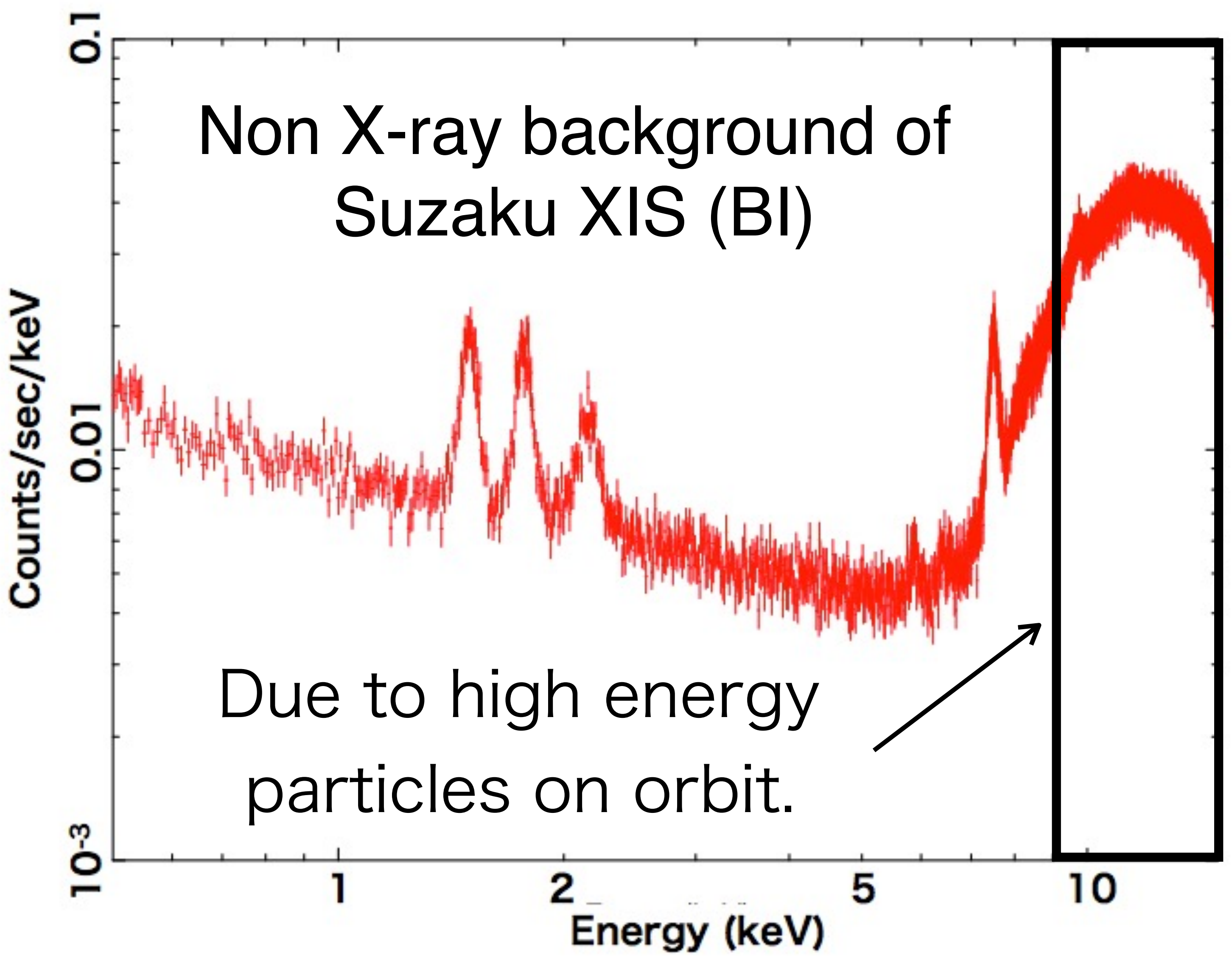
-> **The timing resolution** is too poor (~sec) to make fast timing observation of time variable source.

X-ray

high energy particle







XRPIX for Future X-ray Astronomy

The performance required of a future X-ray astronomical satellite is the following ...

Target Specification

(1) FWHM ≤140 eV at 6 keV

Readout Noise : req. ≤ 10 e^-/ goal ≤ 3 e^-

(2) <100 μm pitch pixel

(3) ~10 μs per event readout (Trigger, Direct Pixel Access)

(4) Wide energy range : 0.3– 40 keV (Thick Depletion Stacks)

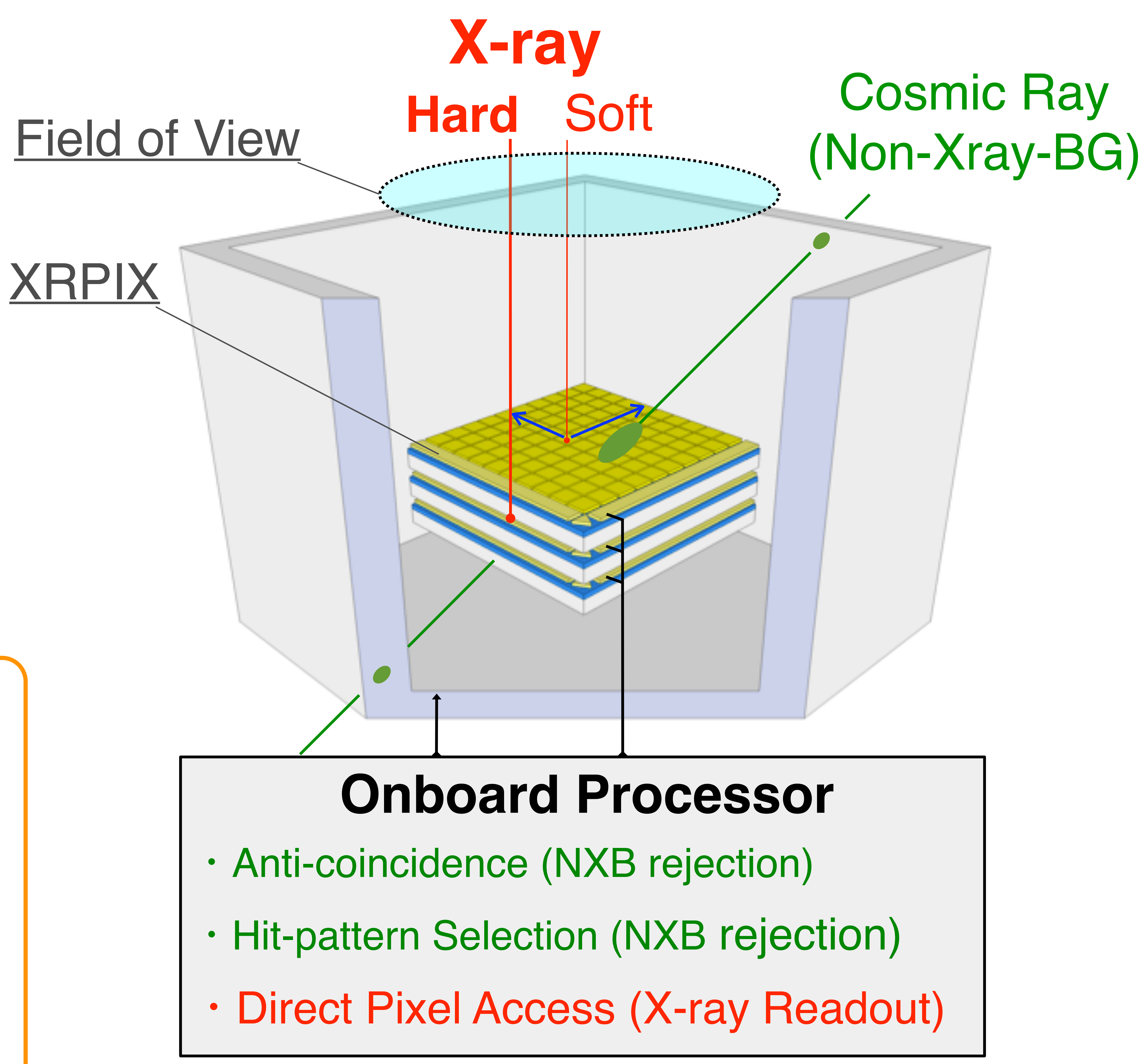
In order to achieve specification, we have been developing X-ray SOI Pixel Detector (XRPIX).

XRPIX has self-trigger function !

-> Realization of event-driven

-> Improve observation efficiency by reducing high-energy electrons generated by charged particles and gamma rays.

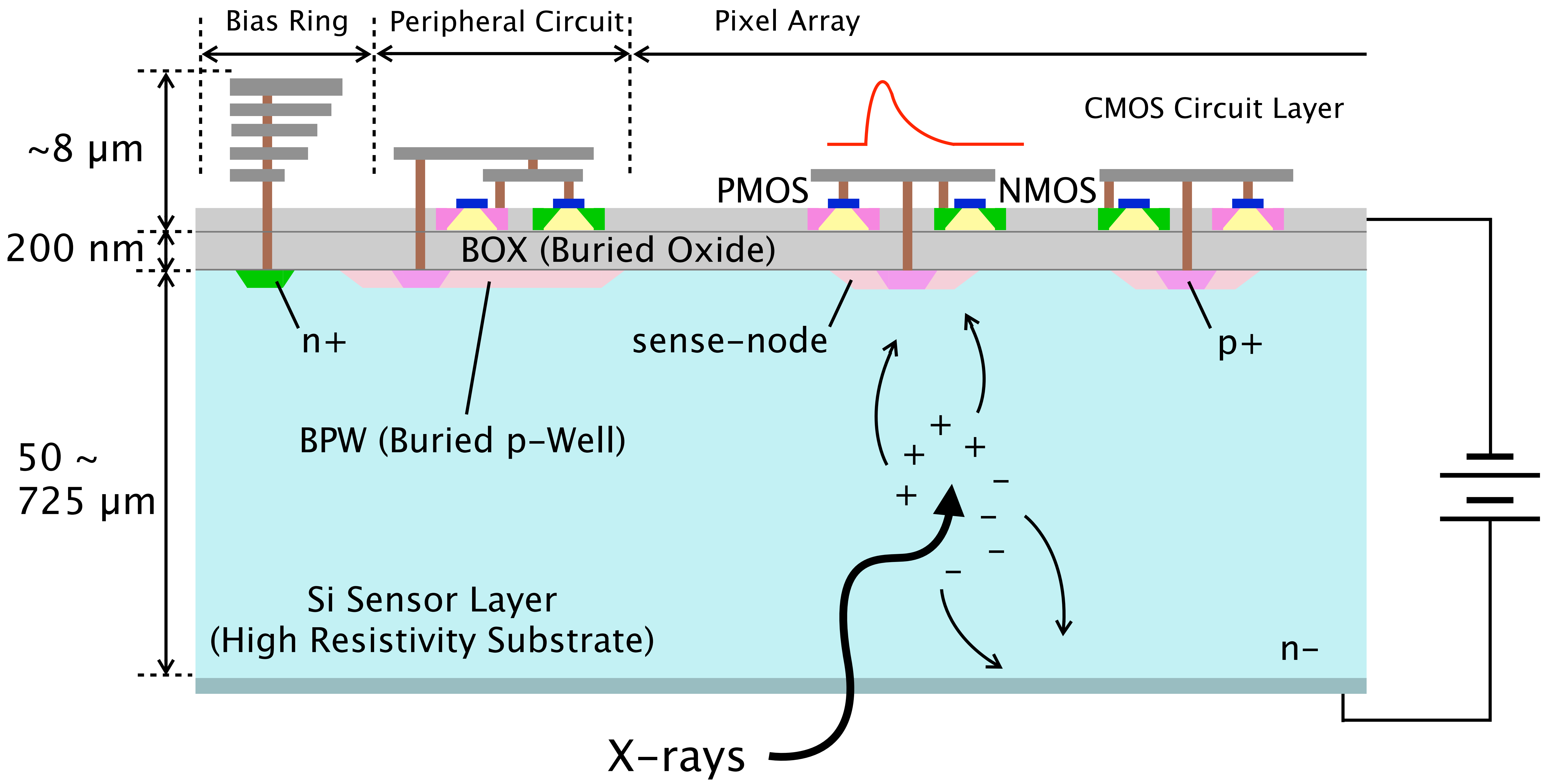
X-ray SOIPIX with Active Shield



SOI Pixel Detector

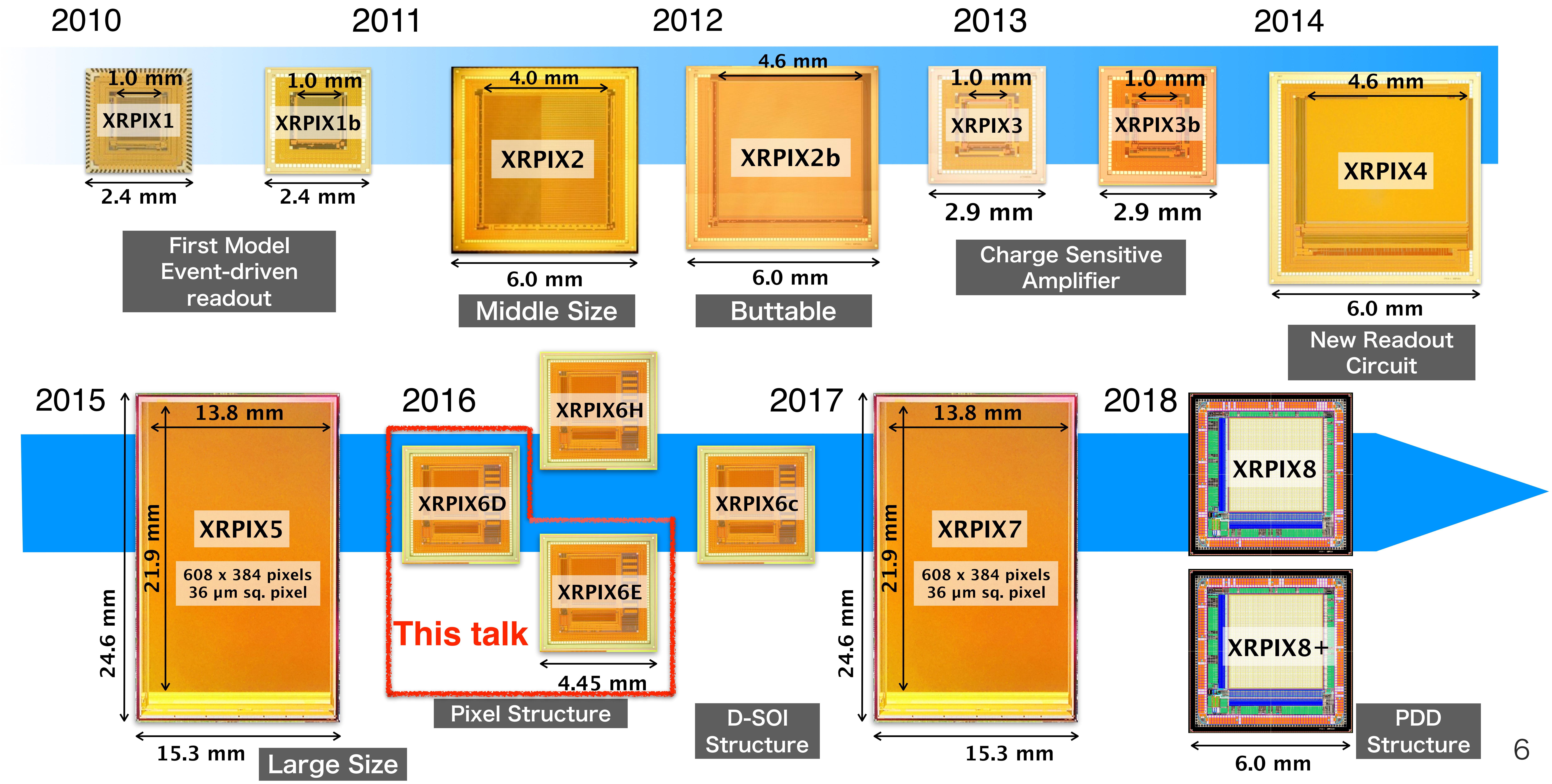
- A monolithic pixel detector with silicon-on-insulator (SOI) CMOS Technology
  -> <u>0.2 μm fully-depleted (FD) - SOI pixel process</u>

- SOI Pixel Detector (SOIPIX) : Processed by LAPIS Semi. Co., Ltd.



Both high X-ray sensitivity and advanced signal processing are compatible!

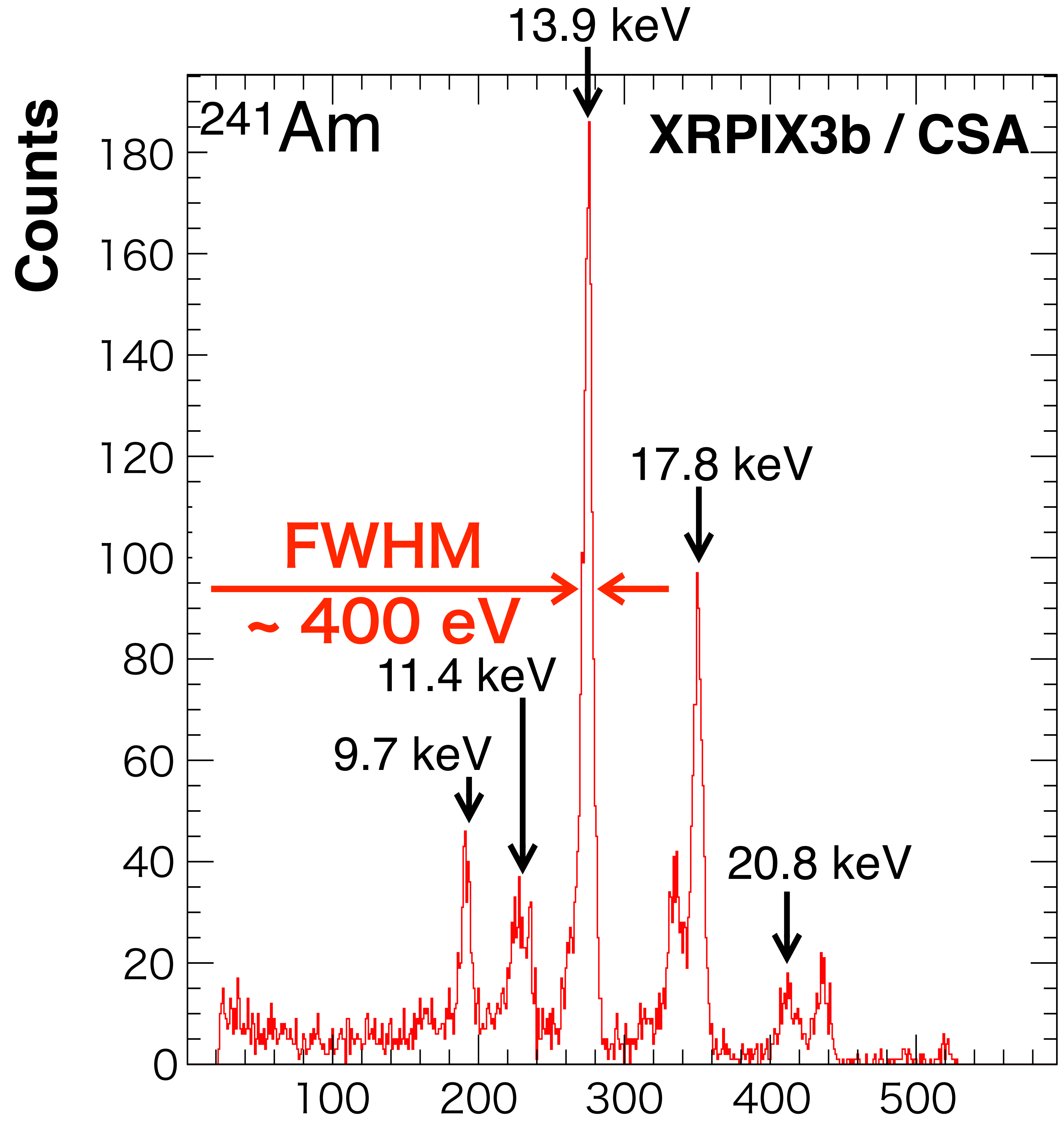
History of XRPIX Series



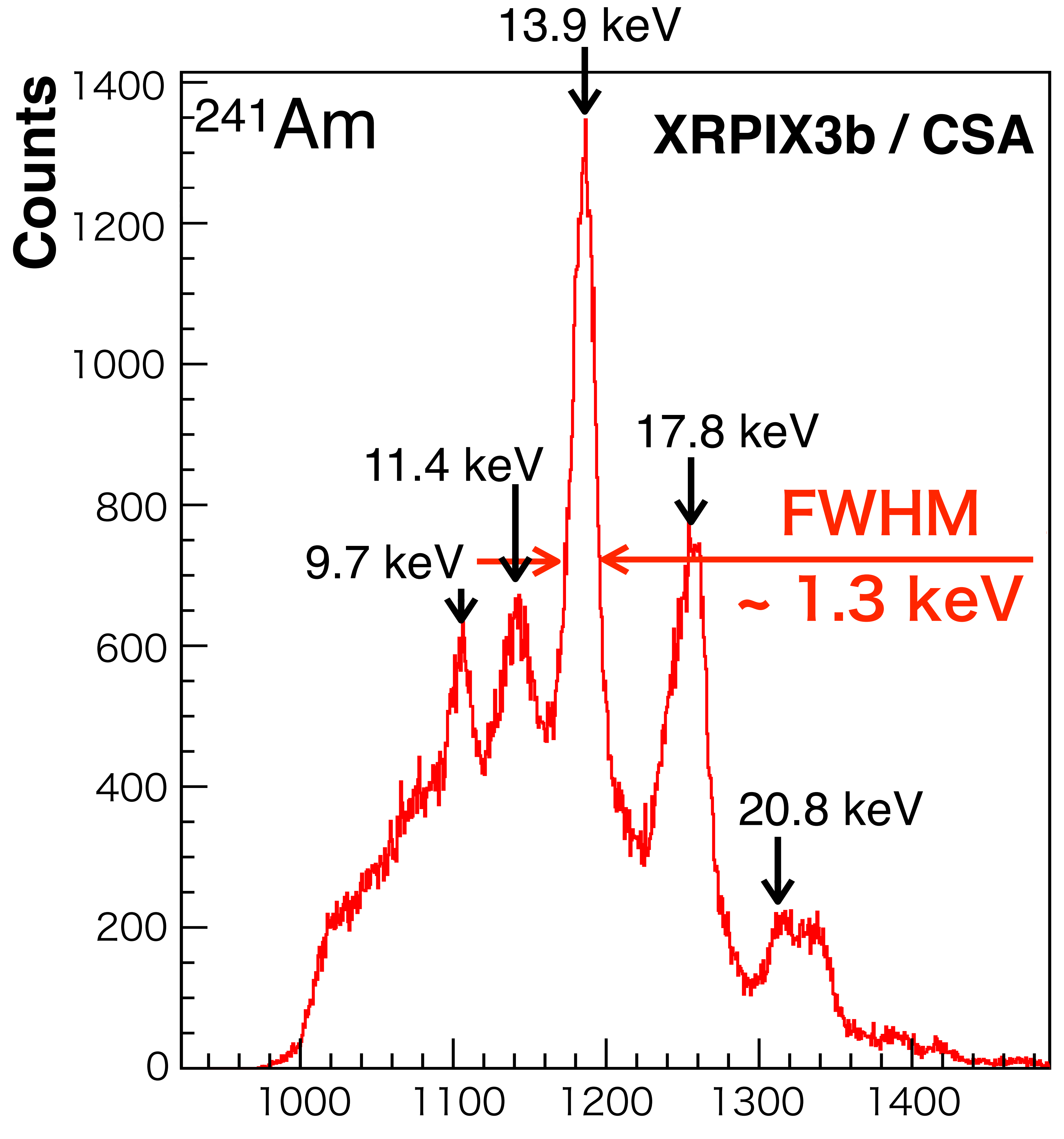
Signal Deterioration by Event-driven mode

We had a critical issue in event-driven mode… The signal is degraded…

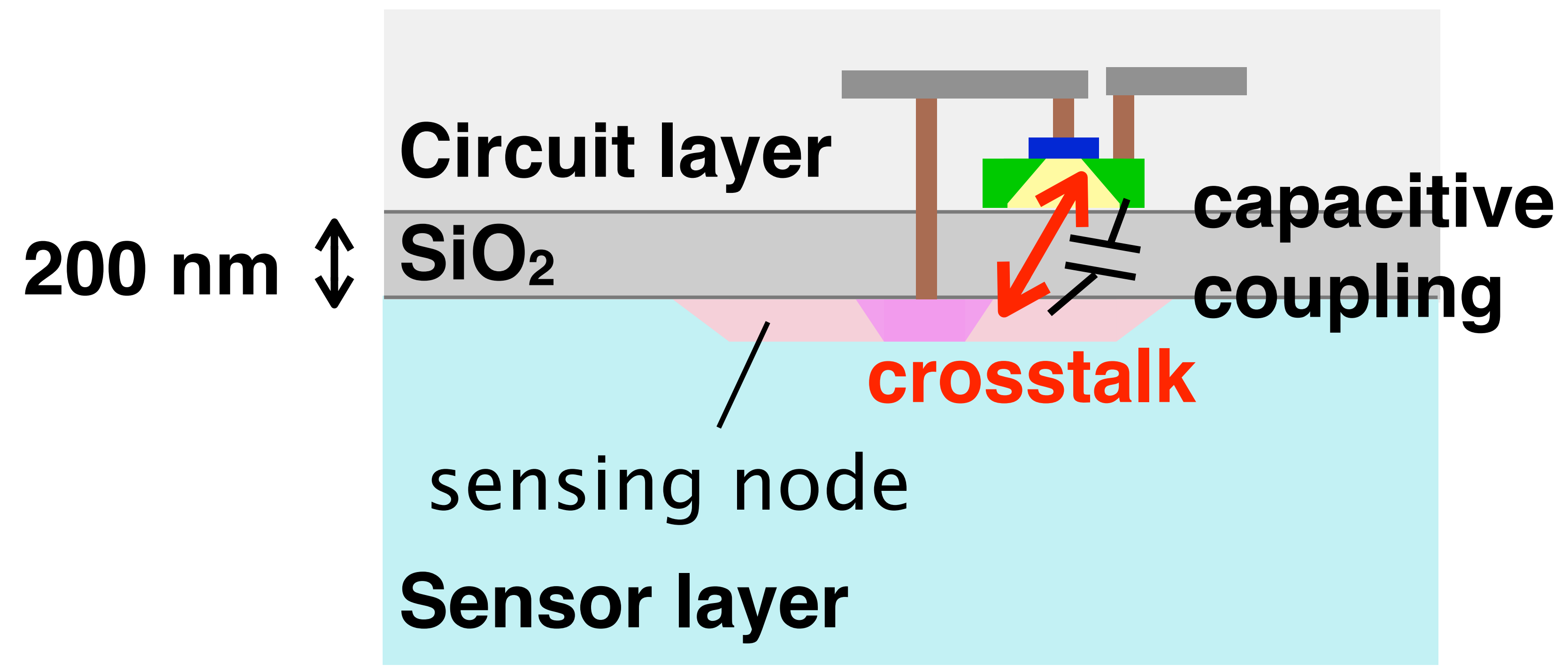
Frame readout mode
(not use trigger)



Event-driven readout mode
(use trigger)

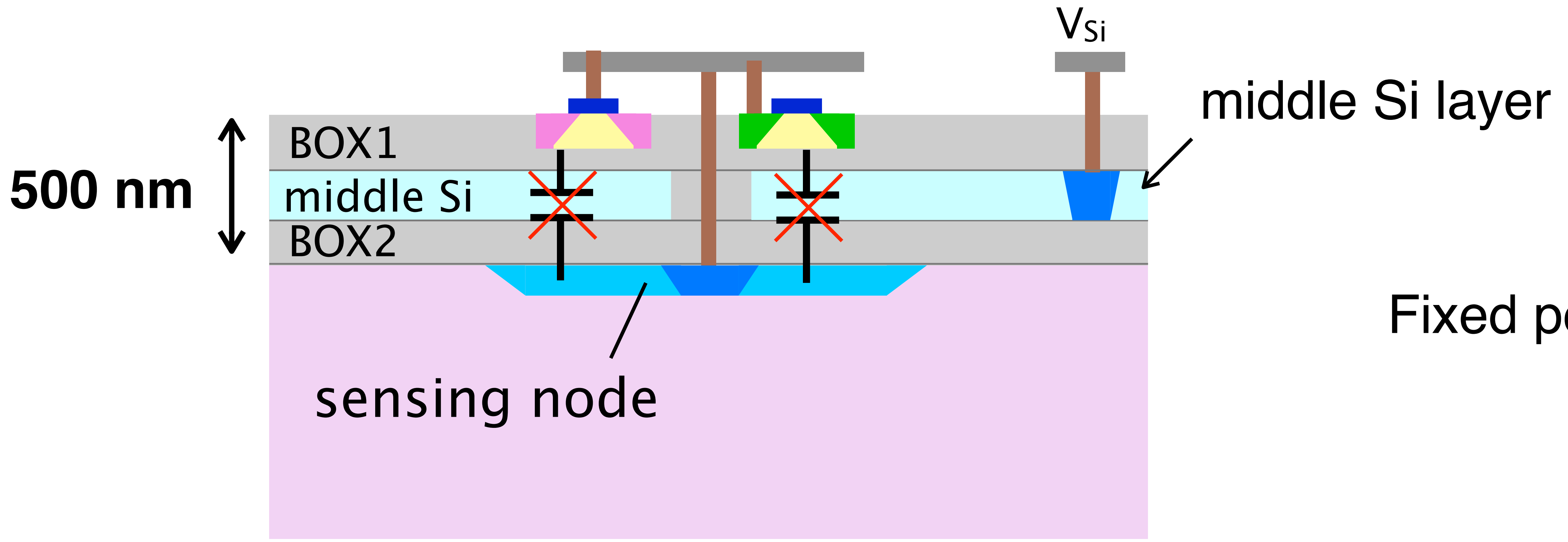


Improvement for interference issue

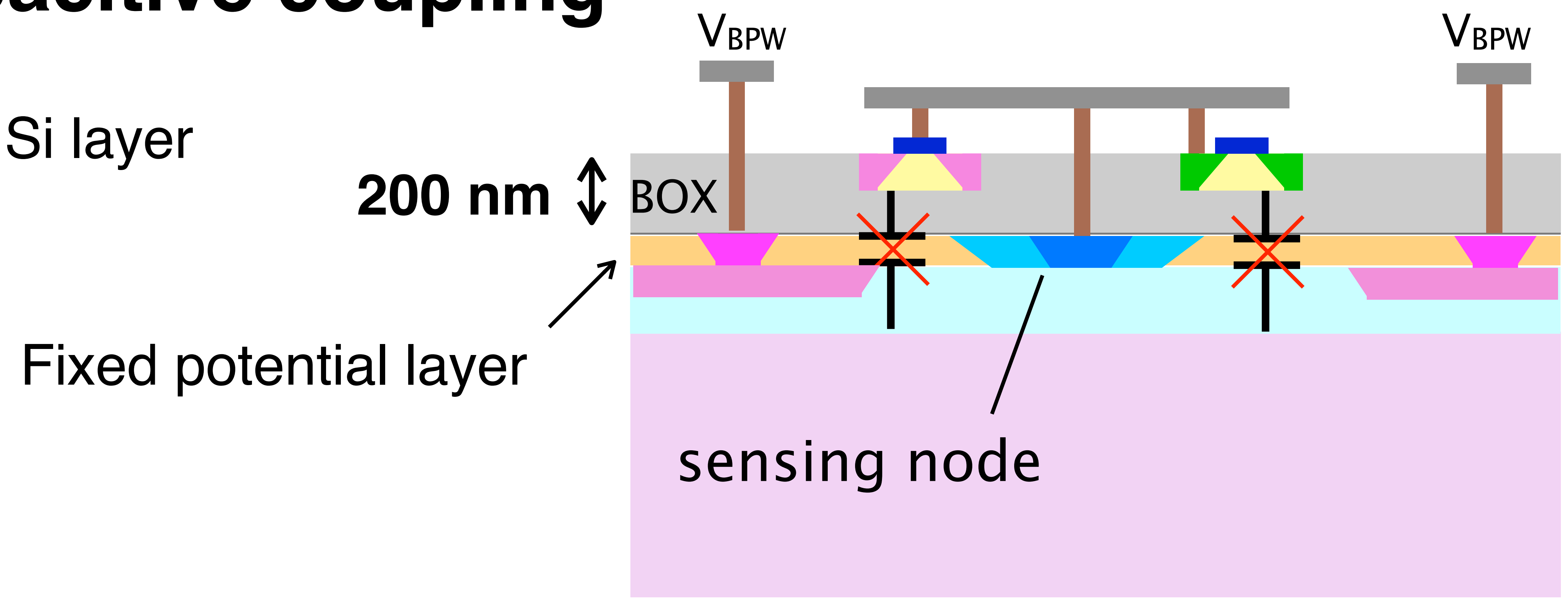


- We understood that the signal degradation was caused by interference of digital signal in the pixel.
- The digital signal transmits a signal change of the comparator inversion to the analog signal via the parasitic capacitance.
  -> It is important to suppress capacitive coupling
  * Takeda+2014, Ohmura+2016

new approach to suppress capacitive coupling



Double SOI (D-SOI) structure
-> XRPIX6D

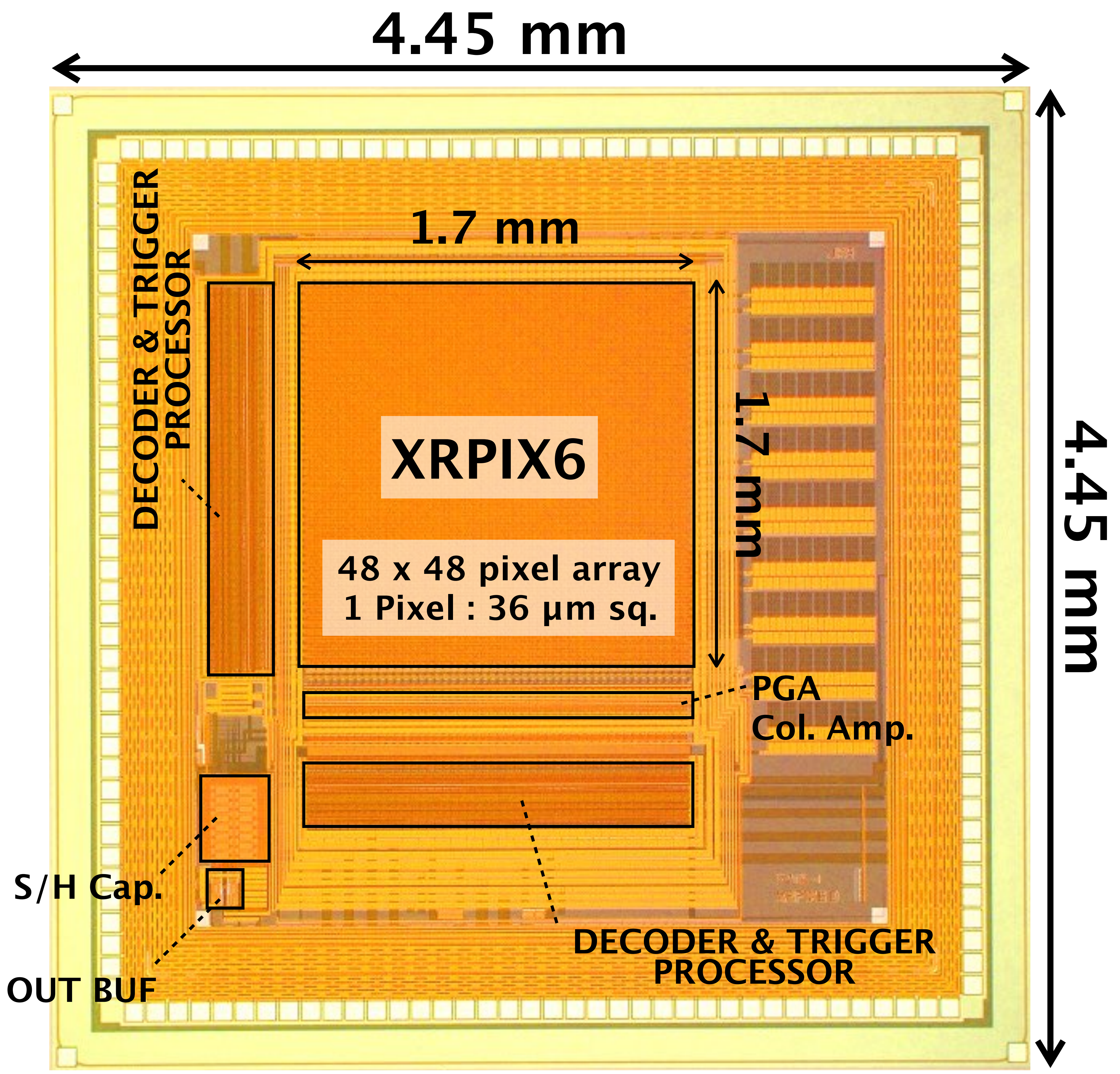


Pinned Depleted Diode (PDD) structure
-> XRPIX6E

XRPIX6 Design Specification

We aim to improve spectroscopic performance by developing advanced sensor structure.

XRPIX6H -> Conventional Single-SOI
XRPIX6D -> Double-SOI
XRPIX6E -> Pinned Depleted Diode (Single-SOI)



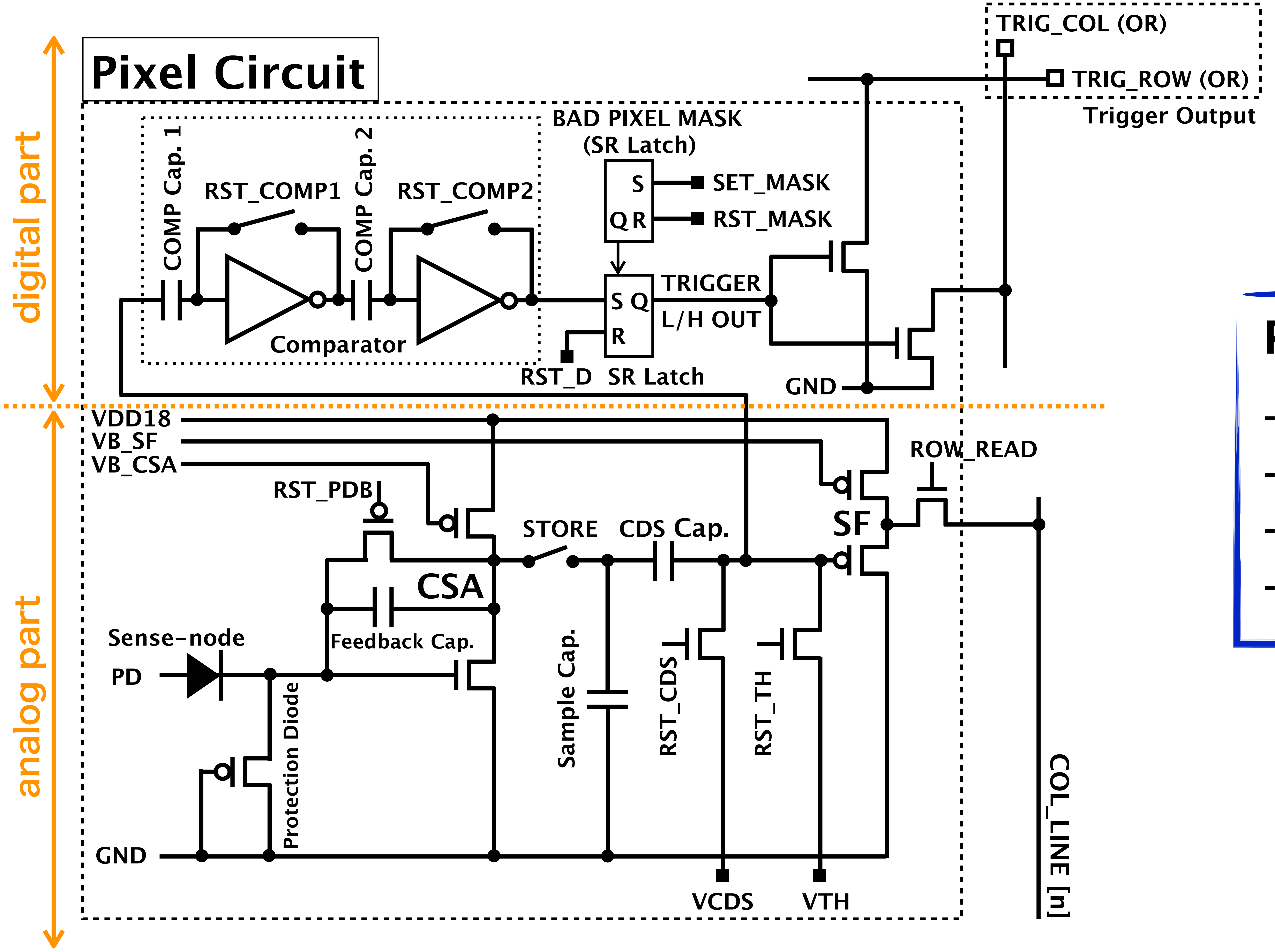
Components

- Chip size : 4.45 mm x 4.45 mm
  (Effective area : 1.7 mm x 1.7 mm)
- Pixel size : 36 μm sq.
- # of pixel : 48 x 48 (= ~2.3k)
- Thickness of sensor layer
  -> 300 μm (CZ wafer / FZ wafer)

Other

- Programmable Gain Amplifier (PGA) circuit for column line.
- Differential output of signal and pedestal level.
- We considered more suitable architect constitution for event-driven readout.
  -> 8 x 8 pixel readout per unit.

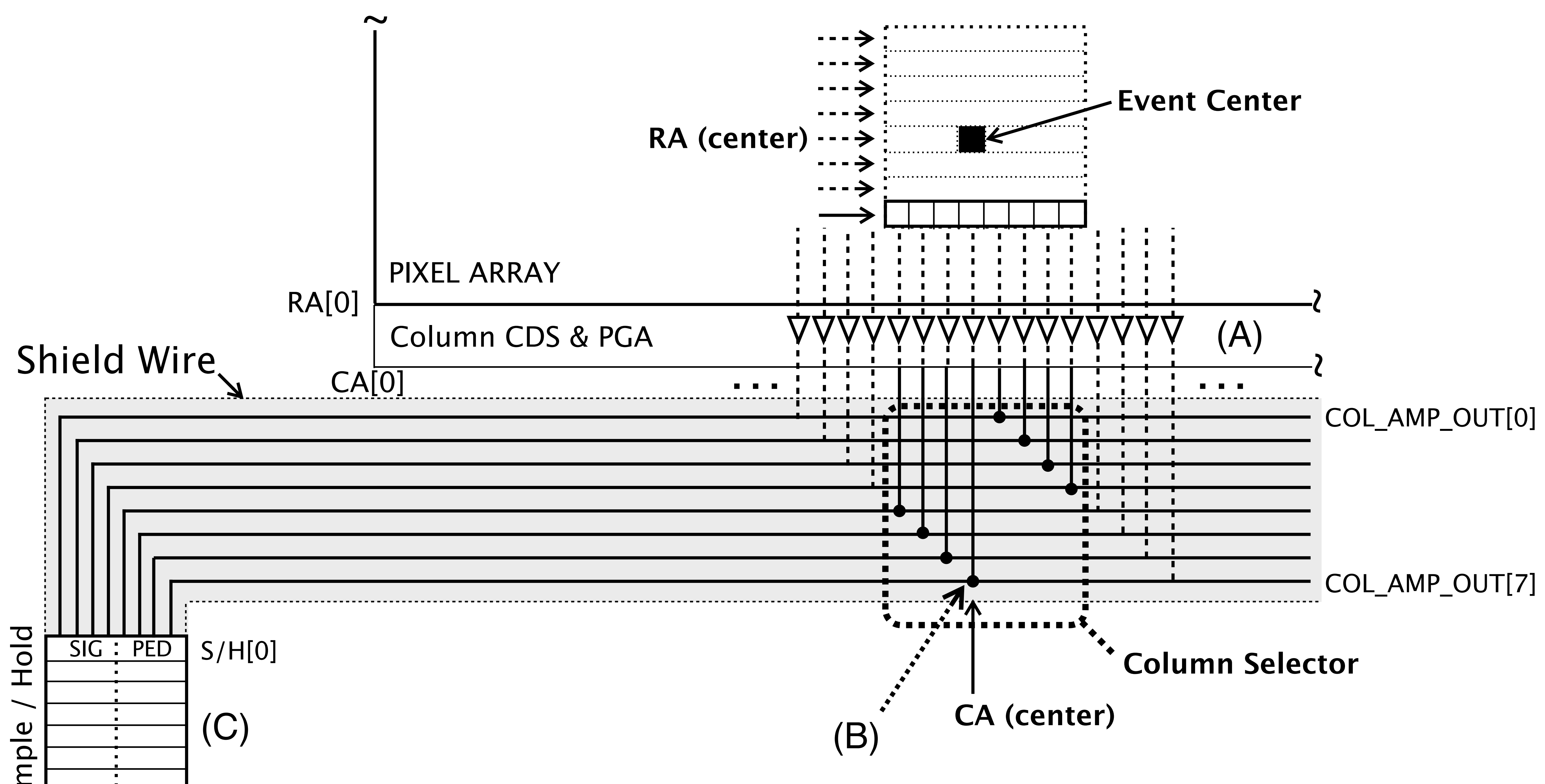
Pixel Circuit

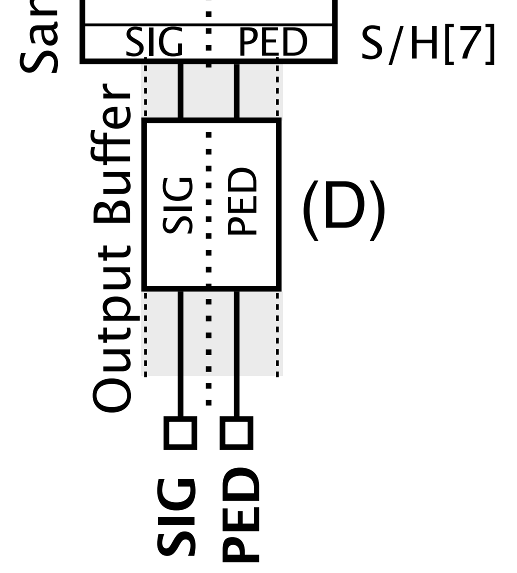


Pixel Circuit consists of …

- Charge-sensitive amplifier (CSA)
- Correlated Double Sampling (CDS)
- Inverter-chopper type comparator
- SR Latch for bad pixel mask

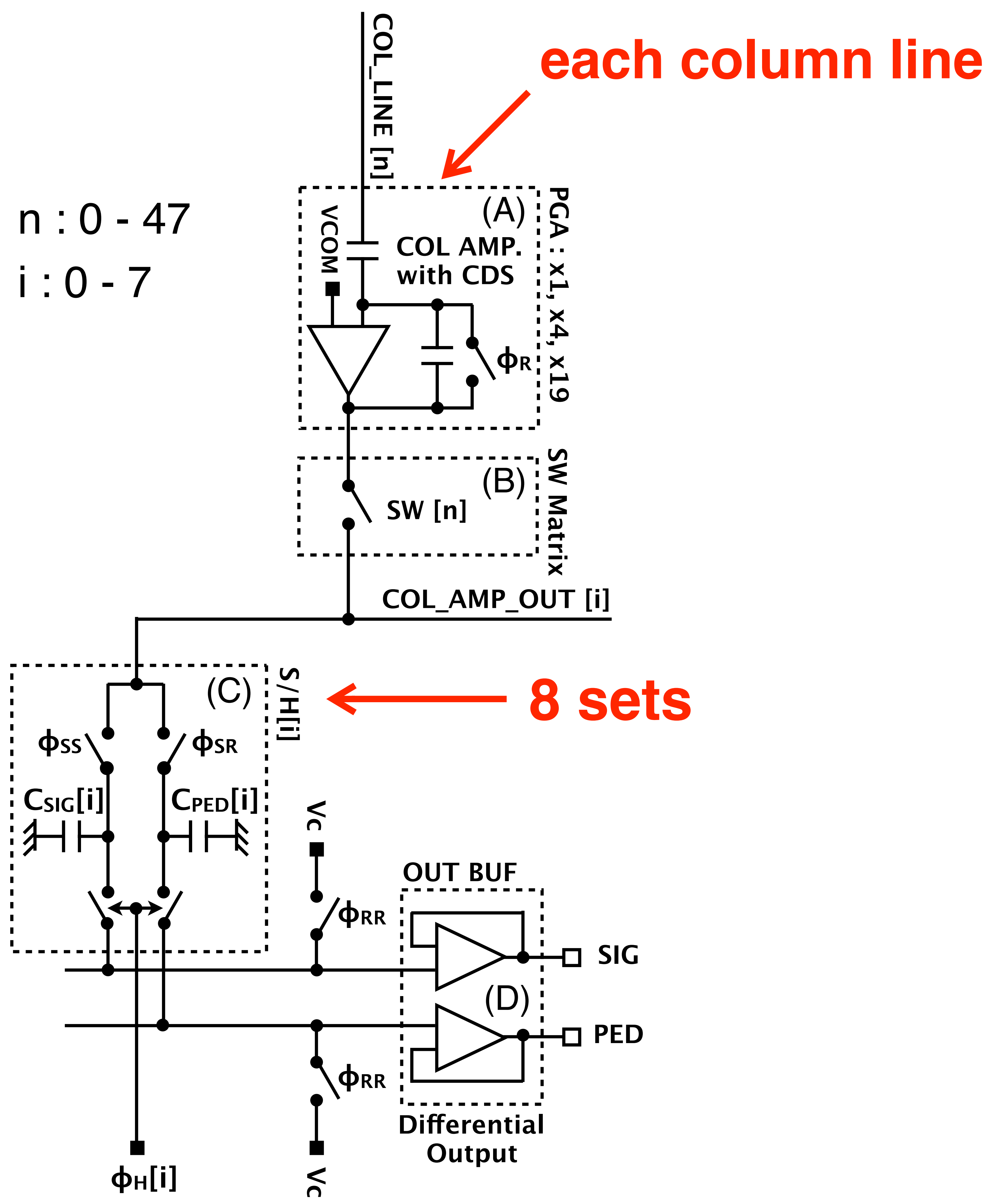
Analog Readout Circuit





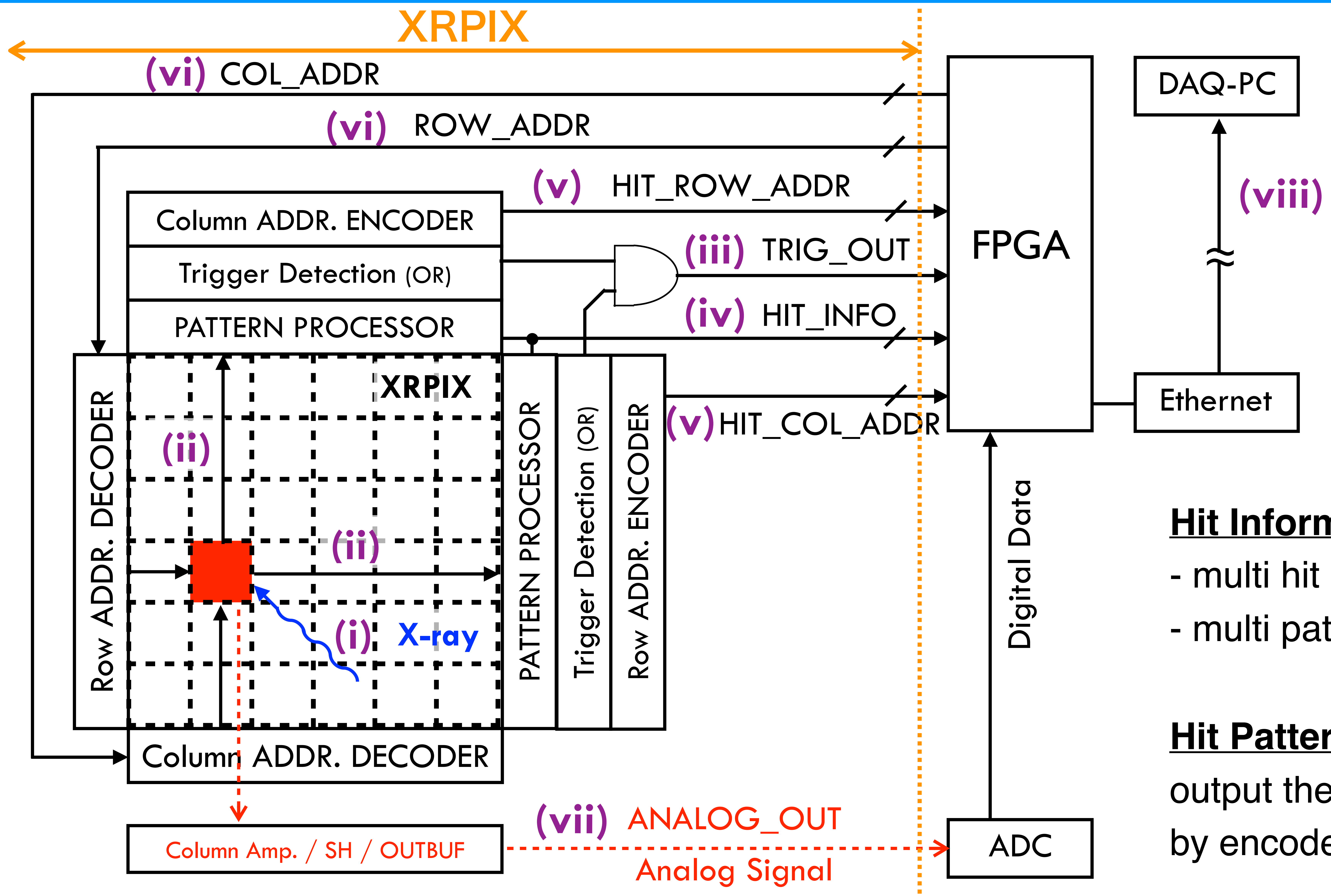
(A) Column amplifier with programable gain.
(B) Switch matrix
(C) Sample / Hold Capacitance
(D) Output buffer

Readout Pixel Unit : 8 x 8 pixels
S/H Cap. : 8 sets
8 pixels scan/line x 8 lines



This configuration is more suitable for event-driven mode.

Event-driven Readout Mode



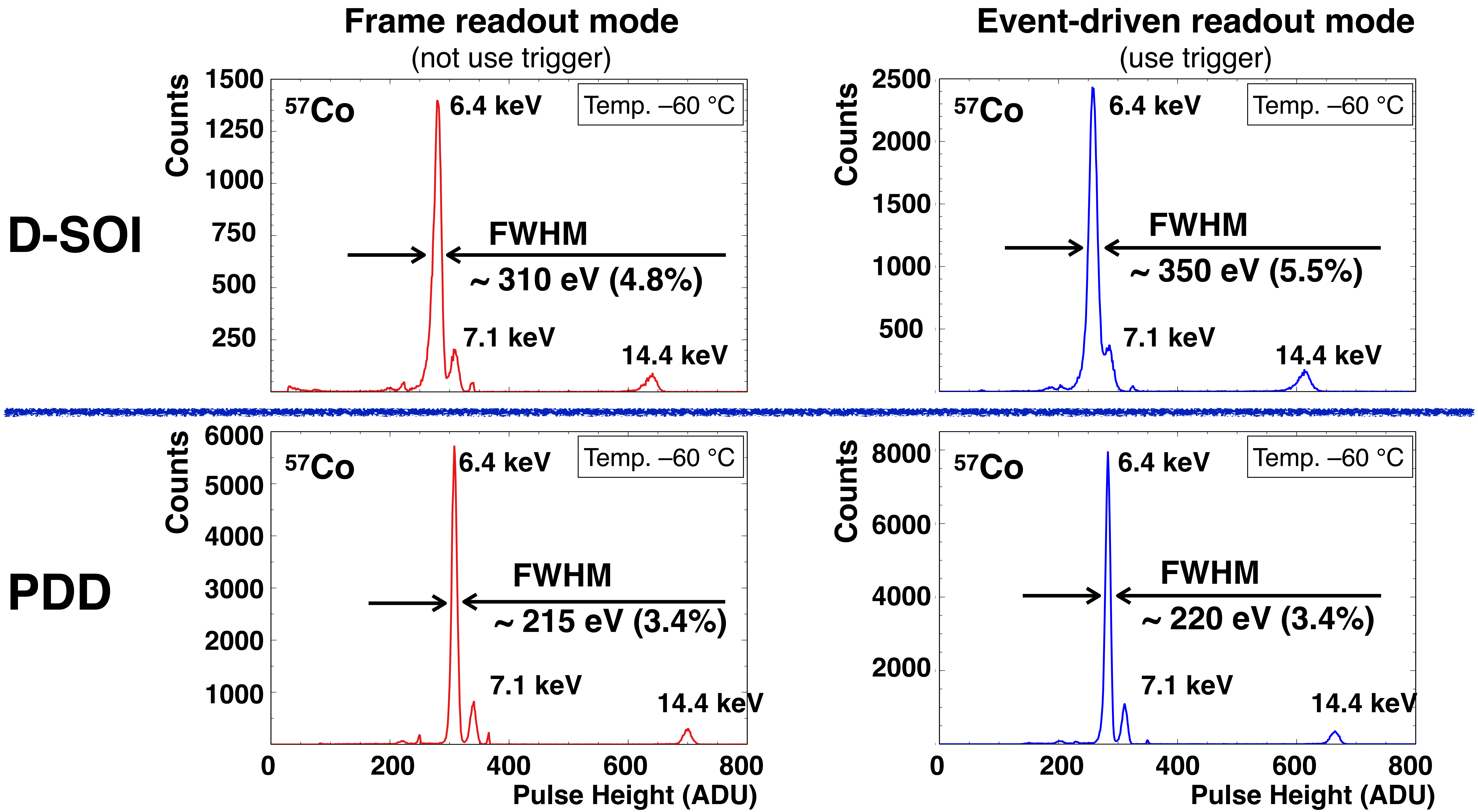
Hit Information

- multi hit ?
- multi pattern ?

Hit Pattern

output the address value
by encoder with pattern scanner

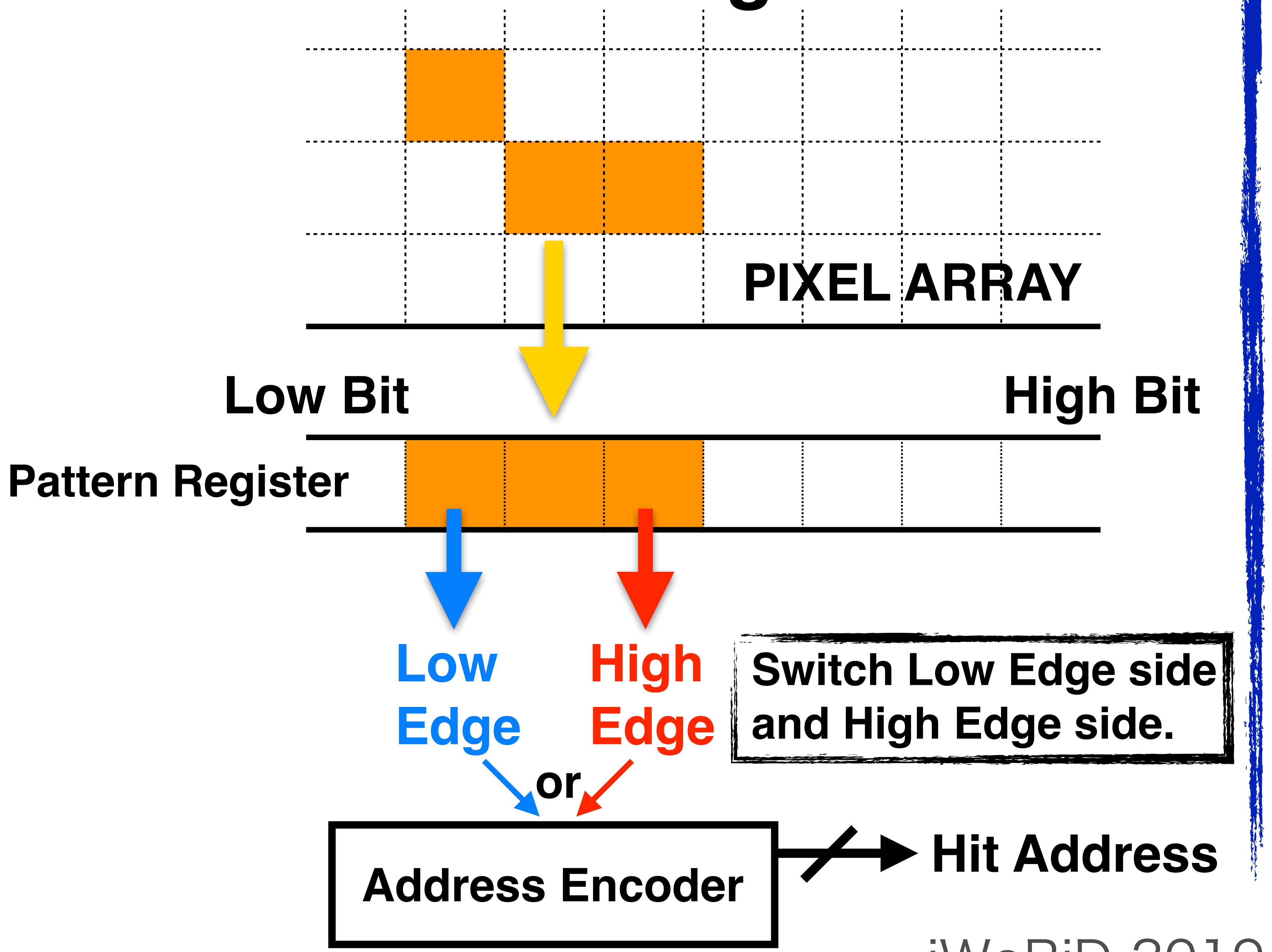
Spectroscopic Performance



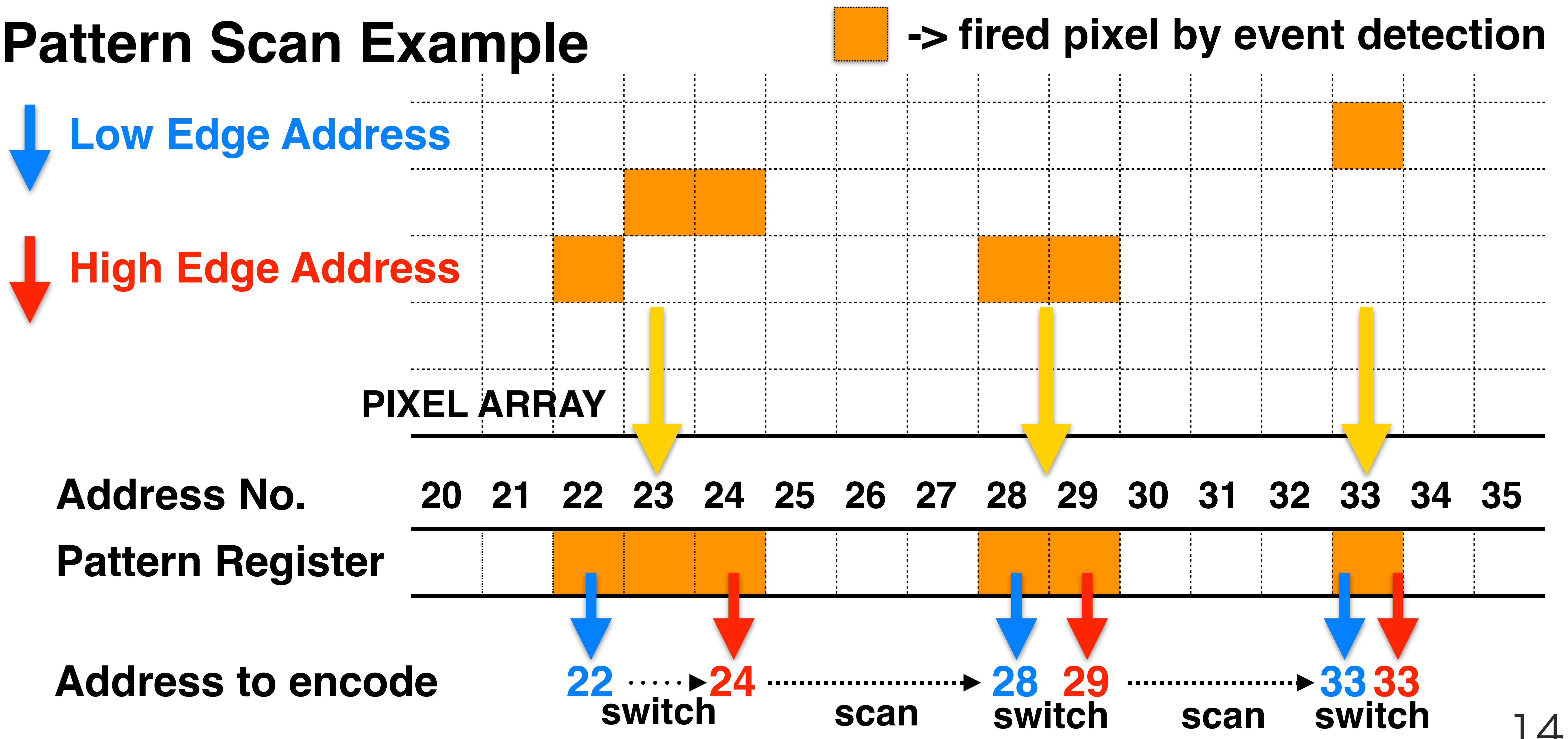
Peripheral Digital Circuit for Event-driven Readout

- XRPIX outputs the address of the place where the event is detected through the encoder circuit.
  -> Independent of Row Address (RA) side and Column Address (CA)
- By switching between “Low Edge” and “High Edge” addresses, we can know the position and size of events detected by only two address (Low / High) conversions.
- The output address is shifted by the input of the scan clock signal.
  -> Pattern scan function

Address Encoding



Pattern Scan Example



Peripheral Digital Circuit for Event-driven Readout

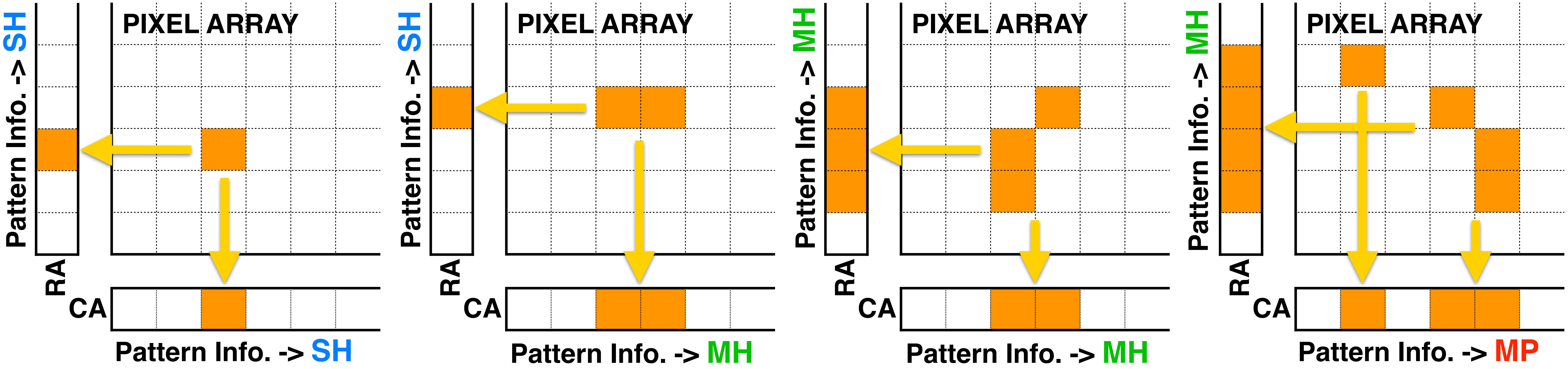
- XRPIX outputs pattern information processed by peripheral digital circuits in the chip.
  -> Independent of Row Address (RA) side and Column Address (CA) side

- Pattern information is classified as follows for each of RA side and CA side.

Single Hit (SH) : one pixel in all
Multi Hit (MH) : one continuous pattern
Multi Pattern (MP) : multiple continuous patterns

Pattern Examples

-> fired pixel by event detection



Test Results of Pattern Classification

- The difference in classification by radioactive source was tested using the pattern information of XRPIX6.
  -> **front illumination** (affects the size of the charge cloud) / 100k events

SH: one pixel in all
MH: one continuous pattern
MP: multiple continuous patterns

- Under the condition that the firing pixel by event detection is two or less, we have the possibility of X-ray.

Summary

- We have been developing an event-driven SOIPIX sensor, “XRPIX”, for future X-ray astronomical satellite mission.
- We realize the event-driven readout mode and very low non-X-ray background by the function of the trigger signal output.
- We designed the new prototype, “XRPIX6D” and “XRPIX6E” with the Double-SOI structure and the PDD structure to improve spectroscopic performance.
  -> chip size: 4.45 mm x 4.45 mm, pixel size: 36 μm sq., number of pixel: 48 x 48 (= ~2.3k)
- We succeeded in improving the spectroscopic performance and suppressing the electrical crosstalk between sensing node and CMOS circuit by XRPIX6D and XRPIX6E.
  -> frame mode: 6D -> 310 eV (4.8%) @ 6.4 keV (FWHM), 6E -> 215 eV (3.4%) @ 6.4 keV (FWHM)
  -> event-driven mode: 6D -> 350 eV (5.5%) @ 6.4 keV (FWHM), 220 eV (3.4%) @ 6.4 keV (FWHM)
- Peripheral digital circuits for event-driven readout work good and can help with X-ray decisions.