Development and characterization of the latest X-ray SOI pixel sensor for a future astronomical mission

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on behalf of the Japan SOI group

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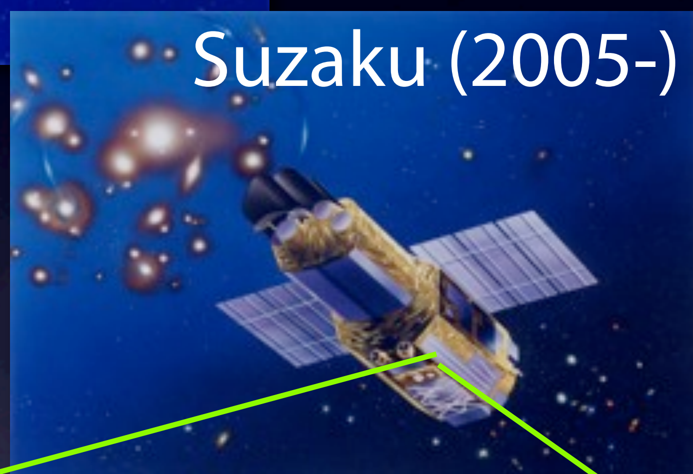
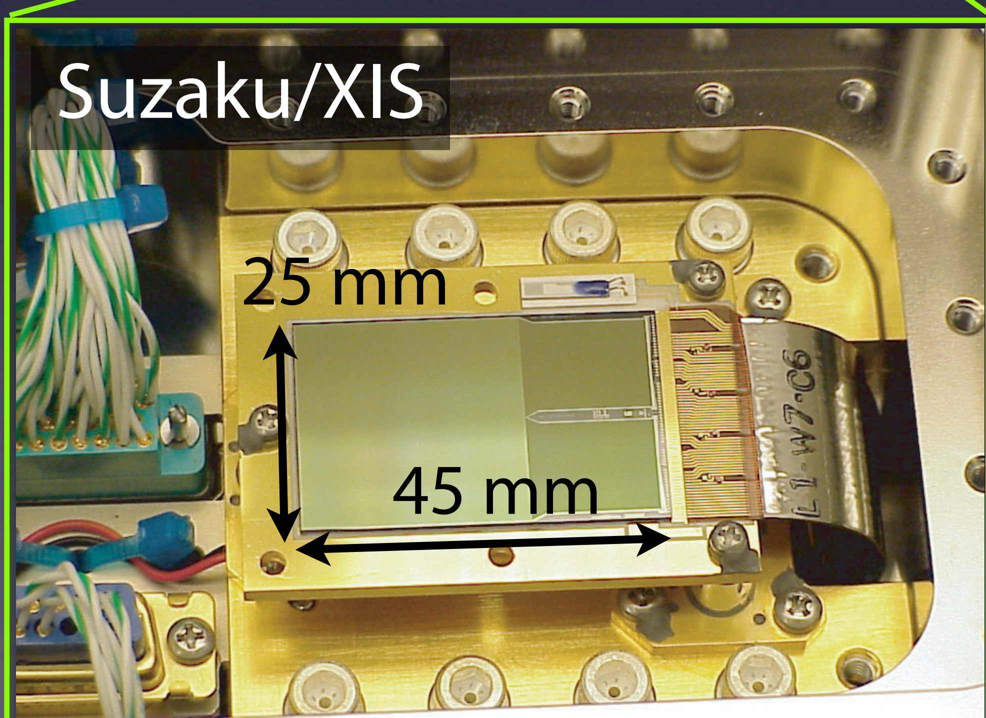
Outline

- Detectors for X-ray astronomy
- Our concept for the new detector
- Characterization of the latest device, “XRPIX2”

X-ray Astronomy & Detector

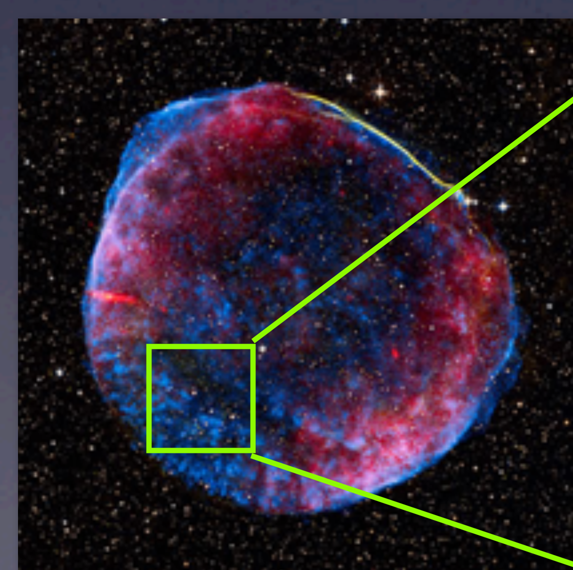


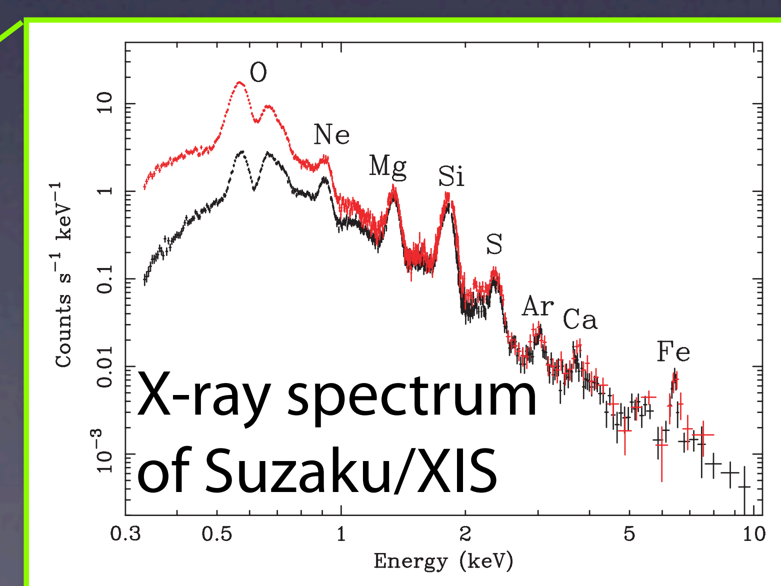


Detectors for X-ray astronomy are launched by satellites.

Since the ASCA satellite launched in 1993, CCDs are widely used for X-ray astronomy.

- Fine pixel pitch (~20 μm)
- Fano limited energy resolution (~130 eV)
- High sensitivity for low energy X-ray (0.5 - 10 keV)

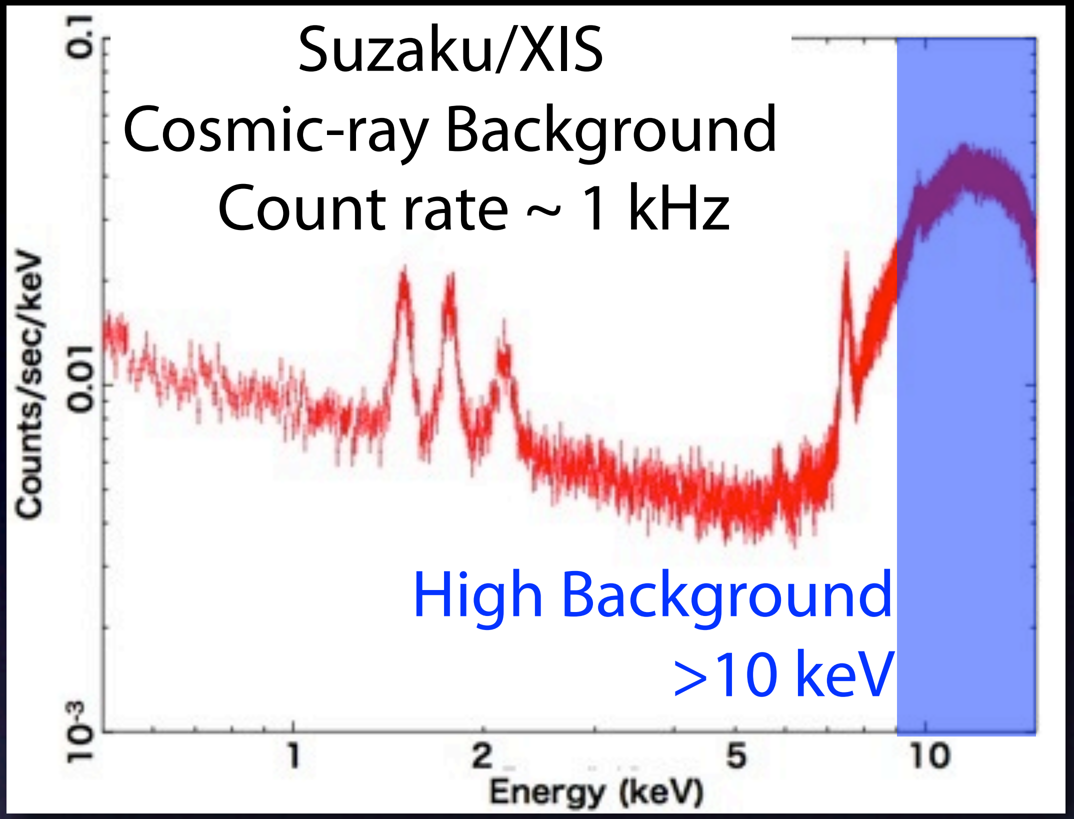




New Imaging Sensor for X-ray

Problems of CCDs

- Charge transfer causes...
  - Low timing resolution (a few sec)
  - Charge loss due to lattice defects
    -> Radiation tolerance is low
- High background above 10 keV
  -> restricts hard X-ray observation



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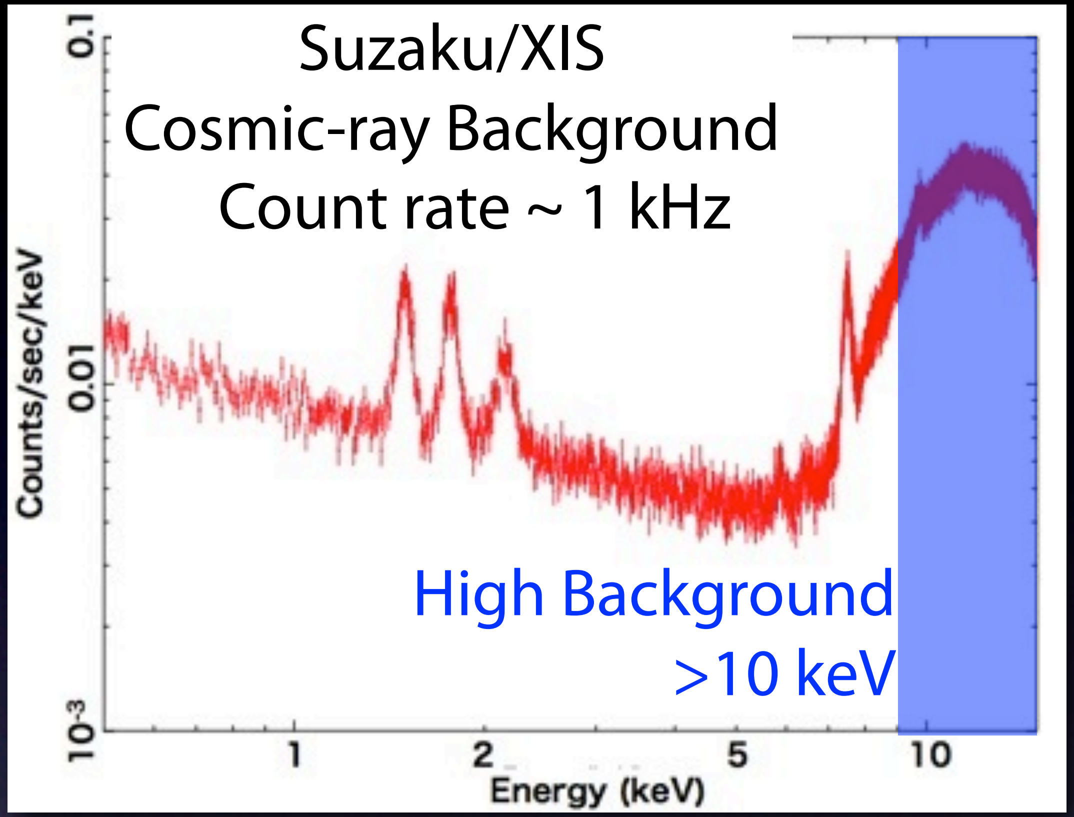
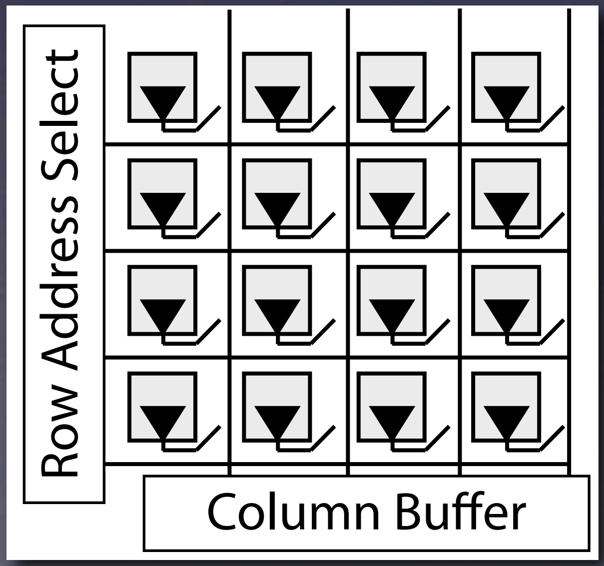


"Active Pixel Sensor" is being developed in various institutes



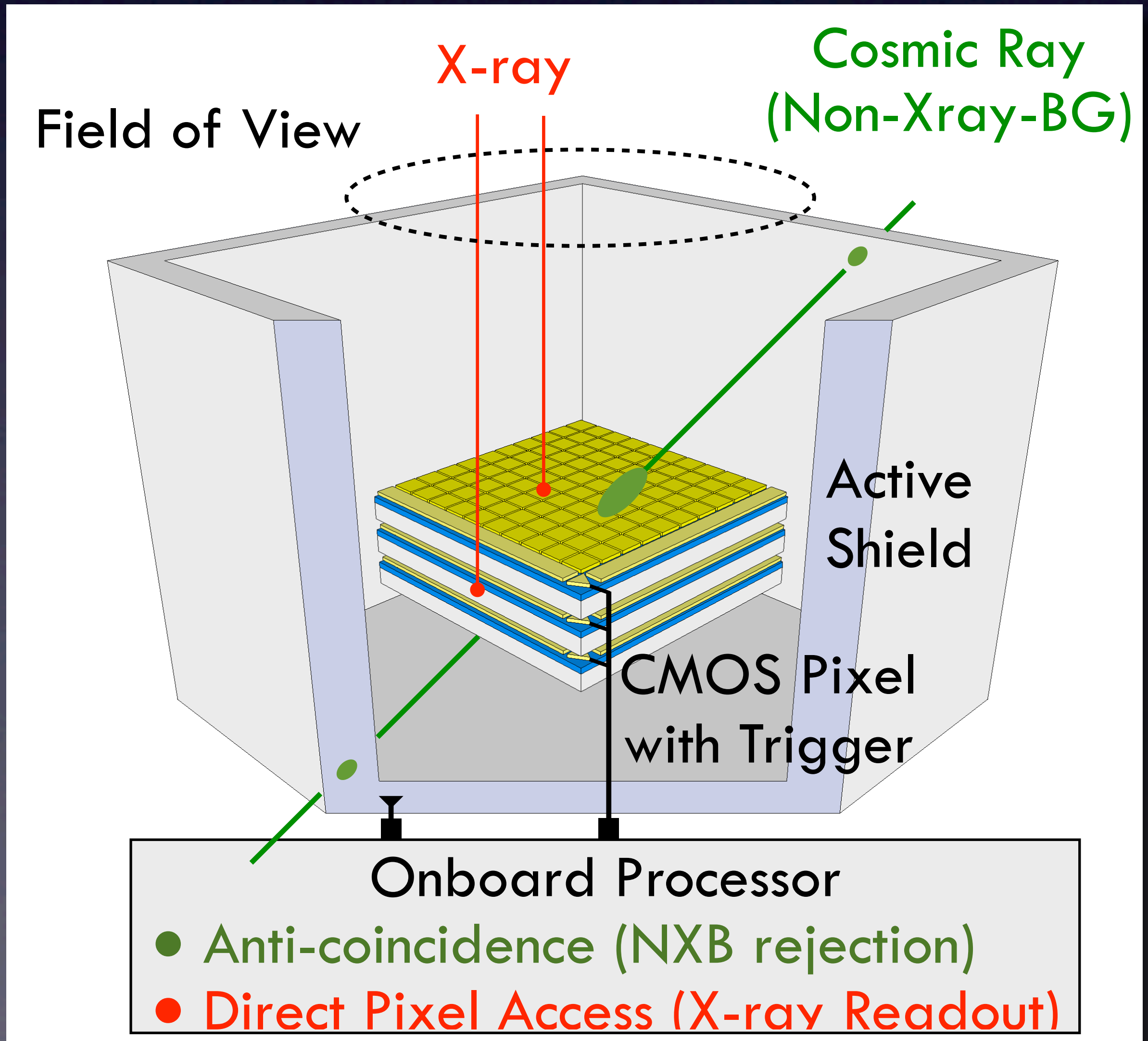
- Convert signal charge to voltage within a pixel
  -> Flexible readout pattern and faster timing resolution
  -> High tolerance to radiation damage
- Built-in integrated circuit

Our Concept = Intra-pixel trigger system

	pixel pitch	Energy Resolution	Radiation Tolerance	Timing Resolution	Bandpass
CCD	<30 µm	Fano limited	Poor	~1 sec	0.5-10 keV
other APS	30-100 µm	Fano limited	Good	~1 msec	0.5-10 keV
our APS	<60 µm	Fano limited	Good	<1 µs	0.5-40 keV

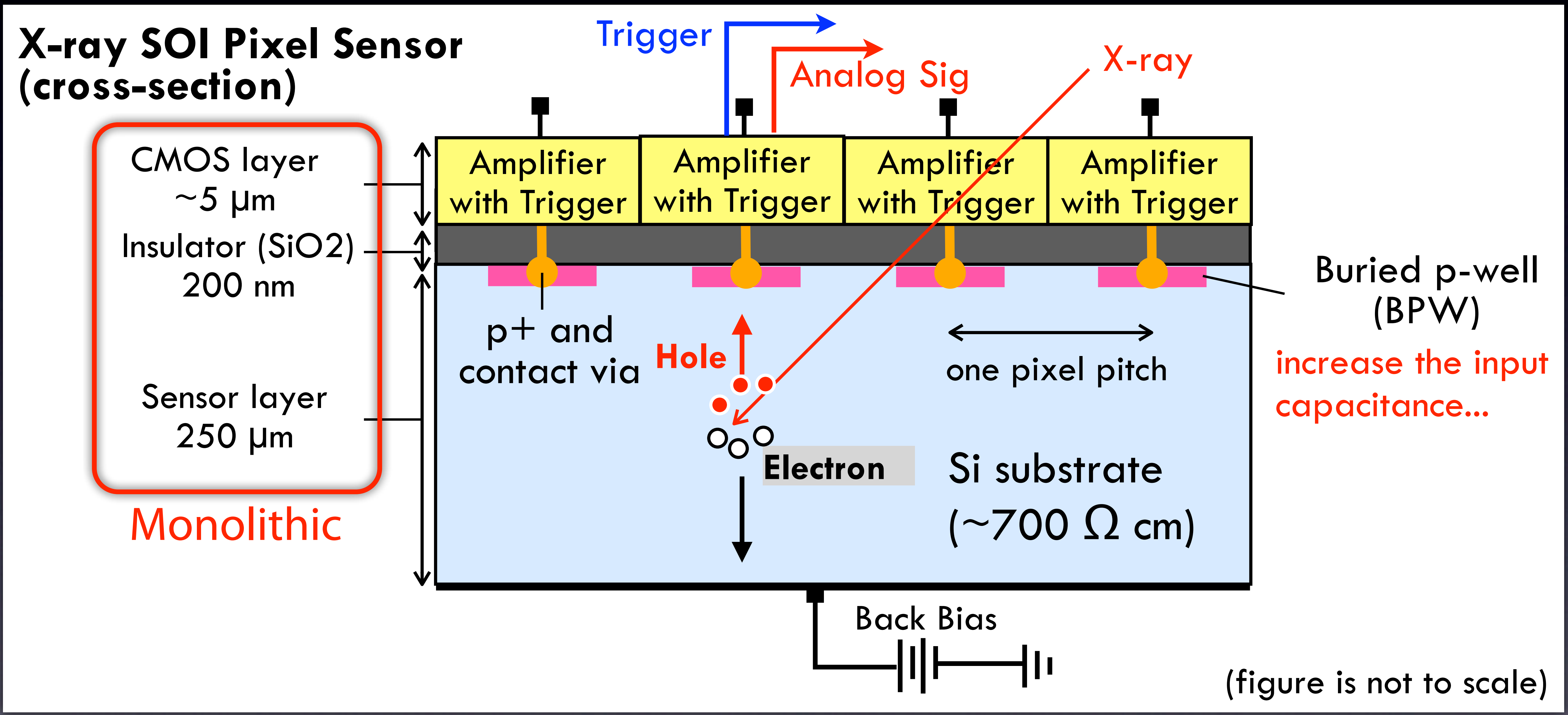
Intra-pixel trigger system acheives

- Very fast timing resolution
- Background rejection with an anti-coincidence system and wide bandpass

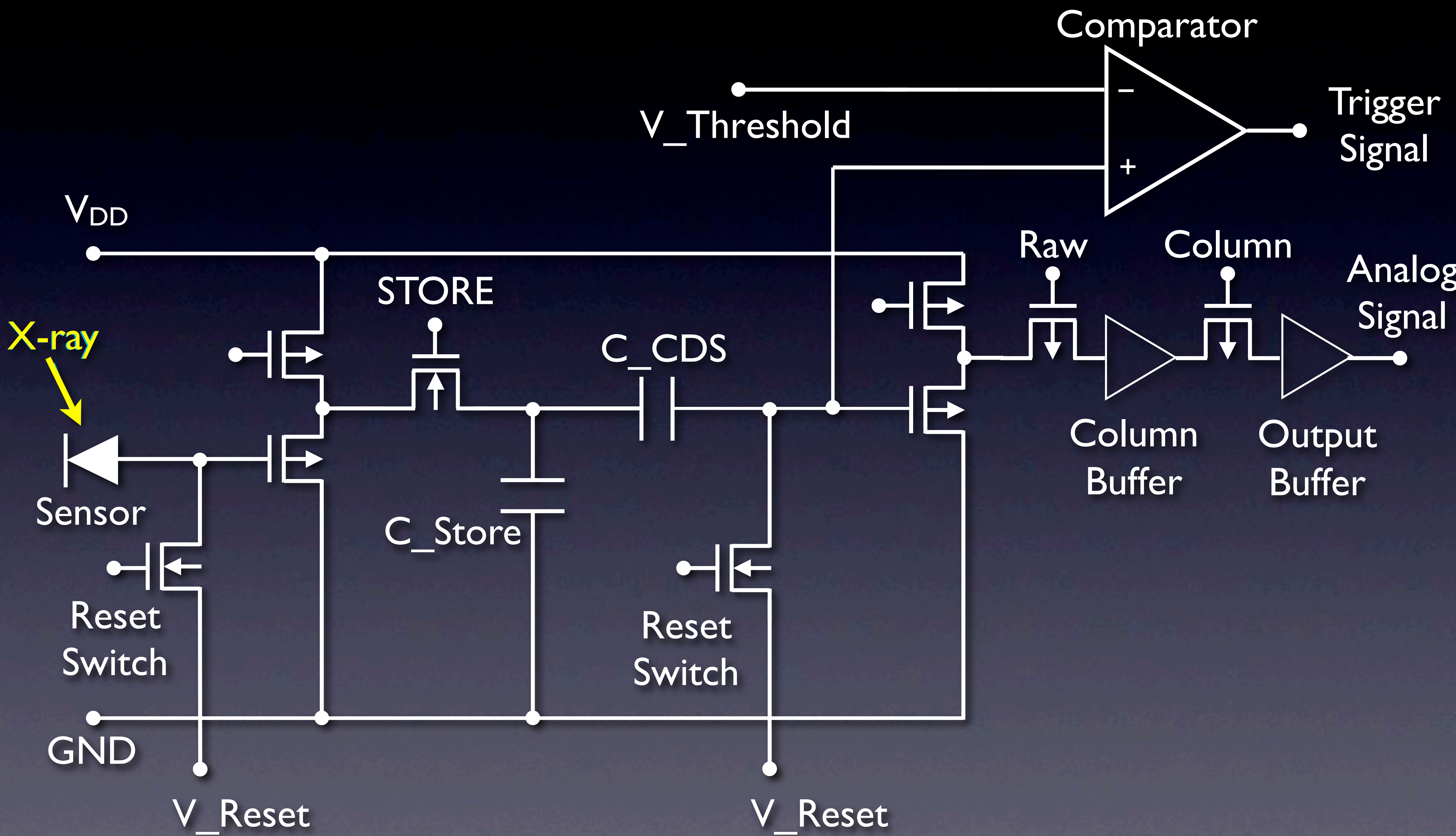


X-ray SOI Pixel Sensor (XRPIX)

We use Silicon-On-Insulator (SOI) wafer for a new APS



Pixel Circuitry in X-ray SOI Pixel Sensor



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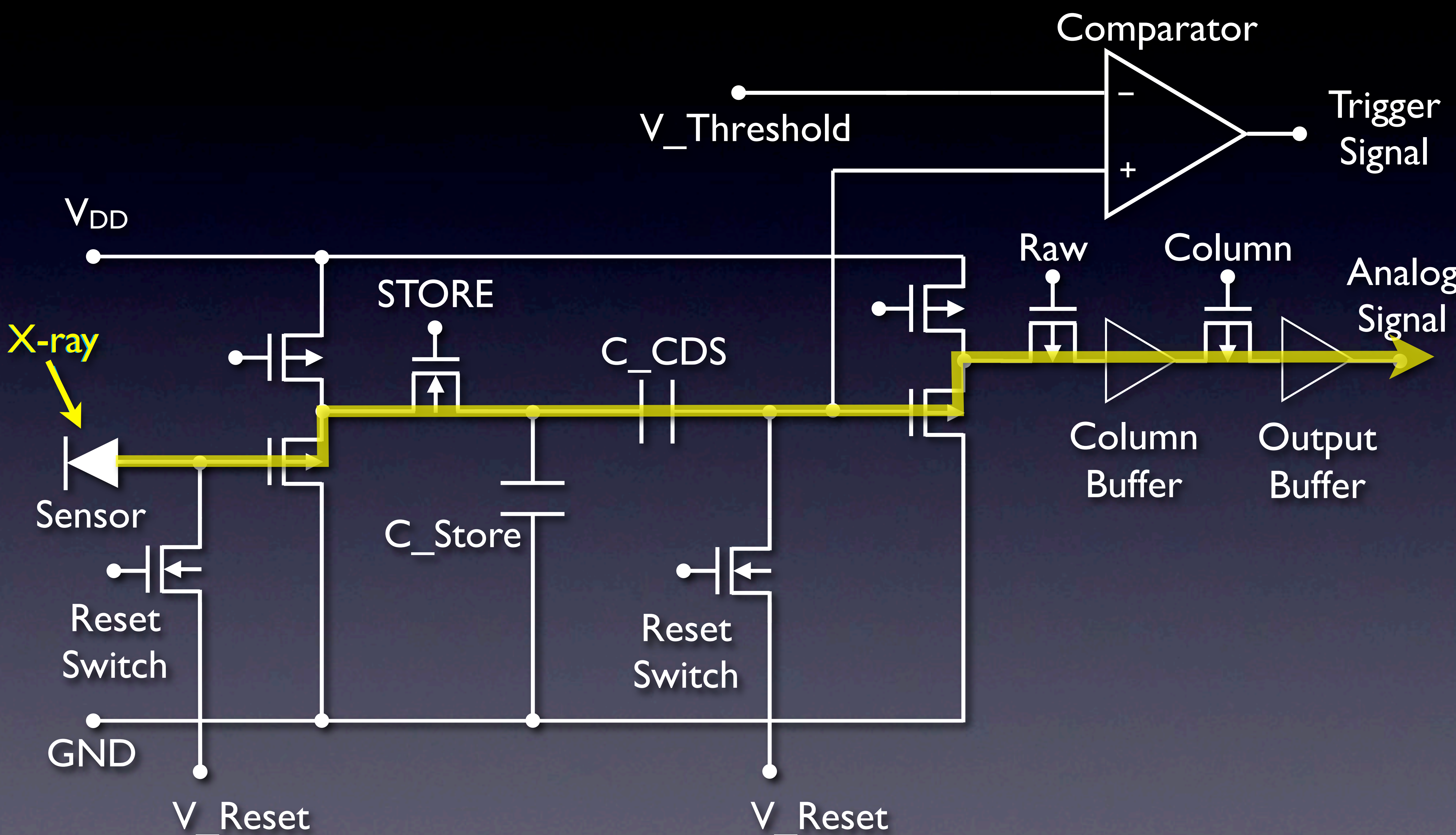

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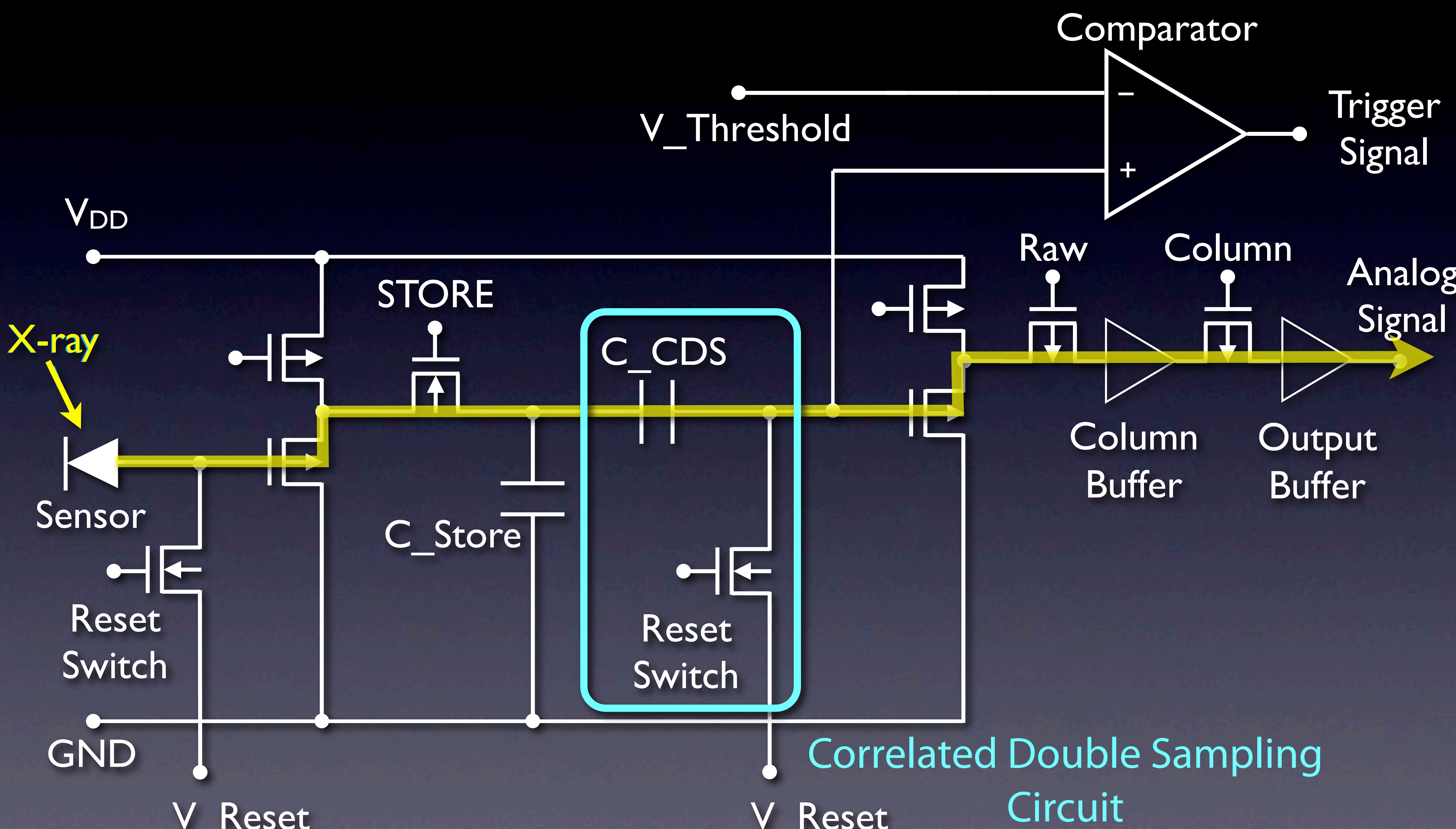

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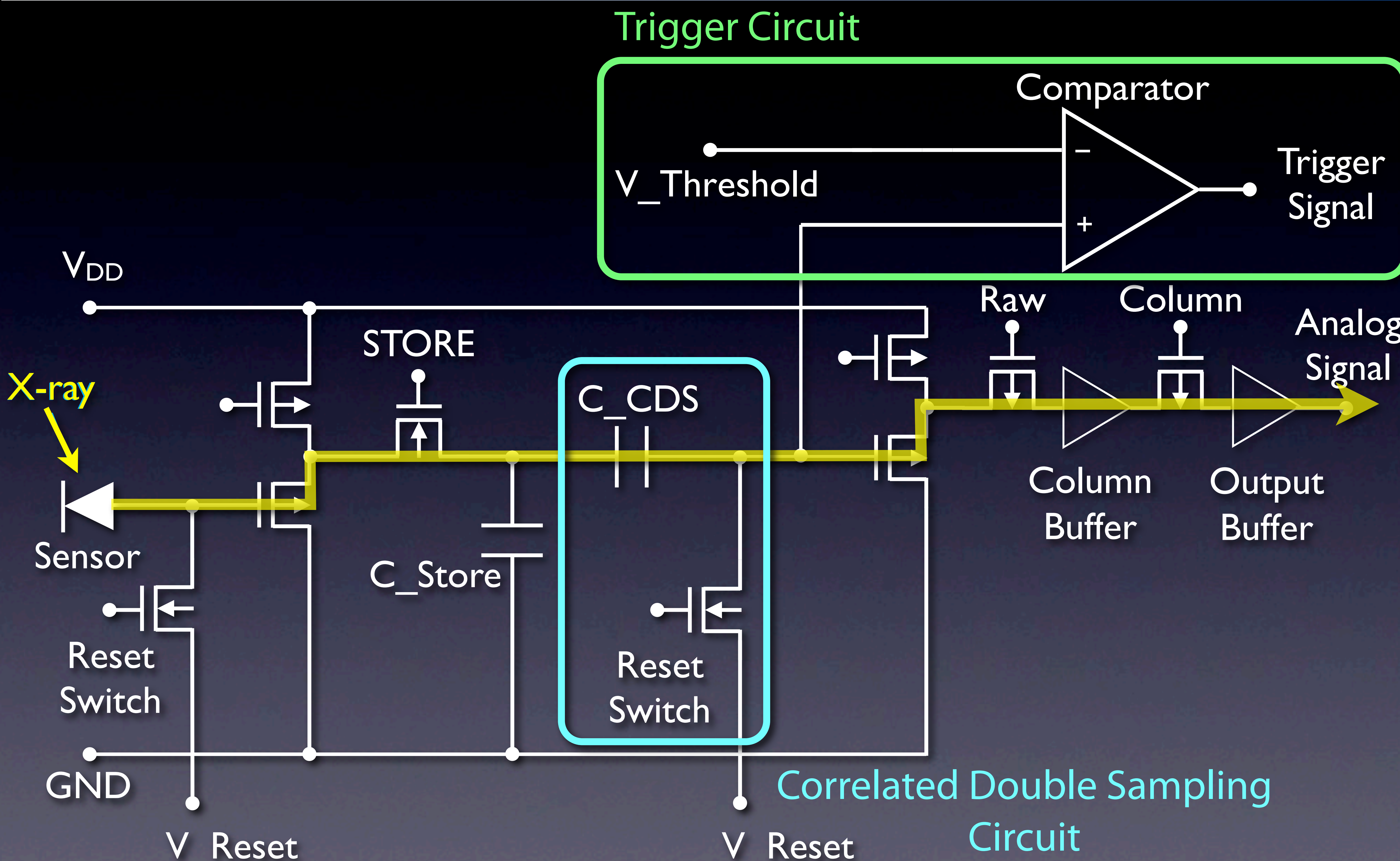
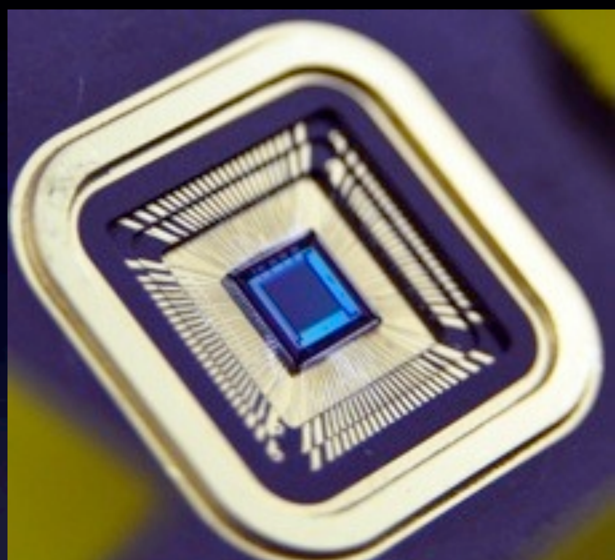
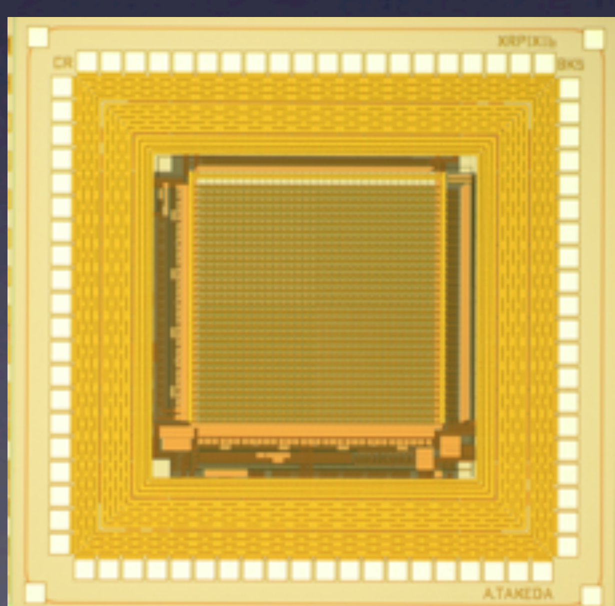


Achievements & Issues of Our Development

XRPIX1 in 2010



XRPIX1b in 2011



Achievements

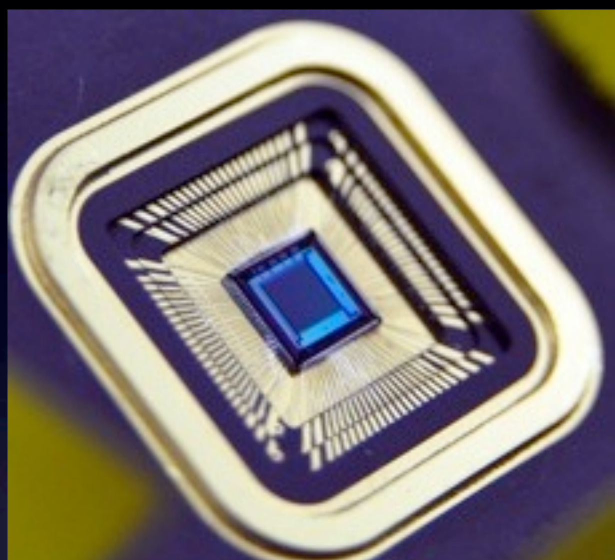
- Small pixel pitch (<30 µm)
- Trigger-driven readout of X-ray signals
- Full depletion of the sensor layer (250 µm)
- Small crosstalk in adjacent pixels (<0.5%)

Issues

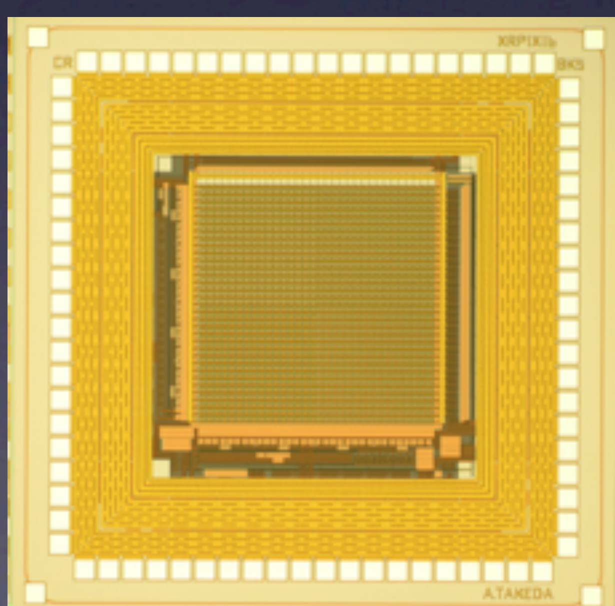
- Poor energy resolution in full frame readout (~1.2 keV @8 keV X-ray)
- Gain degradation in the trigger-driven readout
- Backside illumination test
- Anti-coincidence test

Achievements & Issues of Our Development

XRPIX1 in 2010



XRPIX1b in 2011



Achievements

- Small pixel pitch (<30 μm)
- Trigger-driven readout of X-ray signals
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Issues

most important issue !

- Poor energy resolution in full frame readout (~1.2 keV @8 keV X-ray)
- Gain degradation in the trigger-driven readout
- Backside illumination test
- Anti-coincidence test

New device “XRPIX2”

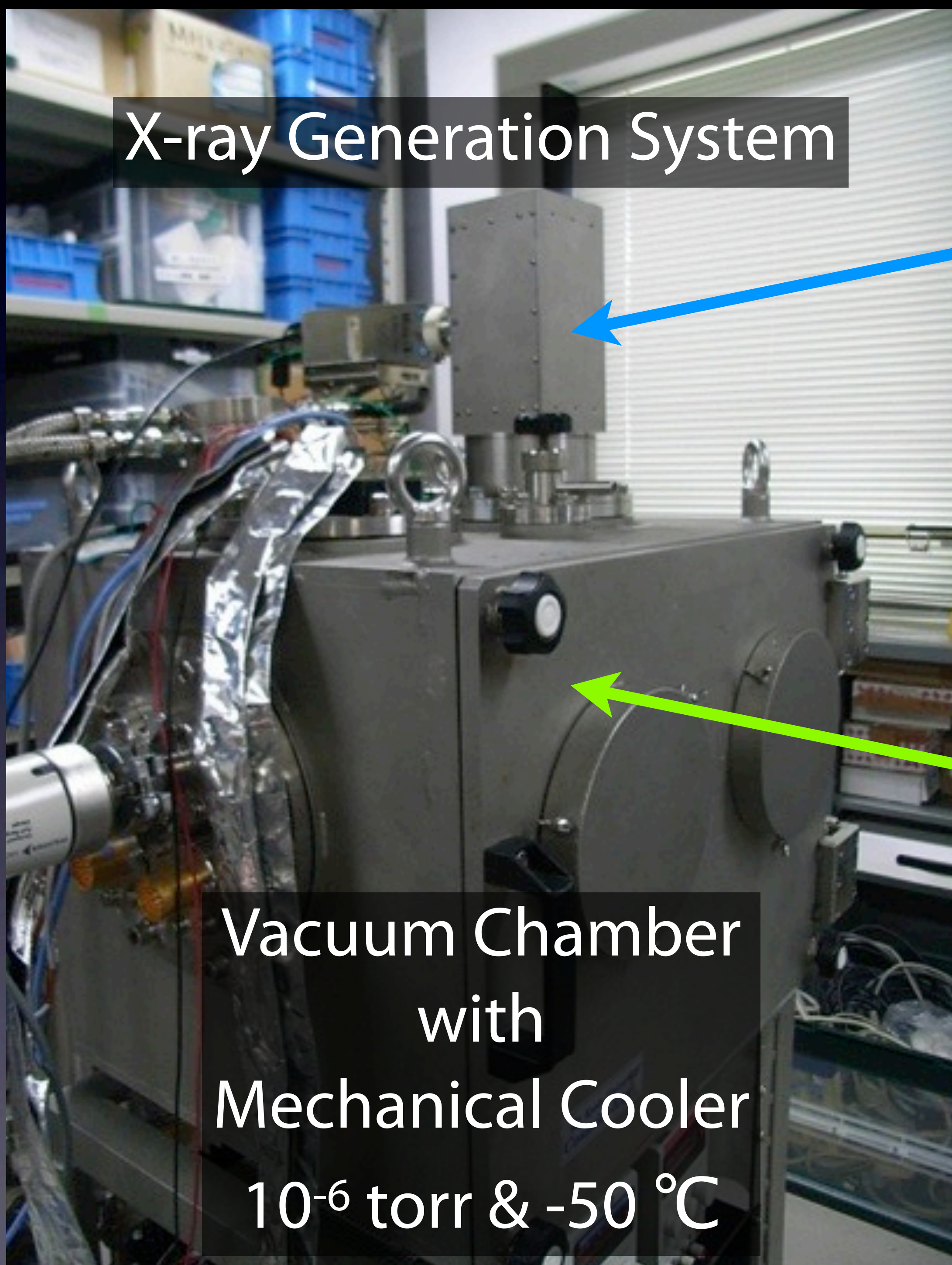
We developed XRPIX2 to improve the spectroscopic performance

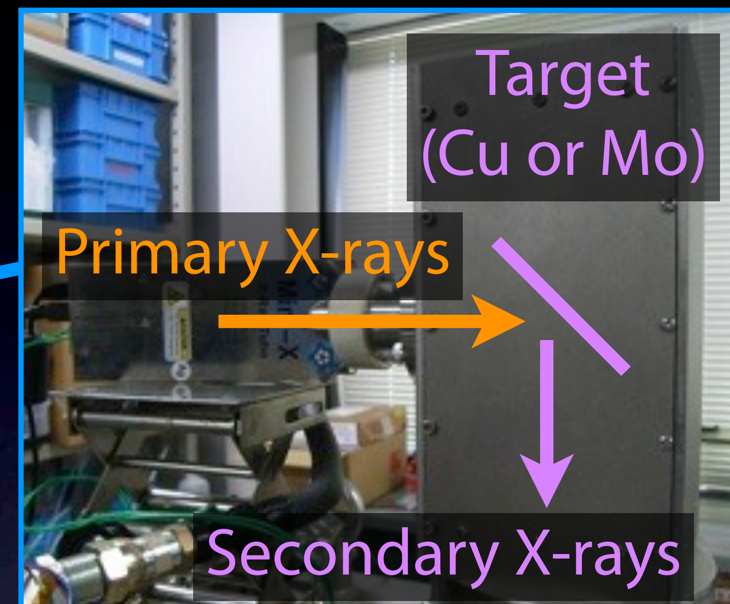
Chip design:

- 0.2 μm FD-SOI process provided by Lapis semiconductor Co. Ltd.
- Resistivity in the sensor layer = 700 Ω cm
- Resistivity in the CMOS layer = 18 Ω cm
- 2 type pixel pitch (30 μm & 60 μm)

Scope of this presentation is characterization of the XRPIX2

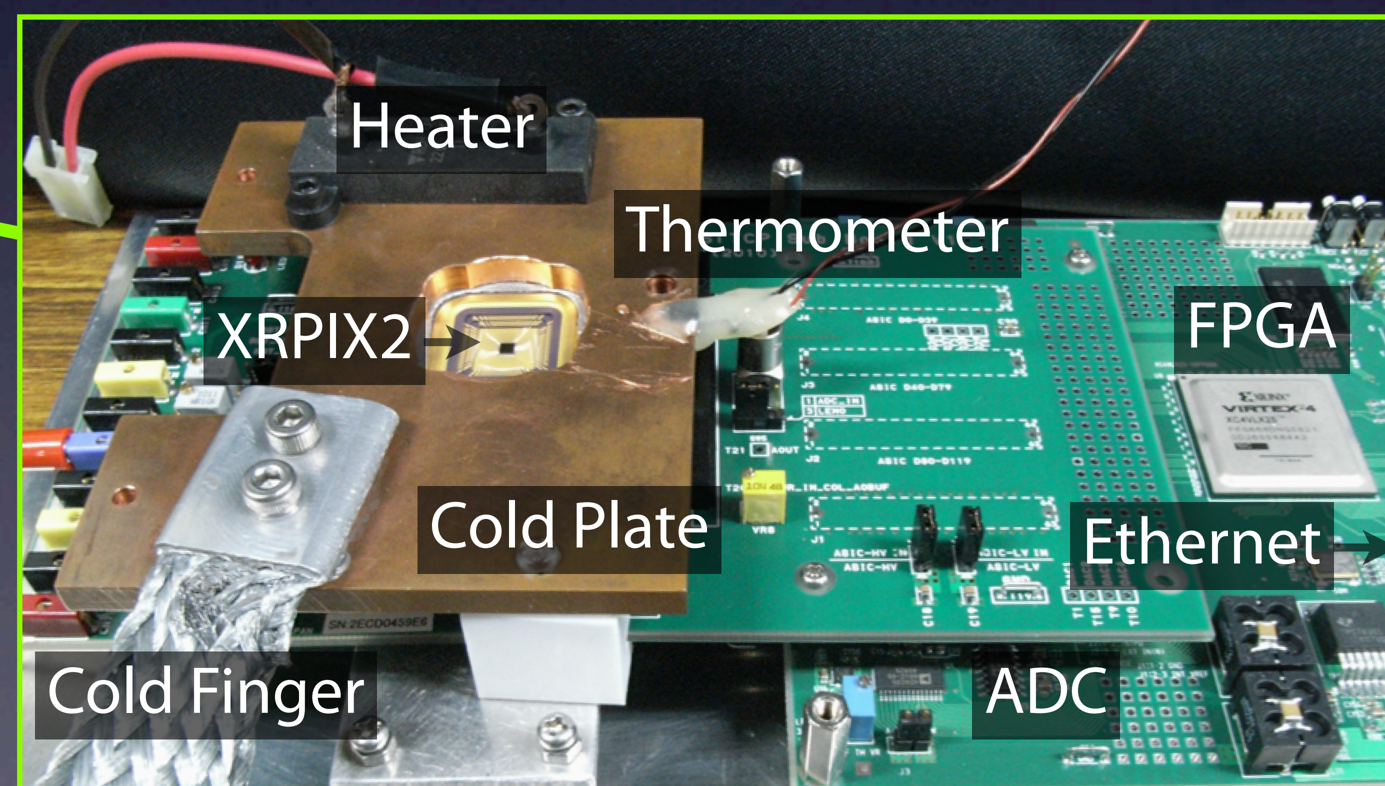
Experimental Setup





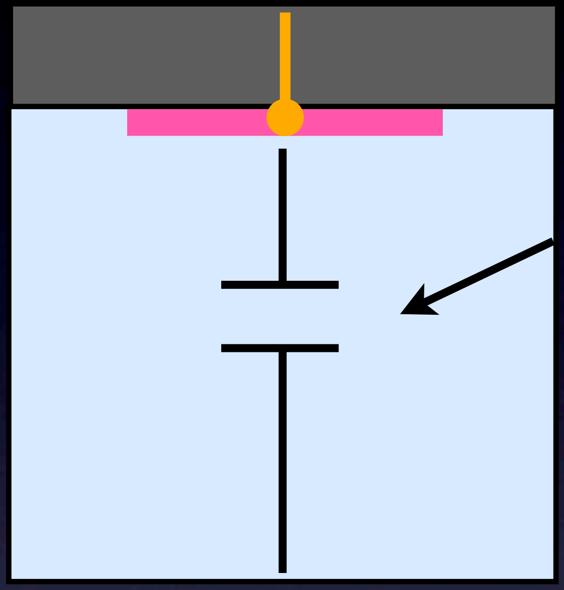
Primary X-rays:
- Mini-X, 30 kV 0.1 mA
- Ag fluorescence
- + bremsstrahlung

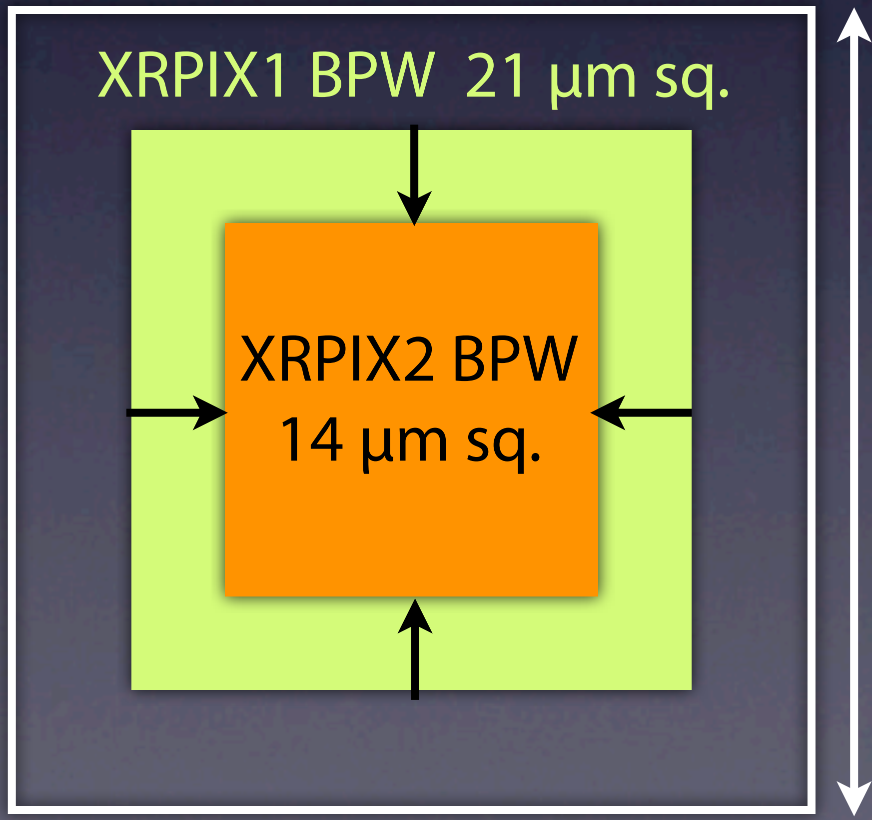
Secondary X-rays:
- Cu fluorescence or
- Mo fluorescence



Configuration of Small Pixel

Object of Small Pixel -> Increasing the Gain and check Uniformity

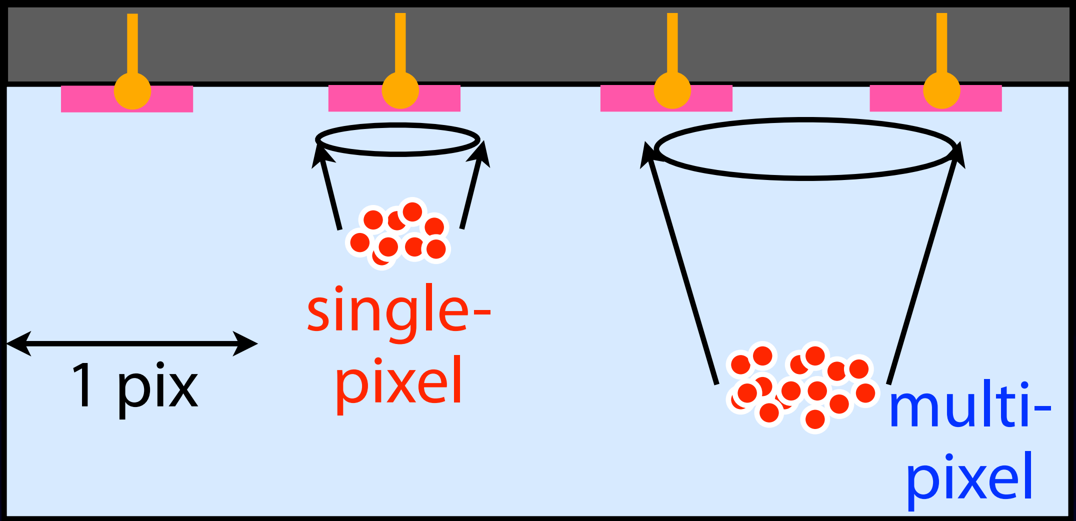


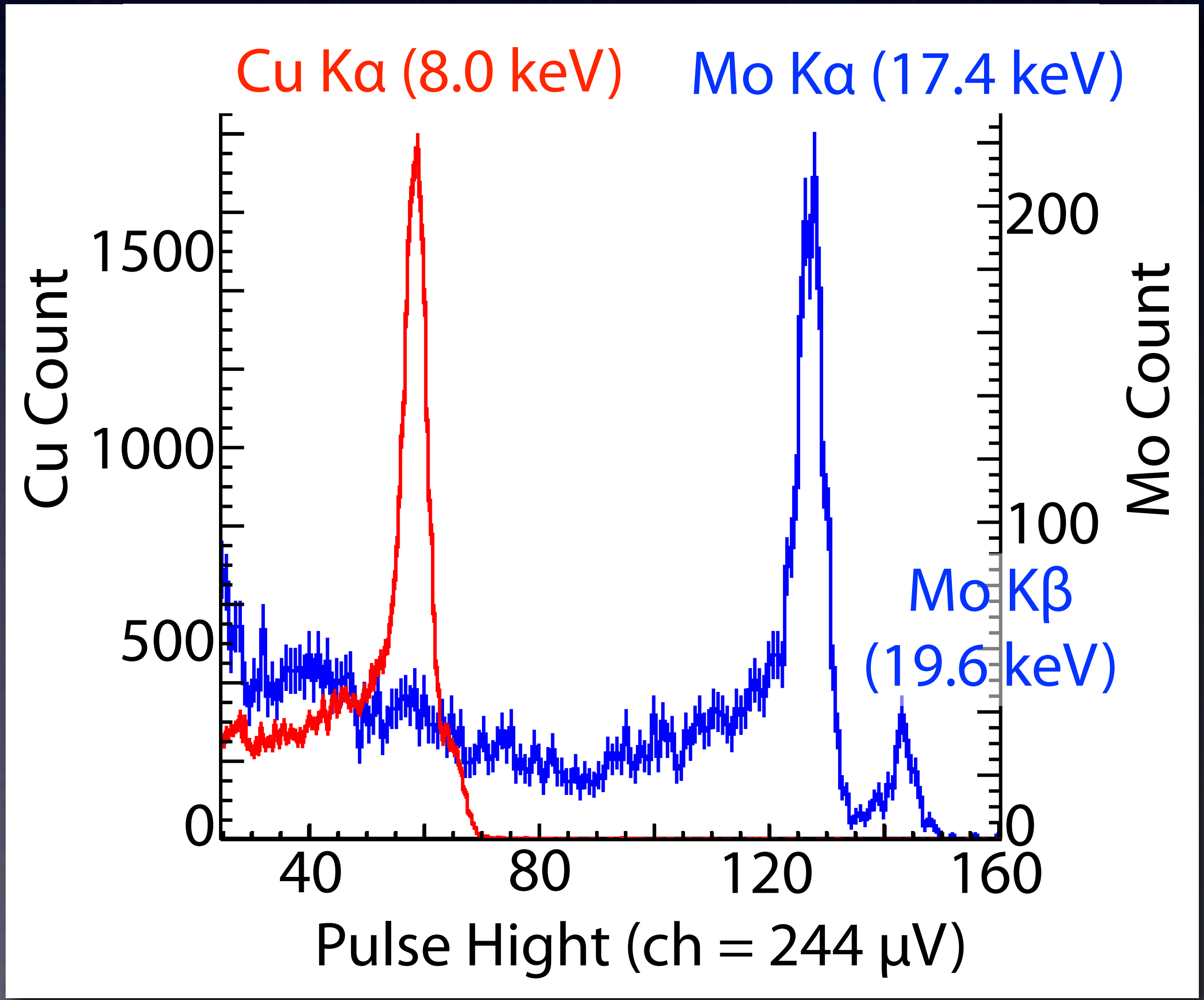


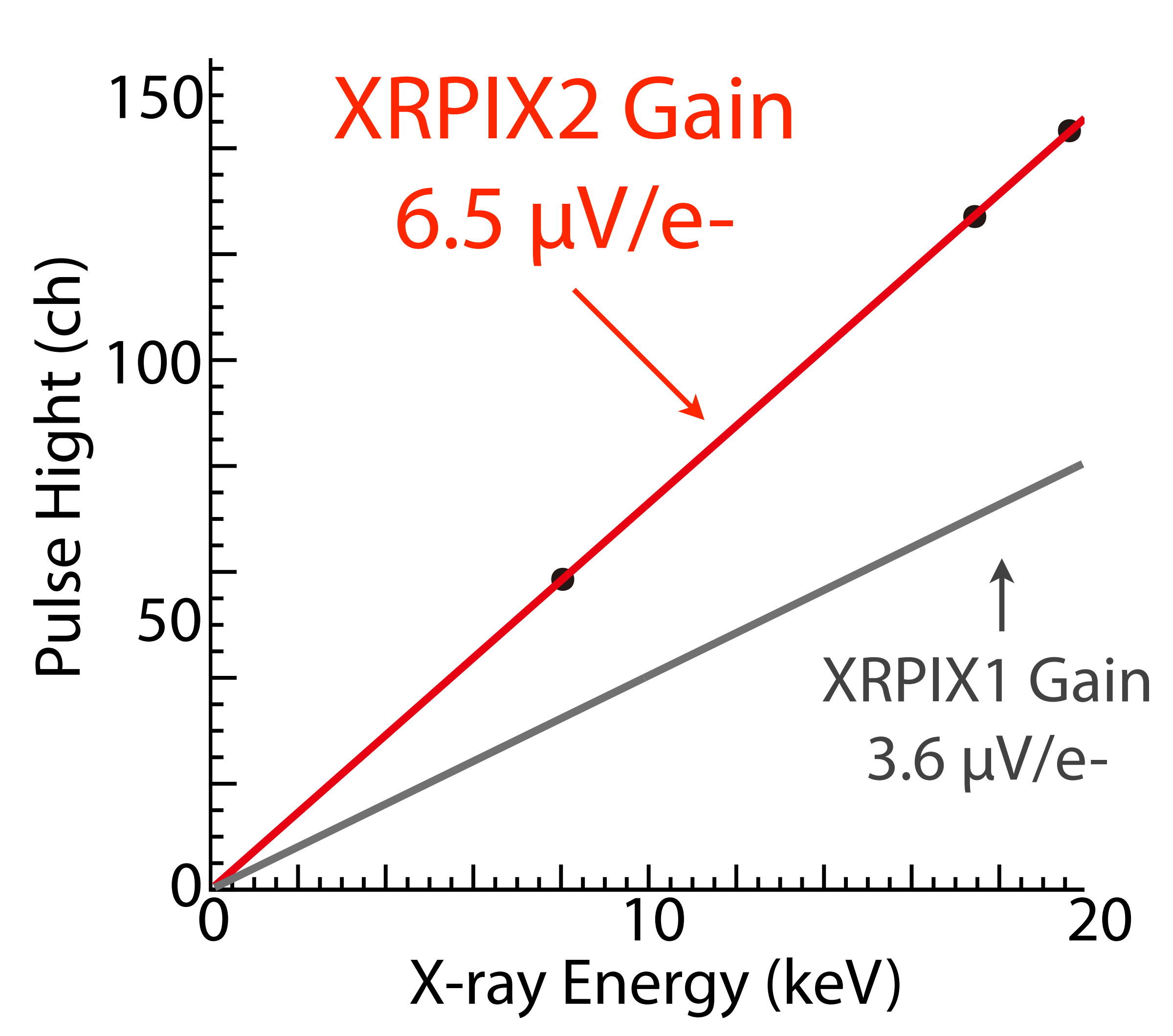
- Half BPW area (400 μm^2 -> 200 μm^2)
- Large pixel format (256 pix -> 9216 pix)

X-ray Sensitivity (Small Pixel)

- Full-frame readout (not trigger driven readout)
- X-ray event selection
  - discard multi-pixel (charge sharing) events and pick up only single-pixel events



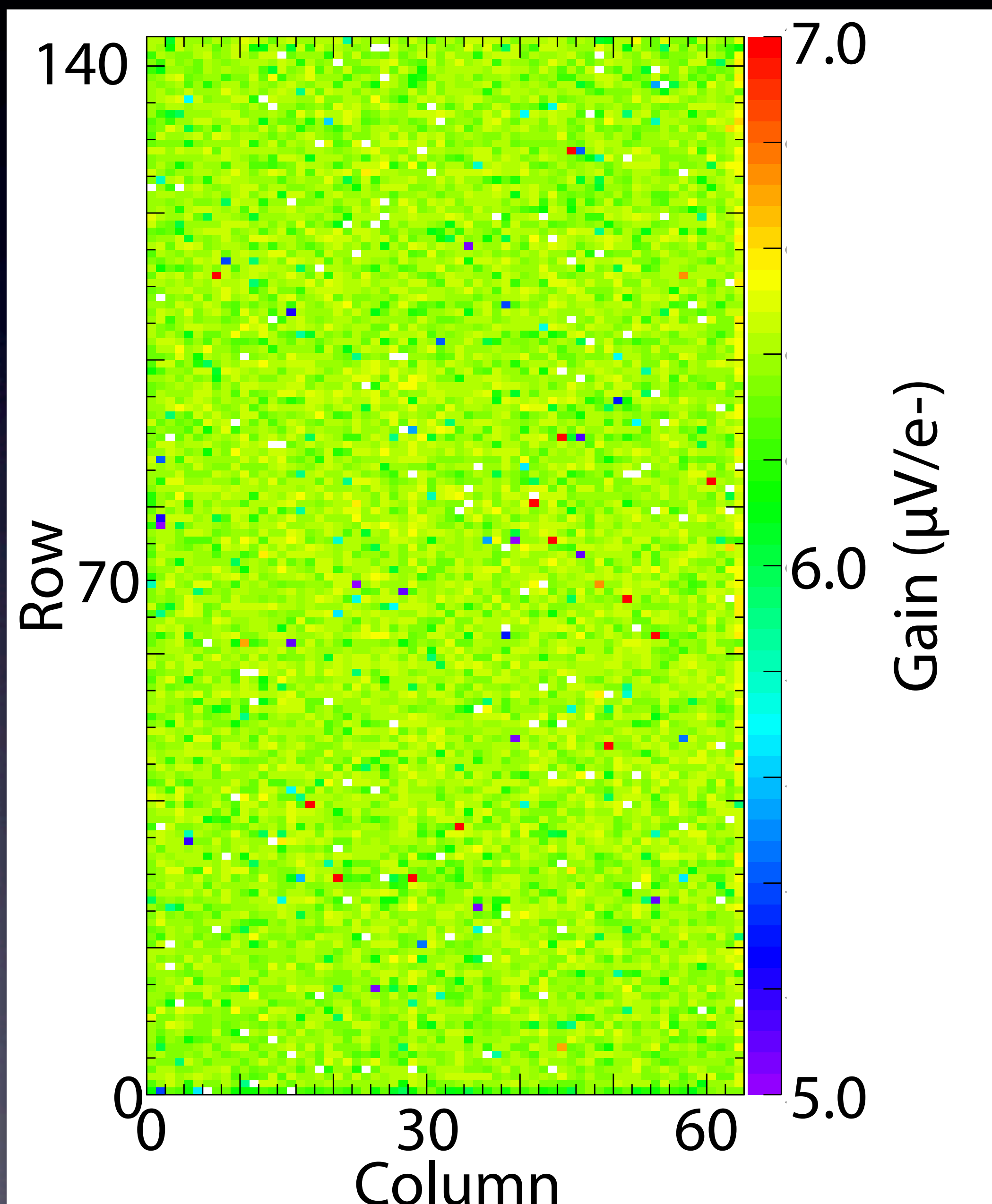




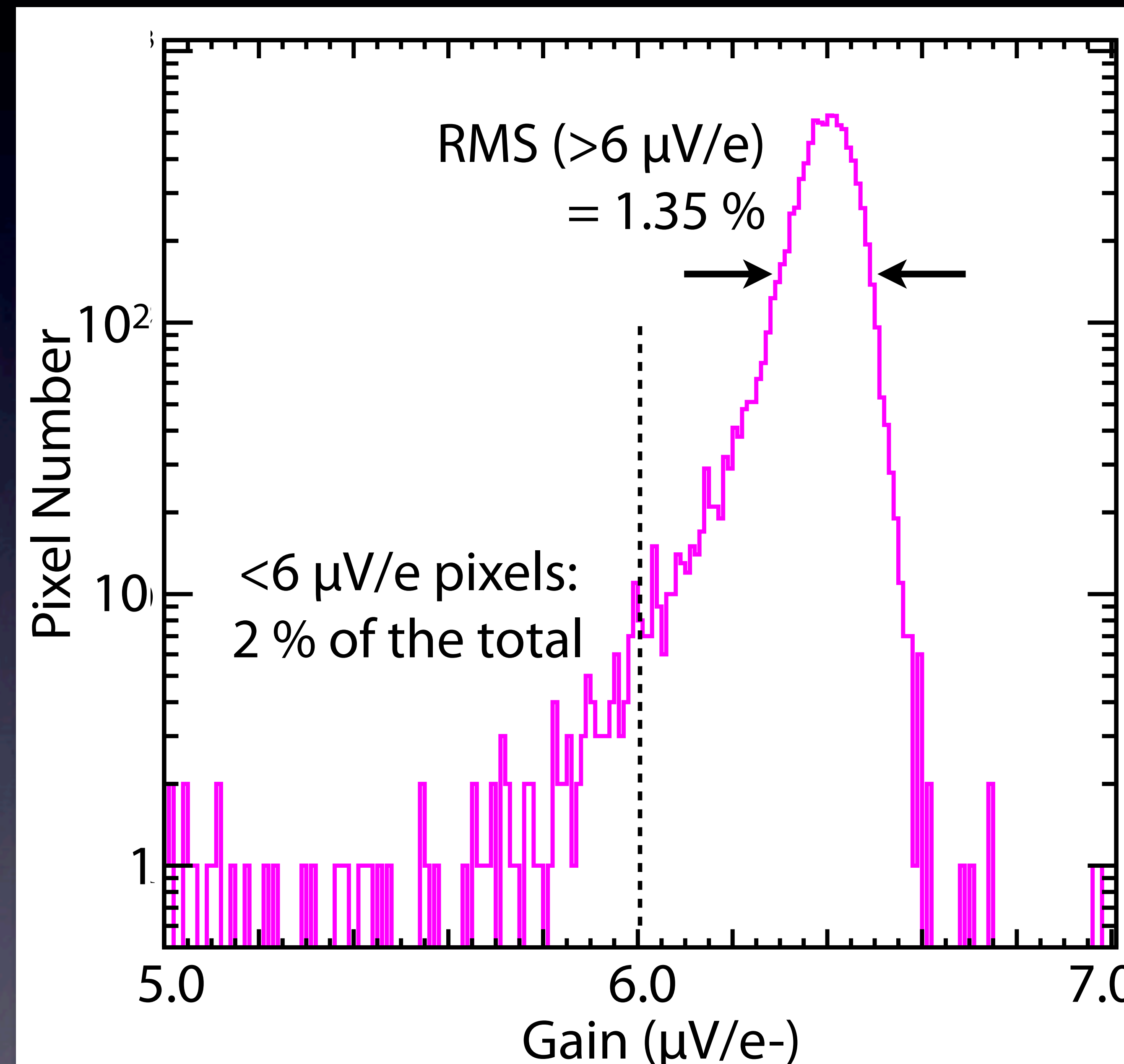
- Gain of XRPIX2 is 1.8 times higher than that of XRPIX1

Gain Uniformity (Small Pixel)

Gain map



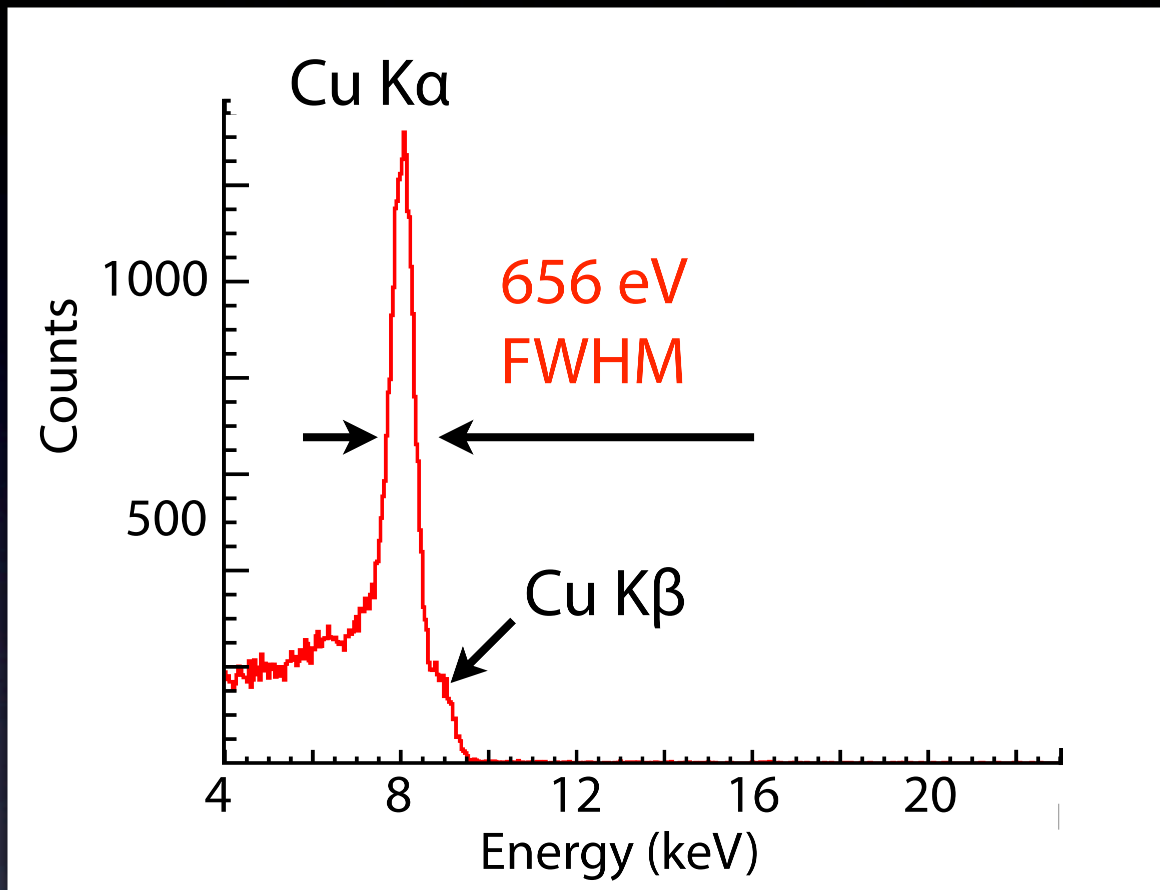
Gain histogram

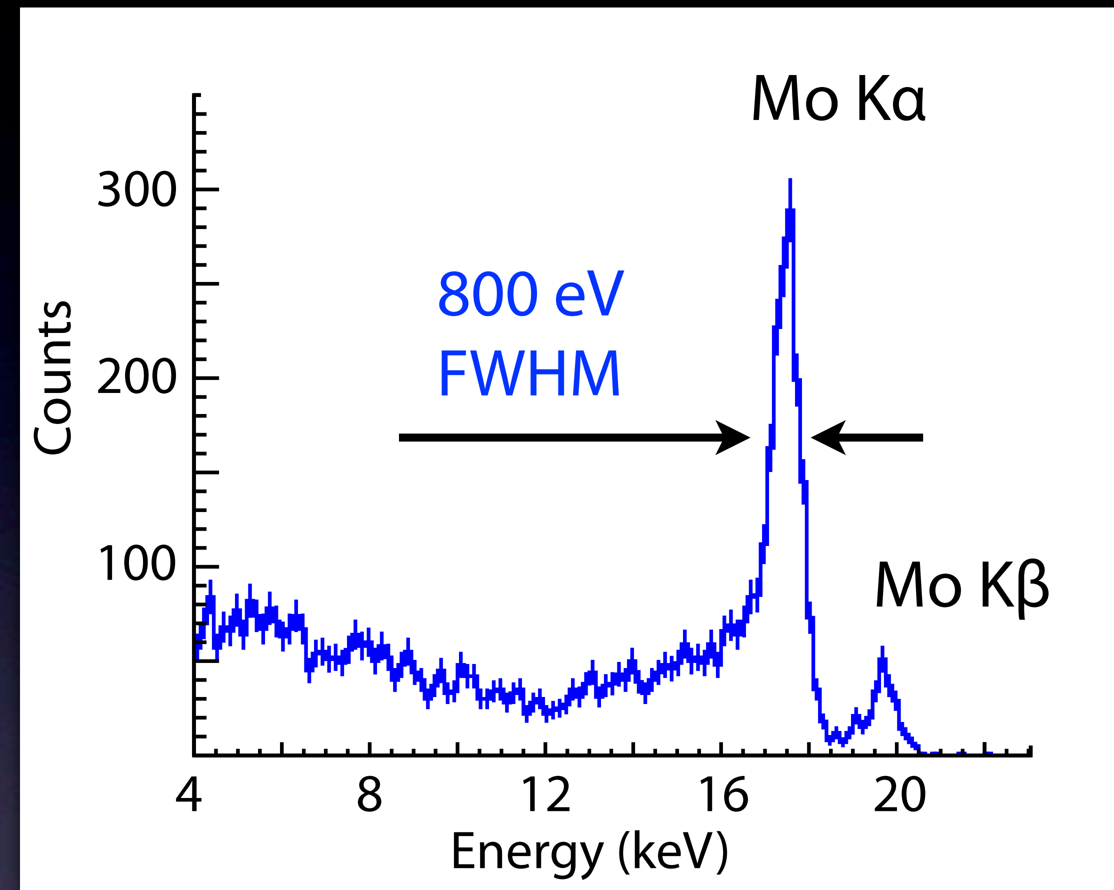


- Gain uniformity is very good even with the large pixel number

Energy Resolution (Small Pixel)

Readout noise = 64 e- (⇔ 129 e- in XPRIX1)



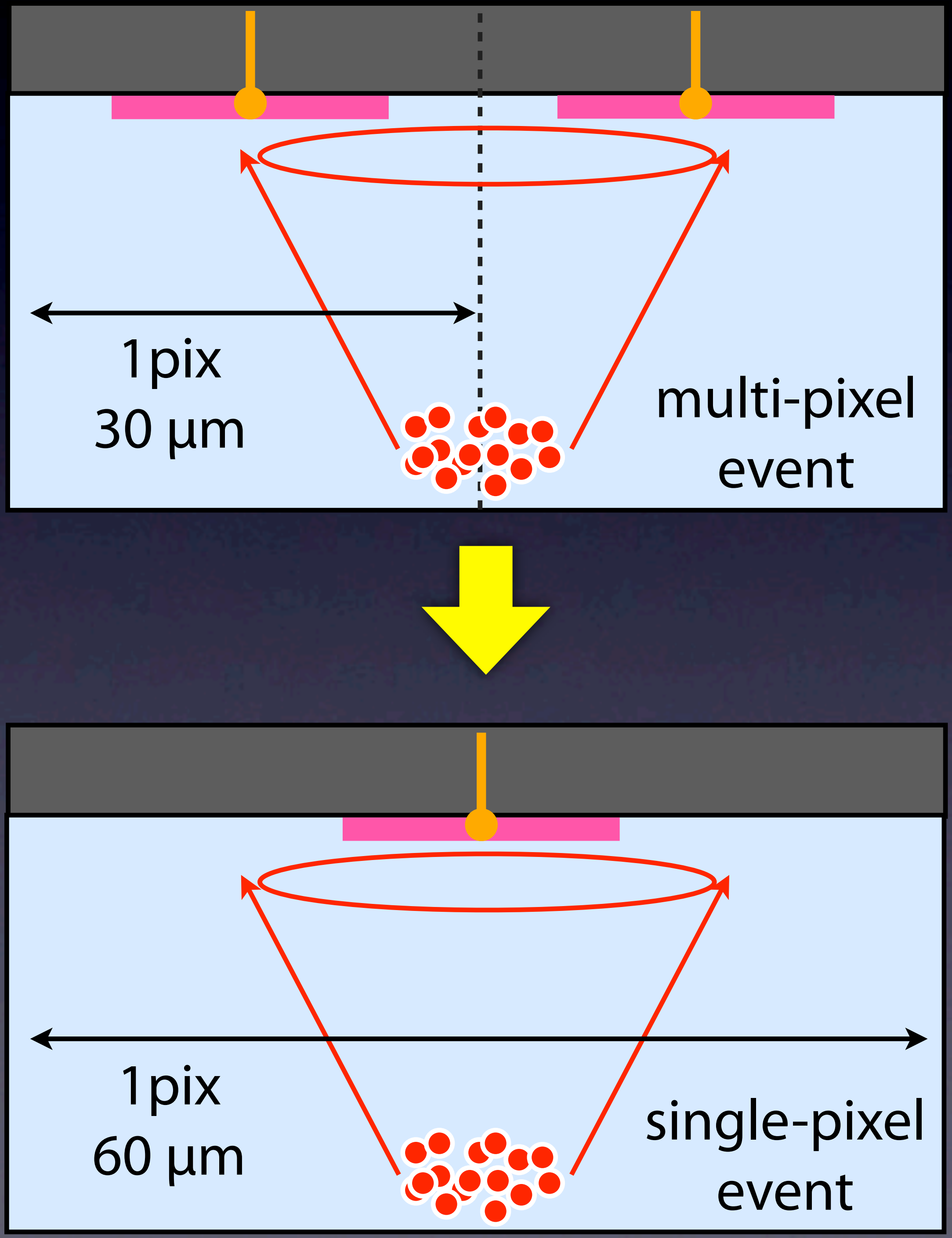


<table>
<tr><th></th><th>Readout Noise</th><th>Fano Noise</th><th>1% Gain Dispersion</th><th>Predicted</th><th>Observed</th></tr>
<tr><td>Cu Kα</td><td rowspan="2">548 eV</td><td>139 eV</td><td>255 eV</td><td>620 eV</td><td>656 eV</td></tr>
<tr><td>Mo Kα</td><td>205 eV</td><td>553 eV</td><td>805 eV</td><td>800 eV</td></tr>
</table>

- Achieve 1.8 times higher resolution than that of XRPIX1

Configuration of Large Pixel 1

Object of Large Pixel 1 -> decreasing charge sharing and Increasing single-pixel events



- Same layout of Small Pixel
- Twice pixel pitch (30 μm -> 60 μm)

Investigation of Charge Sharing

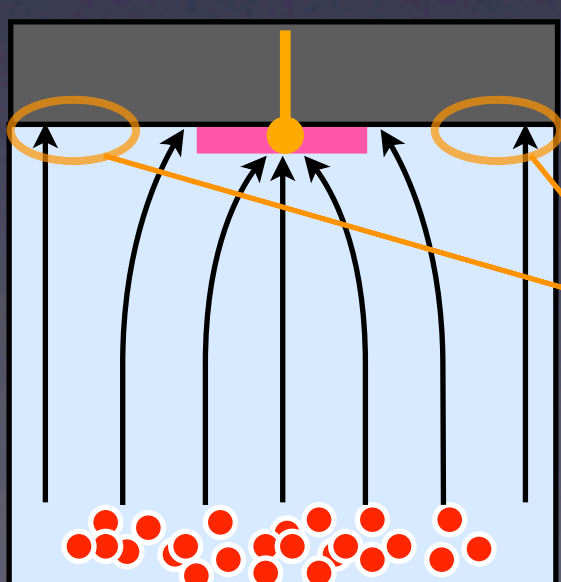
	Single pixel event fraction	
	Small Pixel	Large Pixel 1
Cu Kα	86.1%	96.4%
Mo Kα	66.5%	86.3%

- Increase single pixel events in Large Pixel 1

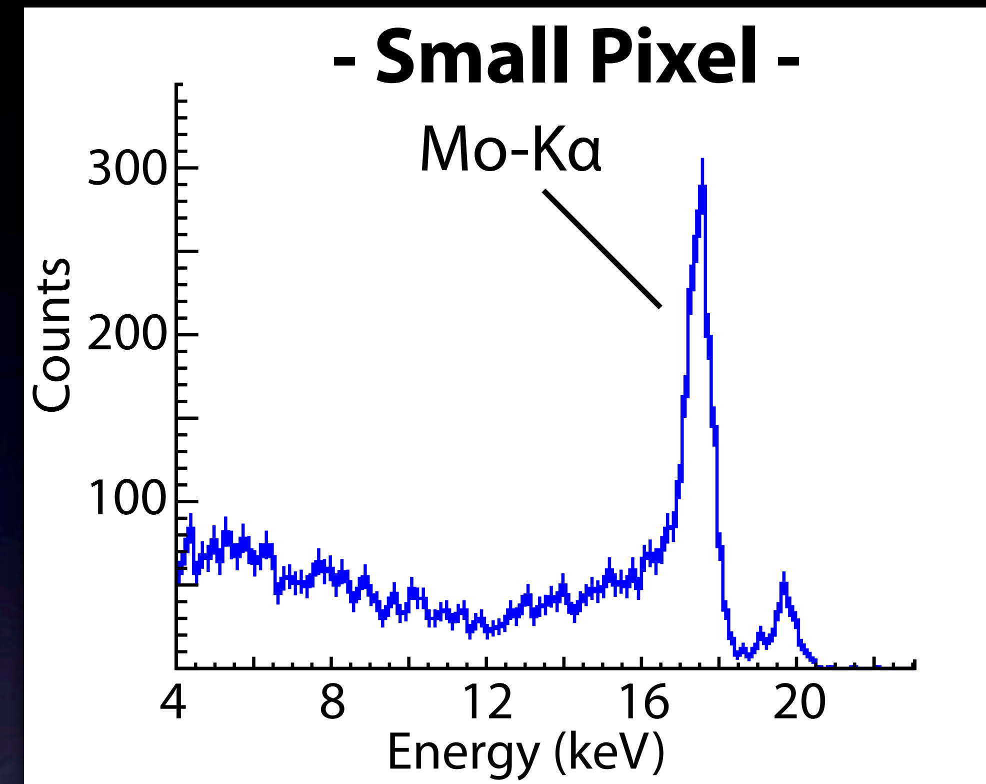
Investigation of Charge Sharing

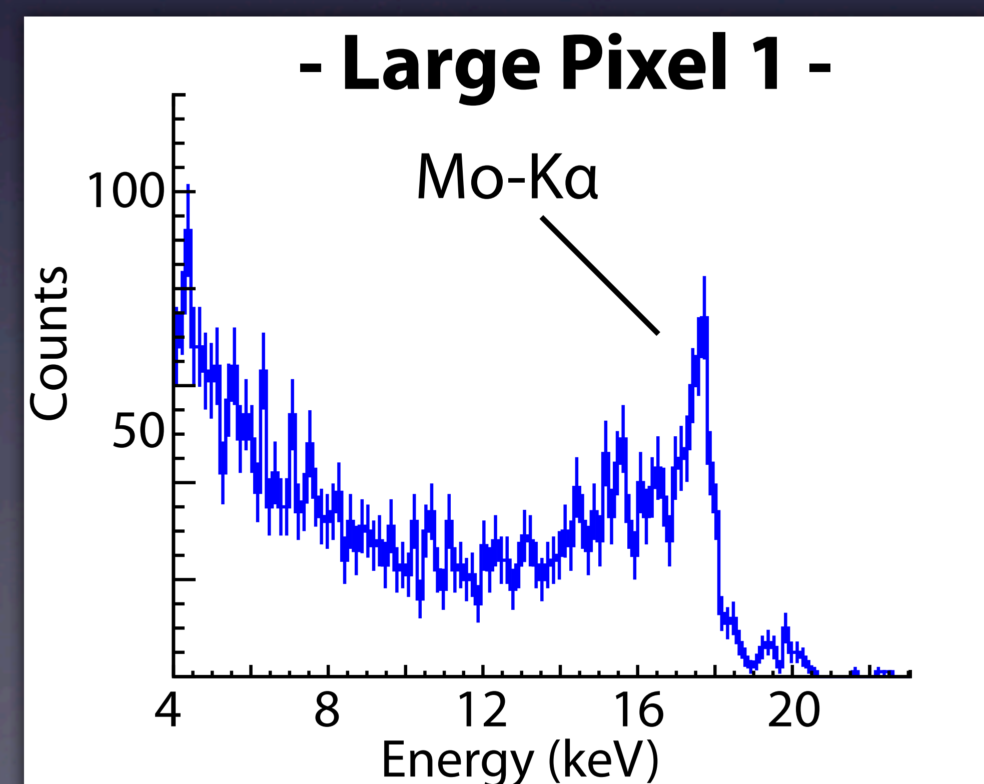
	Single pixel event fraction	
	Small Pixel	Large Pixel 1
Cu Kα	86.1%	96.4%
Mo Kα	66.5%	86.3%

- Increase single pixel events in Large Pixel 1
- Spectral shape is obviously worse than Small Pixel



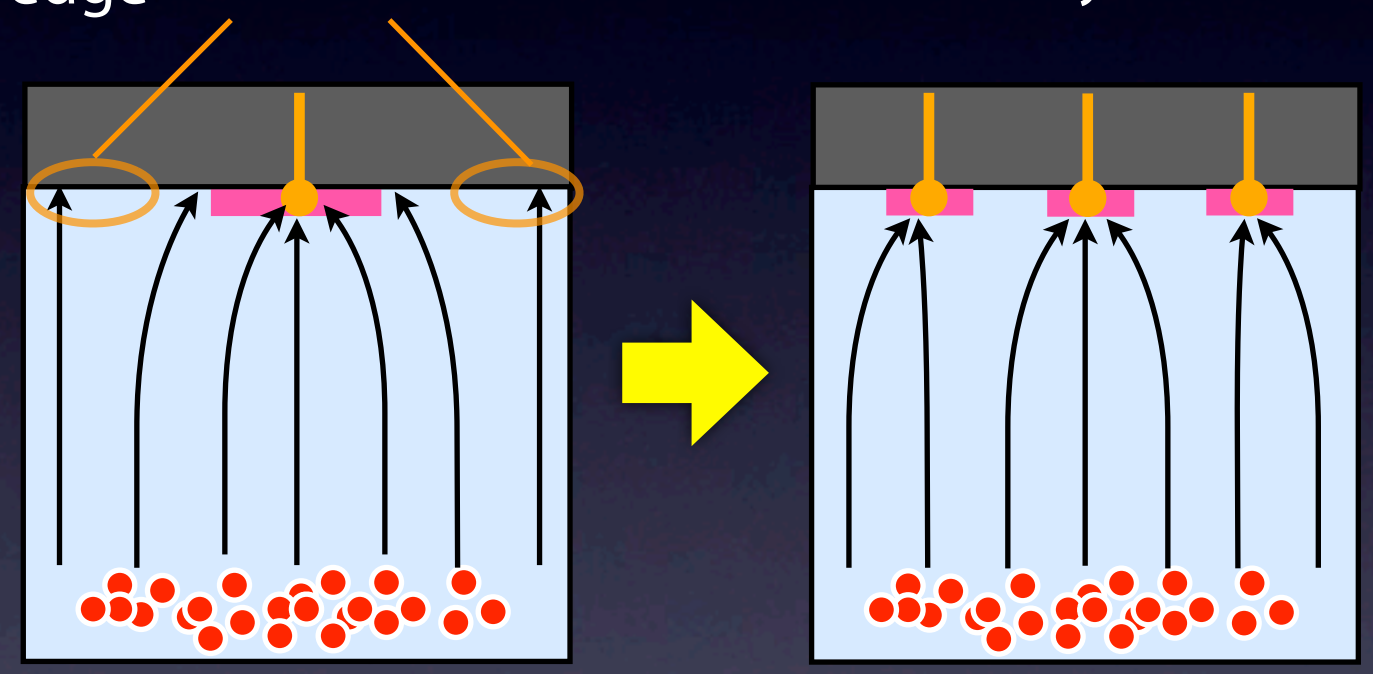
charge collection inefficiency at the pixel edge

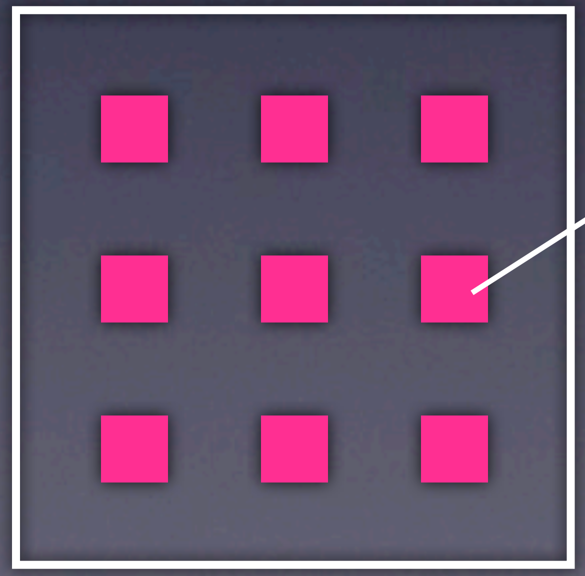




Configuration of Large Pixel 2

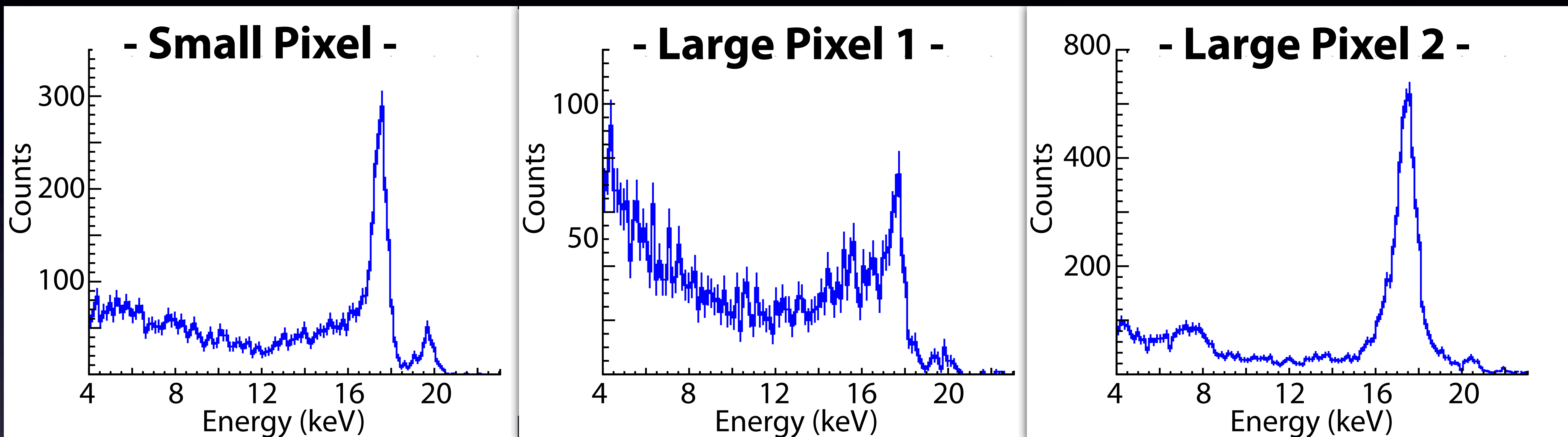
Object of Large Pixel 2 -> Improving the charge collection efficiency





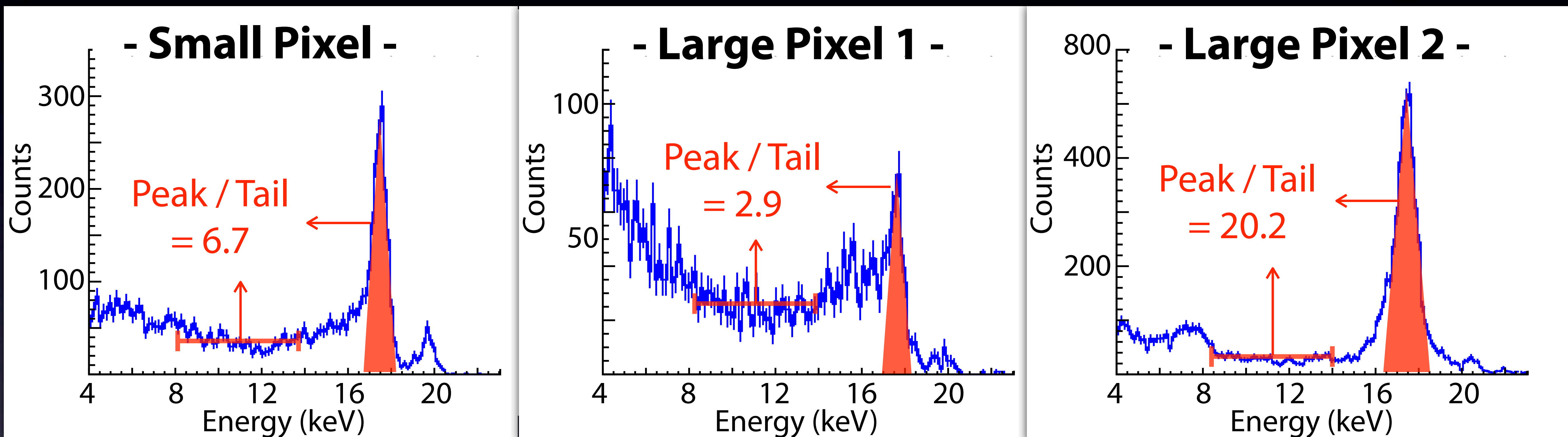
- 9 vias + BPWs
- Total BPW area = 130 μm^2

Charge Collection Efficiency



- Multi-via structure successfully improves the charge collection efficiency.

Charge Collection Efficiency

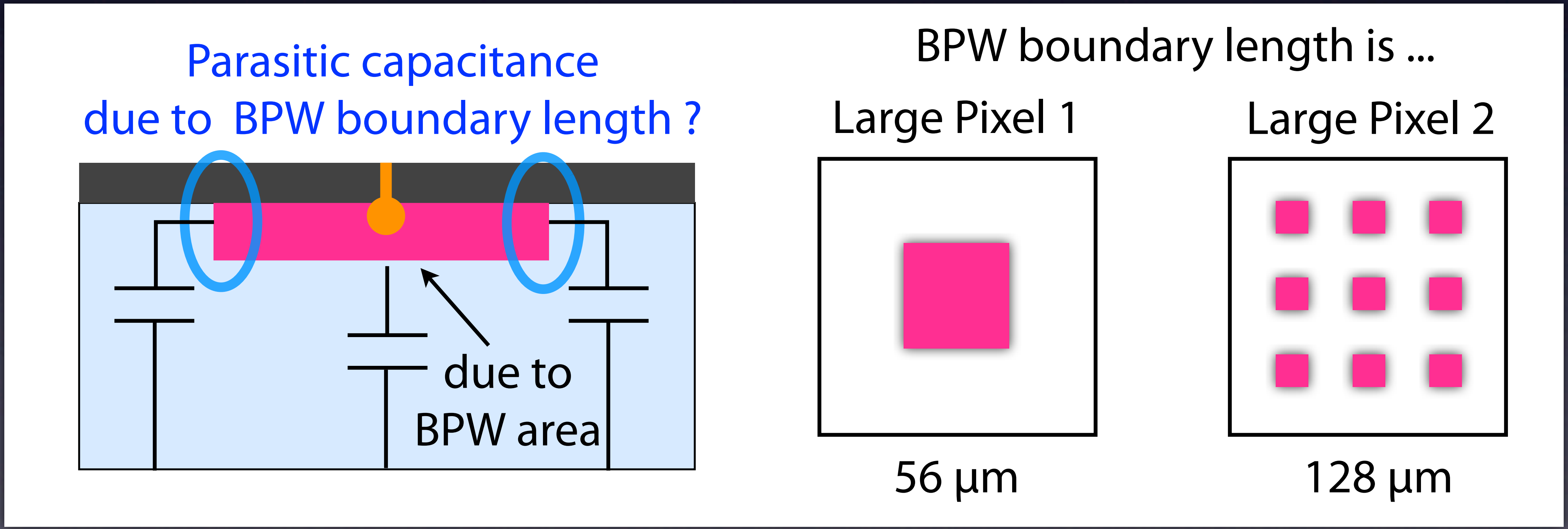


- Multi-via structure successfully improves the charge collection efficiency.

Gain in Large Pixel 2

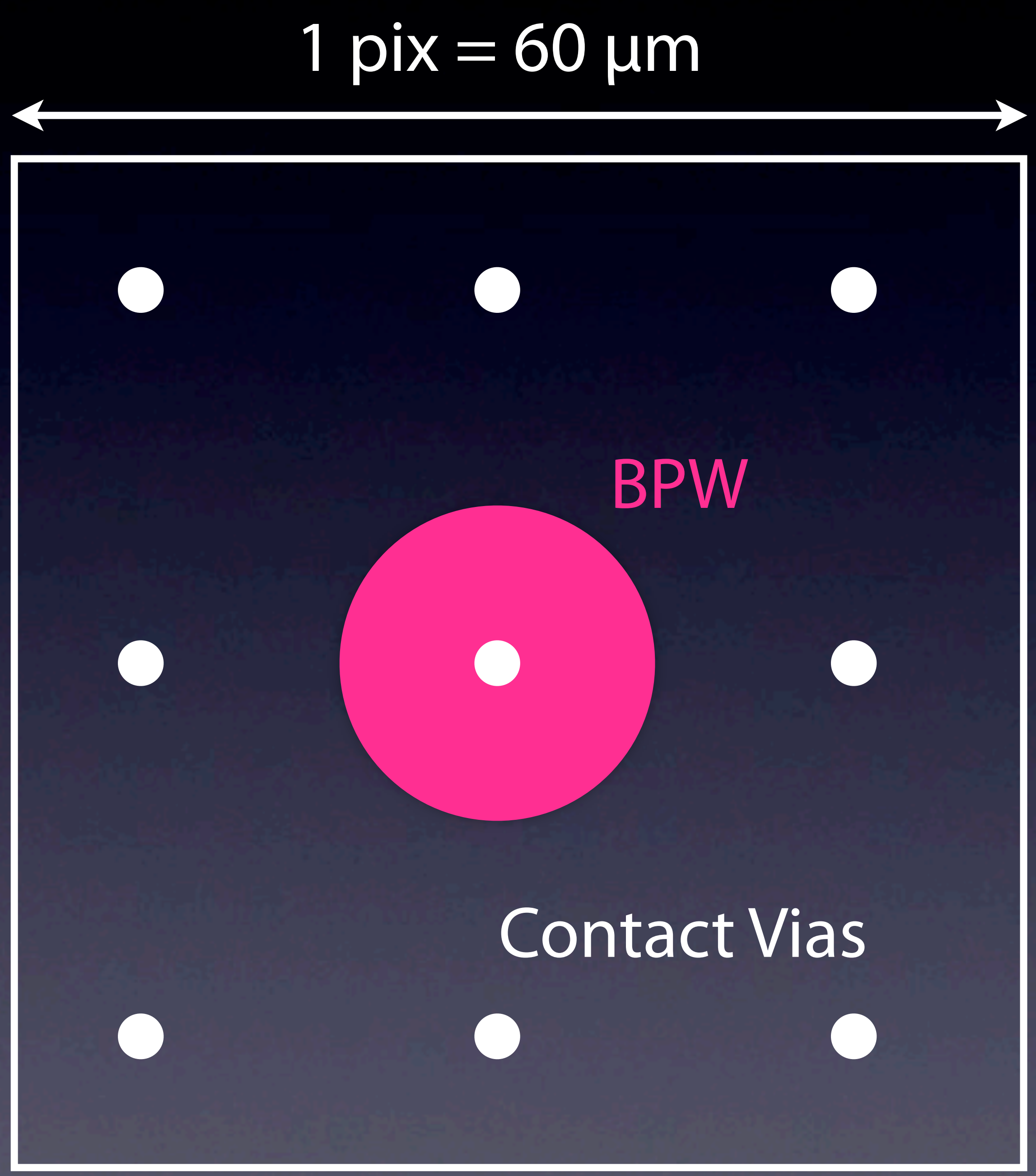
	Small Pixel	Large Pixel 1		Large Pixel 2
Gain	6.5 μV	6.5 μV	1/2 →	3.3 μV

Why does gain decrease in Large Pixel 2 ?



- Simulation for confirmation is underway.

Plan to the Next Chip Design



- Large Pixel Size
  -> Reduce charge sharing
- Multi-via Structure
  -> Increase charge collection efficiency
- One BPW
  -> Increase the gain
- Intra-pixel Charge Amplifier
  -> Increase the gain

Summary & Ongoing Work

Summary

- We are developing X-ray SOI pixel sensor for X-ray Astronomy.
- New device, “XRPIX2”, achieve 1.8 times higher gain and energy resolution than that of XRPIX1. (Gain = 6.5 μV/e-, Energy resolution = 656 eV @8 keV)
- Large pixel pitch decreases charge sharing and multi-via structure improves the spectral shape.

Ongoing Work

- Feedback the results into the next chip design.
- Trigger driven readout with XRPIX2.