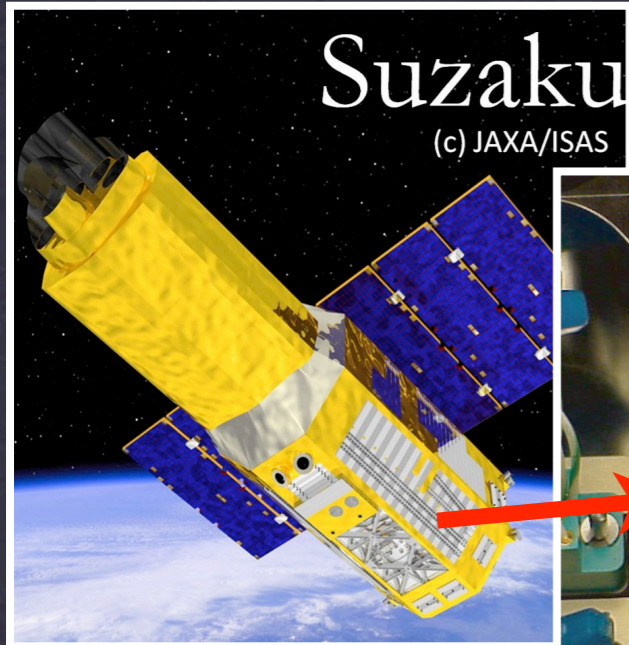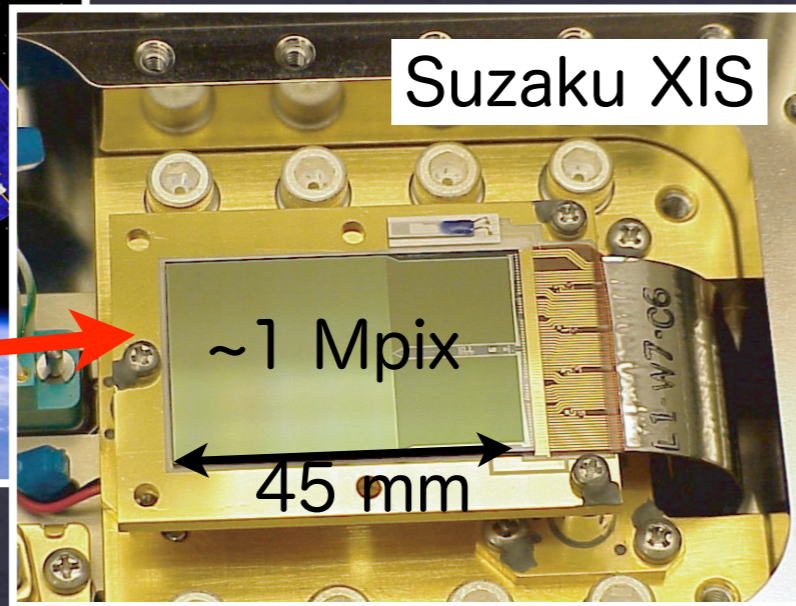# Progress in Development of Monolithic Active Pixel Detector for X-ray Astronomy with SOI CMOS Technology

S. Nakashima, S.G. Ryu, T. G. Tsuru (Kyoto Univ.),

Y. Arai, A. Takeda, T. Miyoshi, R. Ichimiya (KEK/IPNS),

T. Imamura, T.Ohmoto, A. Iwata (A-R-Tec Corp.),

on beharf of SOI group, Japan.

Motivation in X-ray Astronomy

Suzaku
(c) JAXA/ISAS

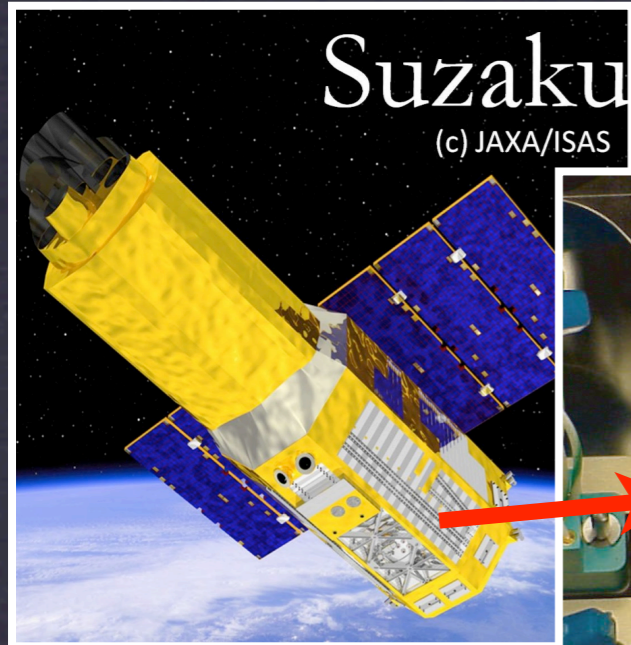Standard Detector
= X-ray CCDs

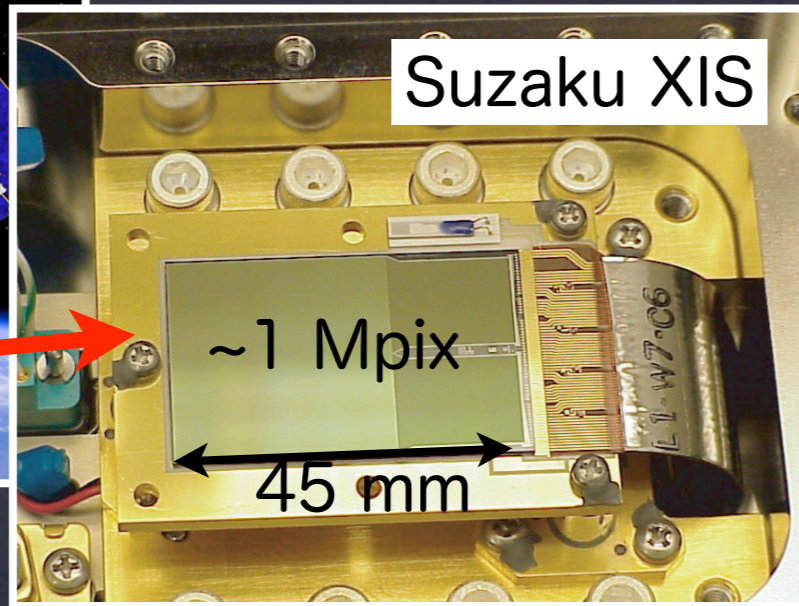Suzaku XIS

~1 Mpix

45 mm

Problems

- Poor time resolution of ~ sec

- Non X-ray background above 10 keV

 – due to cosmic-rays in satellite orbit

	positional resolution	Energy resolution	Timing resolution	observable energy band
CCD	~ 20 μm	2% FWHM@6 keV	~ sec	0.5 - 10 keV

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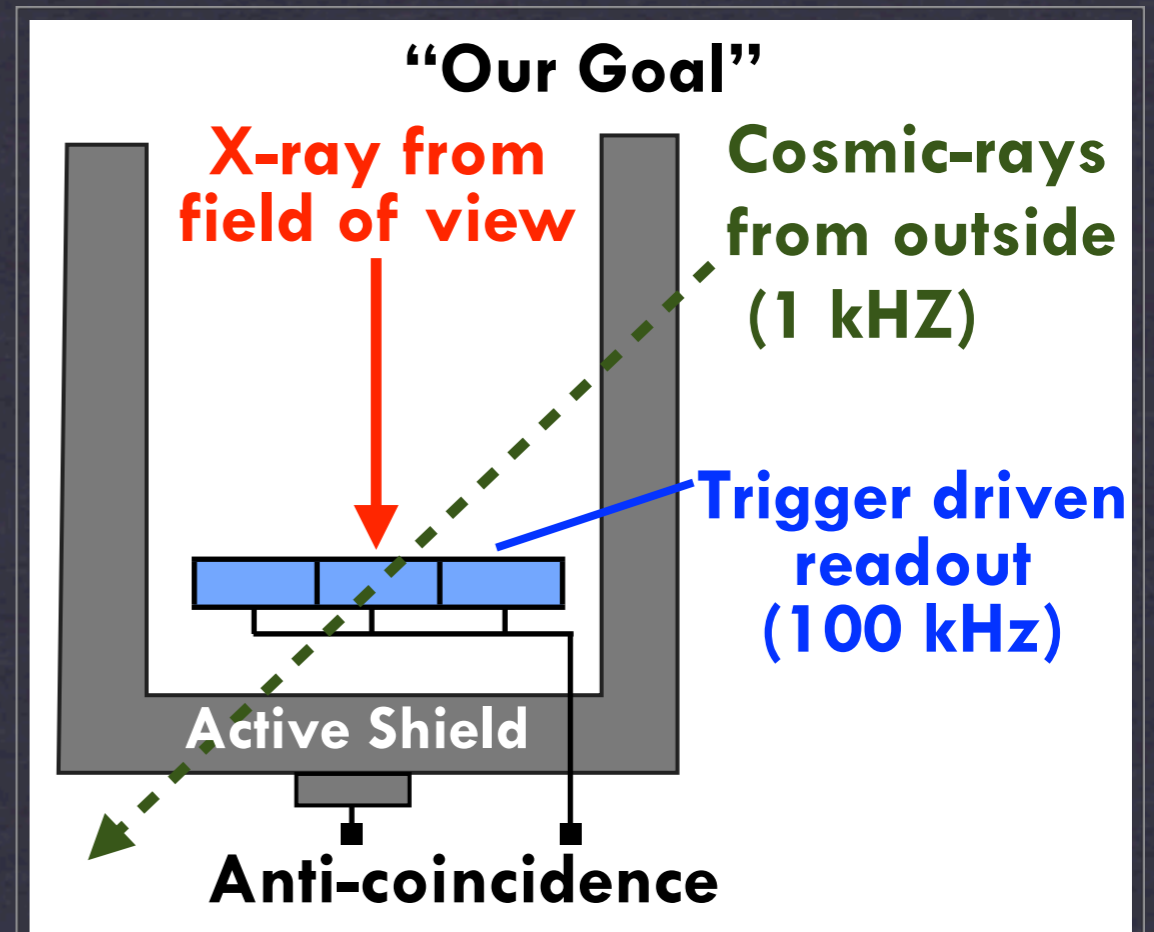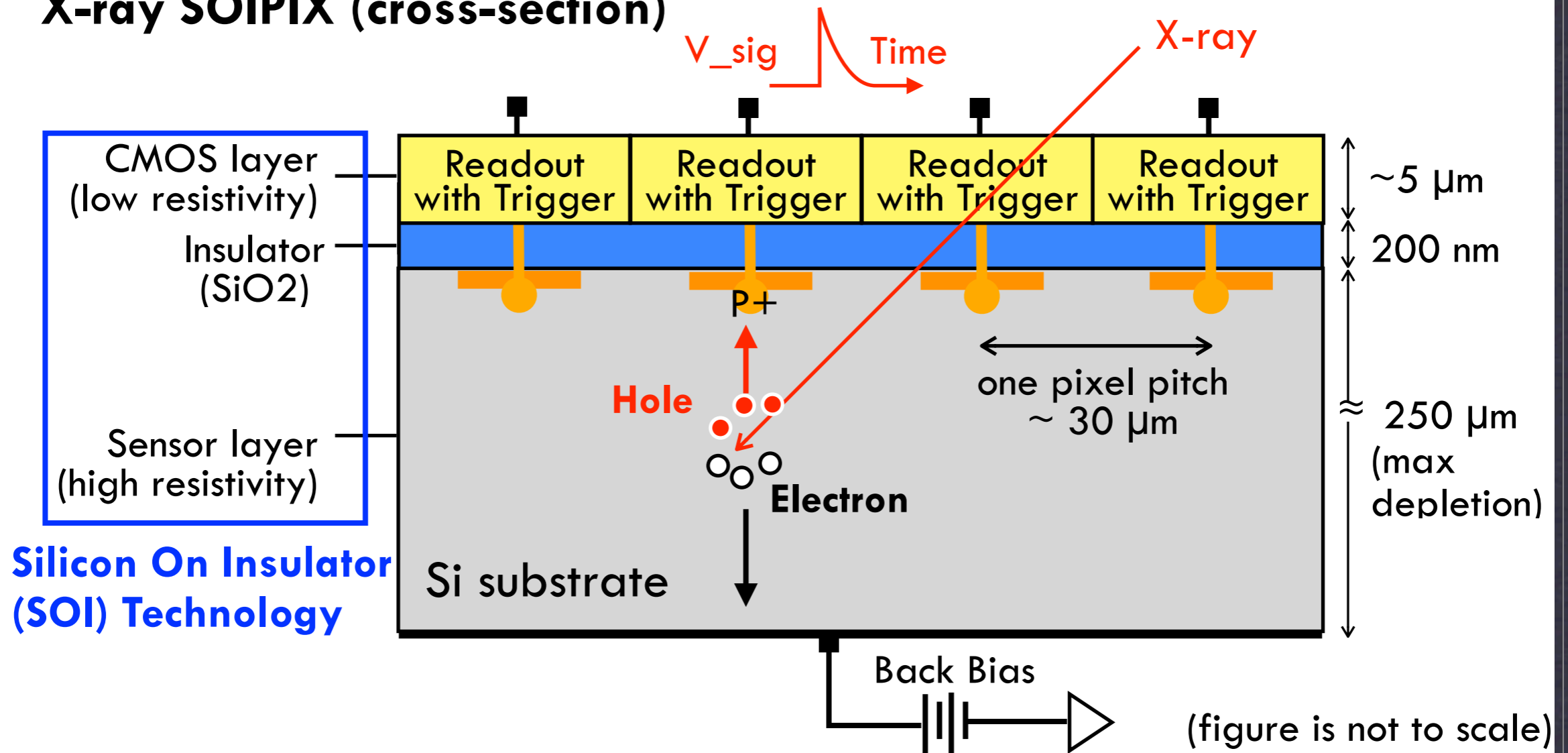
new imaging spectrometer capable of high speed reaout and low background

Problems

- Poor time resolution of ~ sec
- Non X-ray background above 10 keV
  - due to cosmic-rays in satellite orbit

"Our Goal"

X-ray from field of view

Cosmic-rays from outside (1 kHZ)

Trigger driven readout (100 kHz)

Active Shield

Anti-coincidence

	positional resolution	Energy resolution	Timing resolution	observable energy band
CCD	~ 20 μm	2% FWHM@6 keV	~ sec	0.5 - 10 keV
Novel Detector	< 30 μm	2% FWHM@6 keV	< 10 μsec	0.5 - 40 keV

Concept of X-ray SOIPIX

X-ray SOIPIX (cross-section)

V_sig   Time

X-ray

CMOS layer
(low resistivity)

Insulator
(SiO2)

Readout with Trigger	Readout with Trigger	Readout with Trigger	Readout with Trigger

~5 μm

200 nm

P+

Hole

one pixel pitch
~ 30 μm

≈ 250 μm
(max depletion)

Sensor layer
(high resistivity)

Electron

Silicon On Insulator (SOI) Technology

Si substrate

Back Bias

(figure is not to scale)

- Monolithic pixel sensor by Silicon on Insulator (SOI) Tech
- Si sensor + CMOS readout circuit with trigger
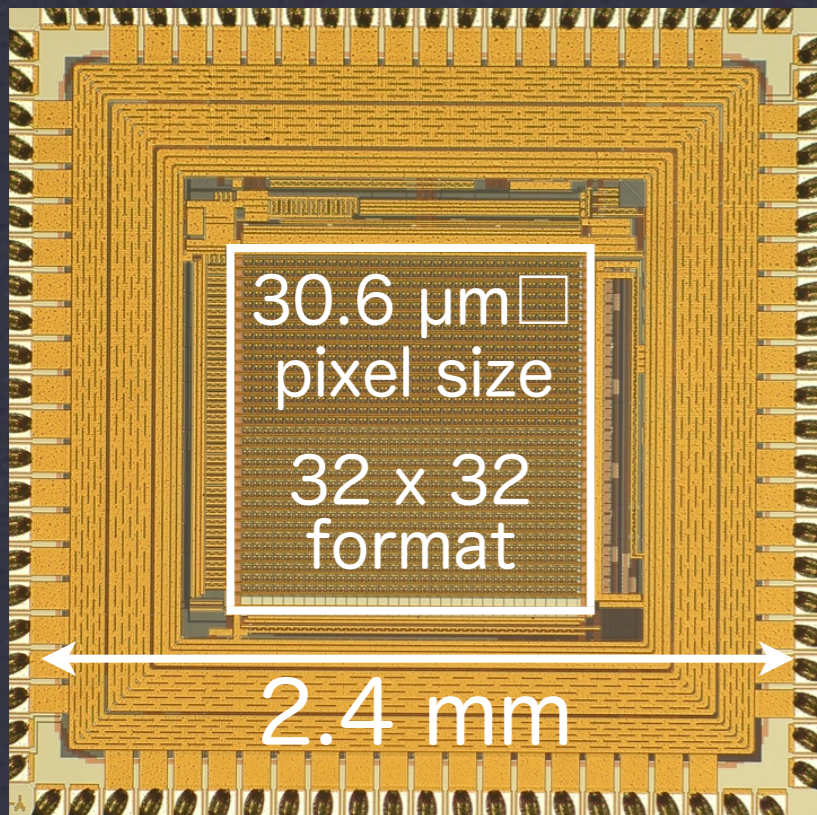- Many advantages over conventional hybrid CMOS sensor

Prototype: XRPIX1

30.6 μm□ pixel size

32 x 32 format

2.4 mm

XRPIX1: First prototype
Ryu reported @IEEE-NSS2010
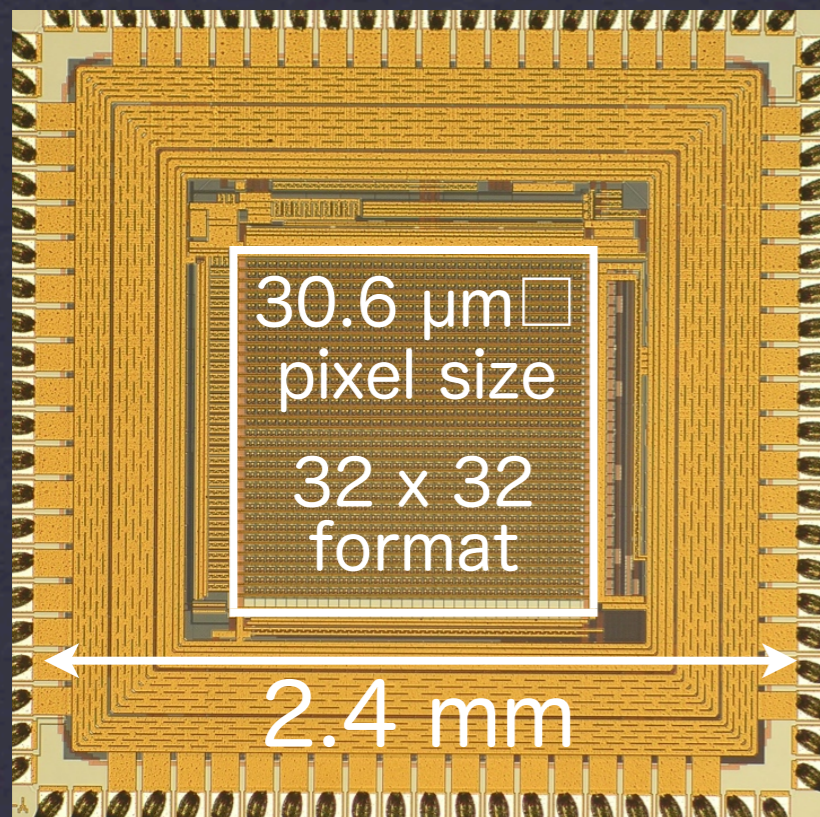
- Confirmed the capabilities of X-ray imaging spectroscopy and the trigger function
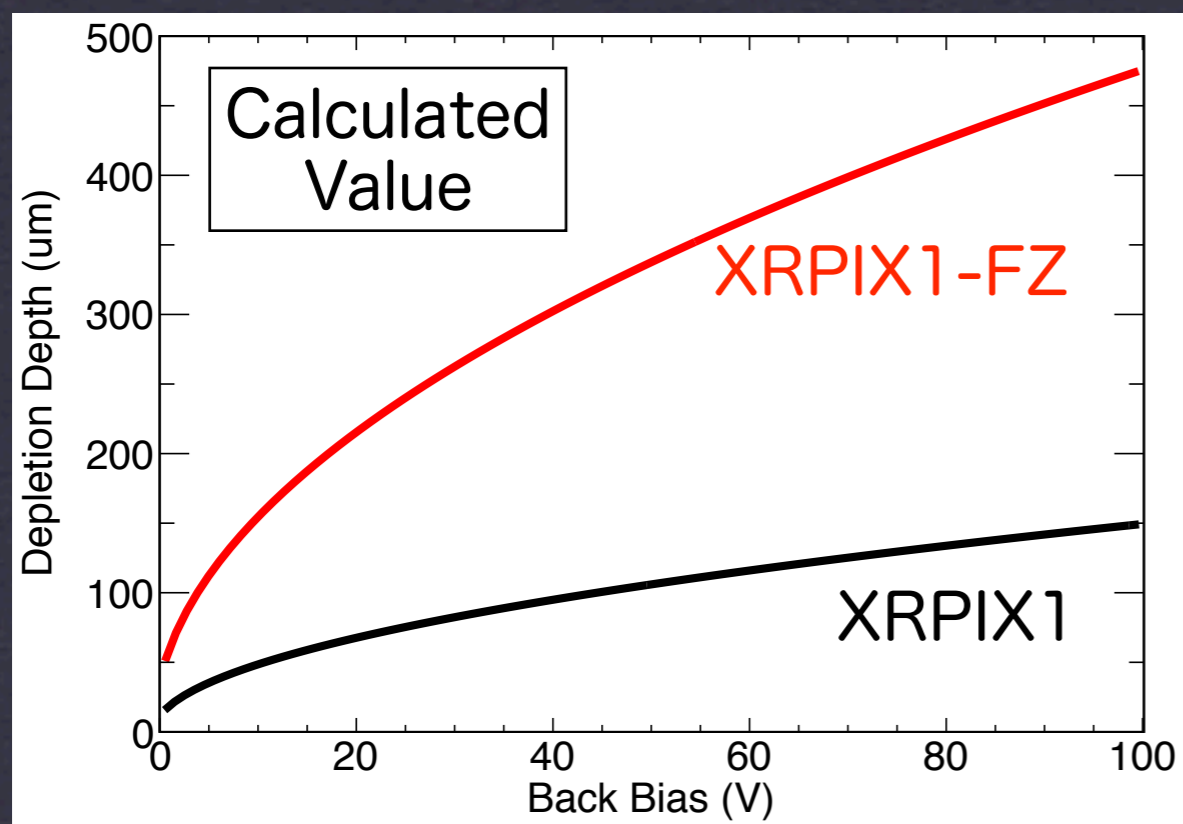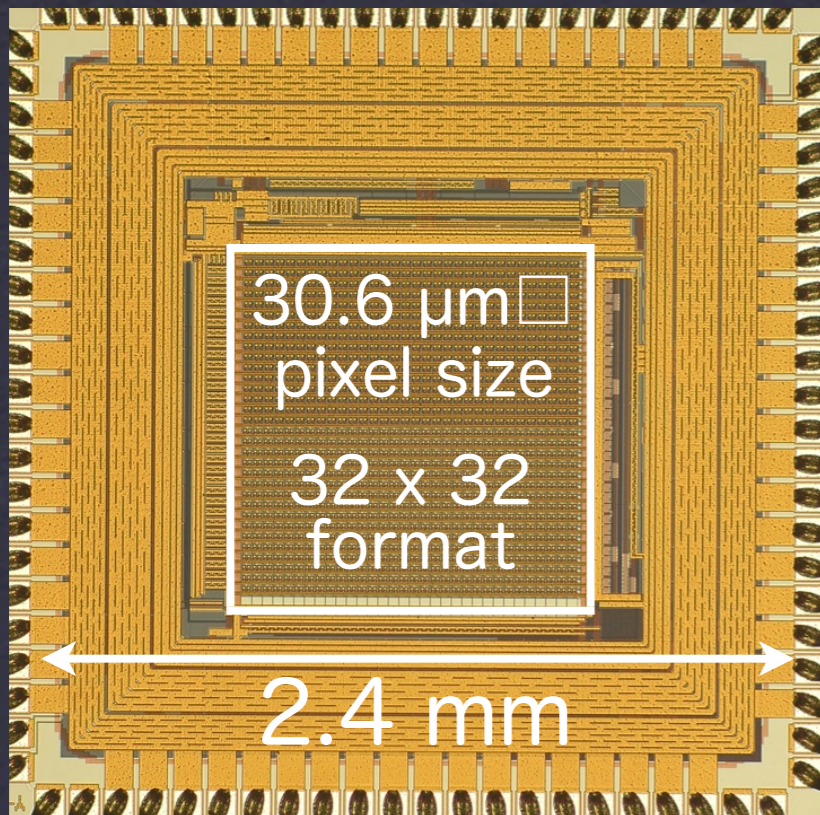- Depletion layer of 140 μm

Prototype: XRPIX1

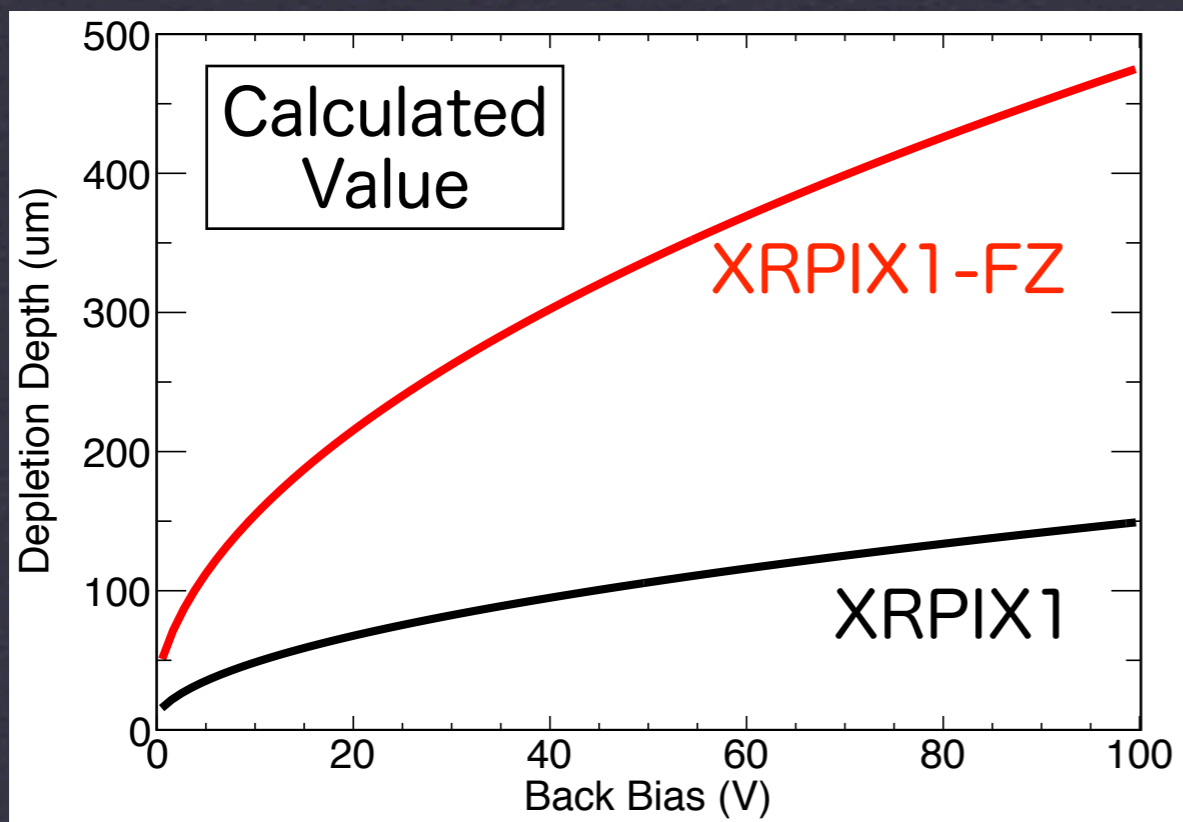30.6 μm□ pixel size

32 x 32 format
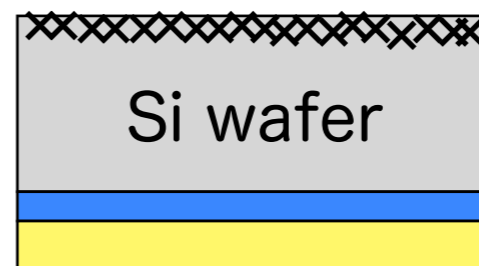
2.4 mm

XRPIX1: First prototype
Ryu reported @IEEE-NSS2010

- Confirmed the capabilities of X-ray imaging spectroscopy and the trigger function
- Depletion layer of 140 μm

XRPIX1-FZ: Thick depletion layer

- Resistivity 7 kΩcm (XRPIX1 = 0.7 kΩcm)
- Chemical Mechanical Polish (CMP) treatment to backside of the sensor layer

Calculated Value

XRPIX1-FZ

XRPIX1

Depletion Depth (um)

Back Bias (V)

Prototype: XRPIX1

30.6 μm□ pixel size

32 x 32 format

2.4 mm

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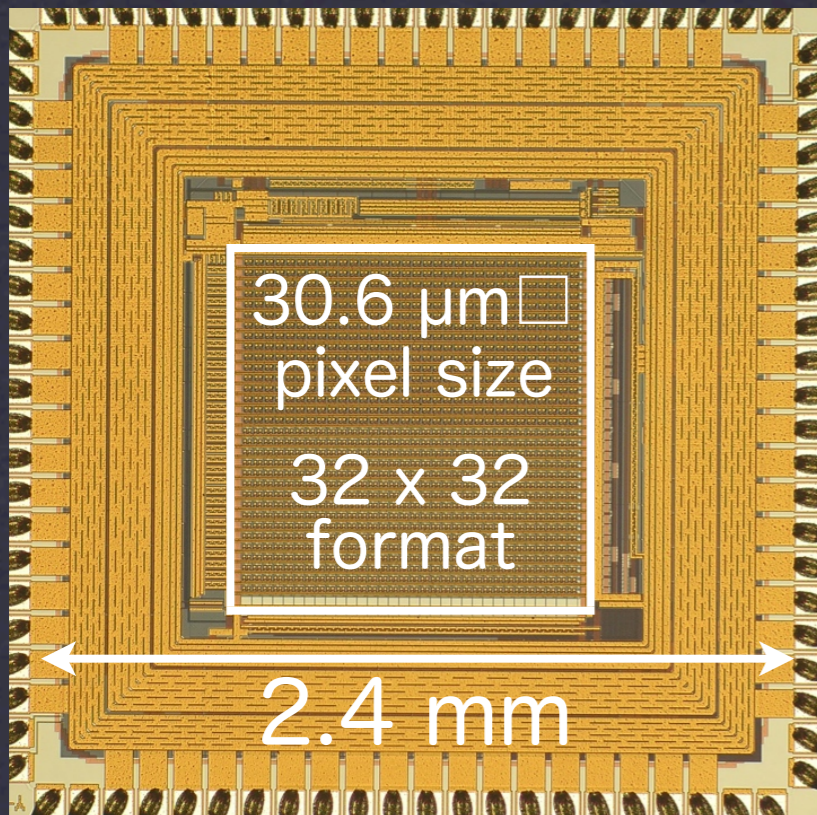Rough backside...

Si wafer

Before CMP

Prototype: XRPIX1
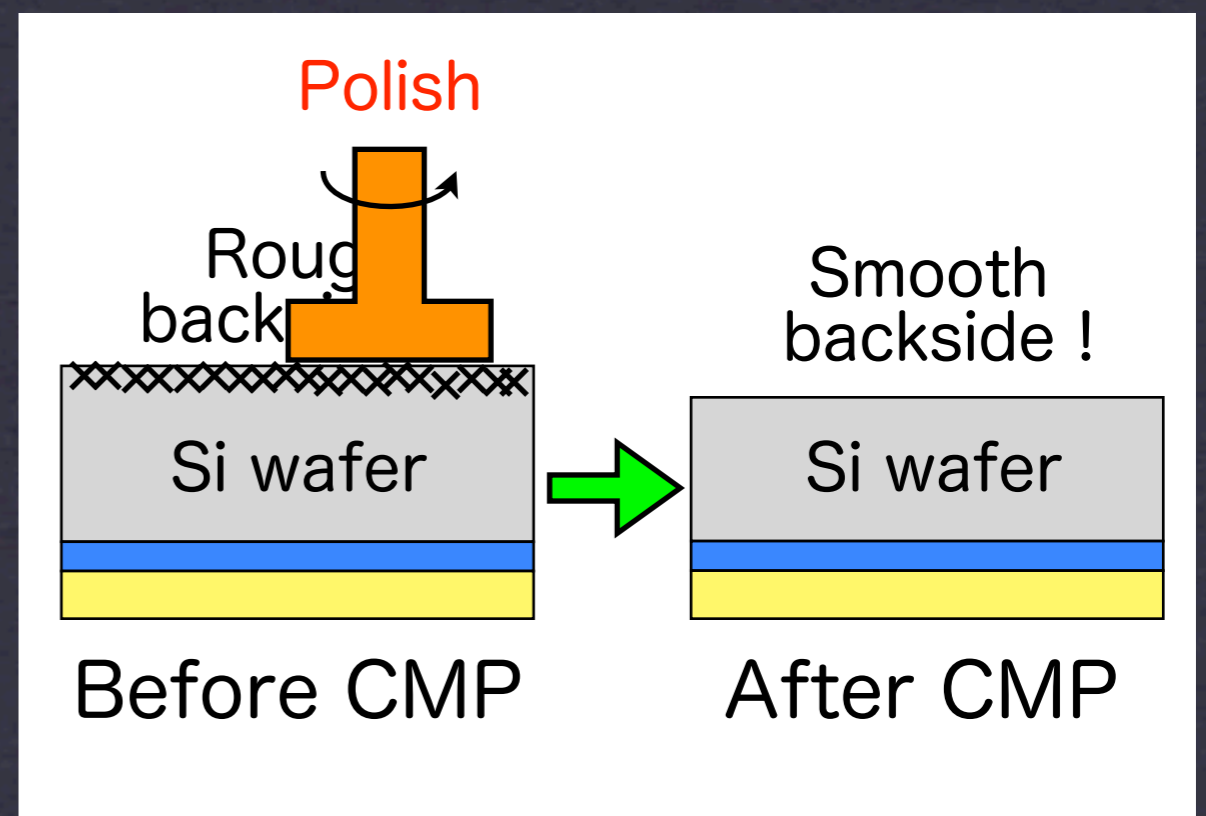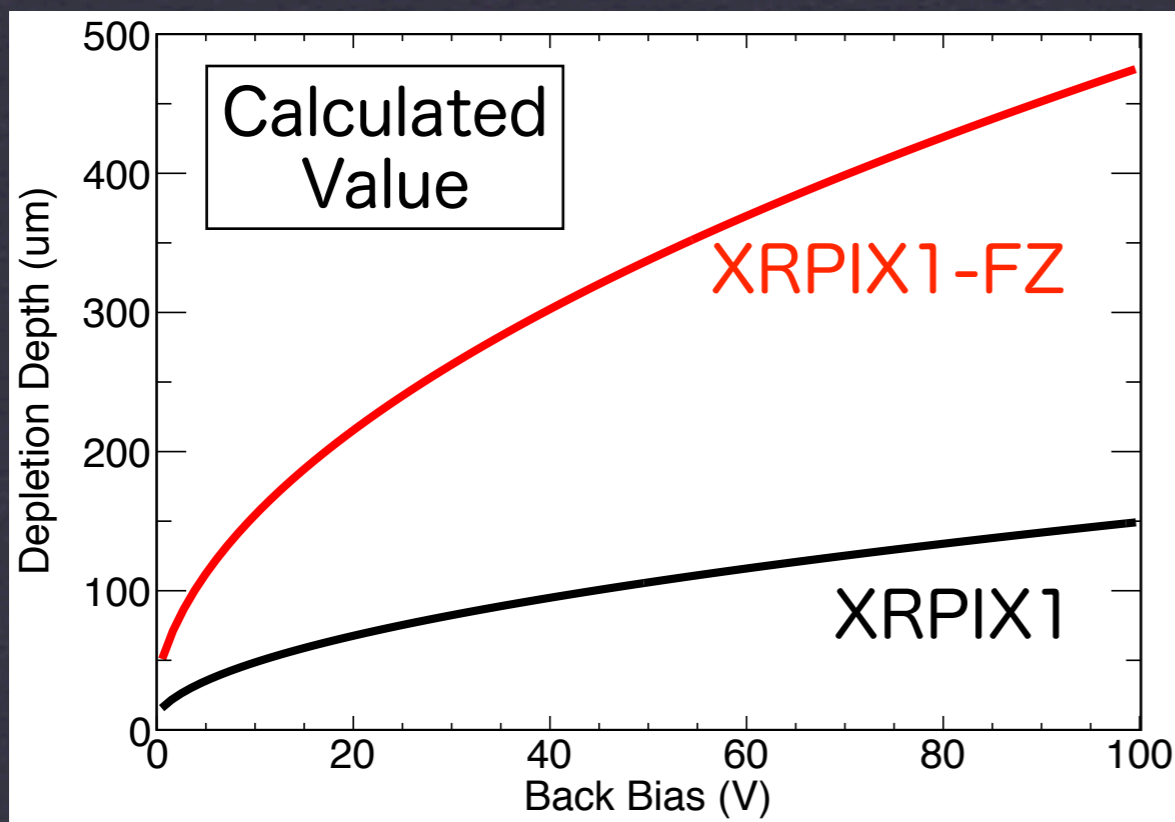
XRPIX1: First prototype

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30.6 μm□ pixel size

32 x 32 format

2.4 mm

Calculated Value

XRPIX1-FZ

XRPIX1

Depletion Depth (um)

Back Bias (V)

Polish

Rough backside

Smooth backside !

Si wafer

Si wafer

Before CMP

After CMP

CMOS Circuit of XRPIX1-FZ

- The design of the circuit is same as that of XRPIX1
- Trigger function -> OFF in this test
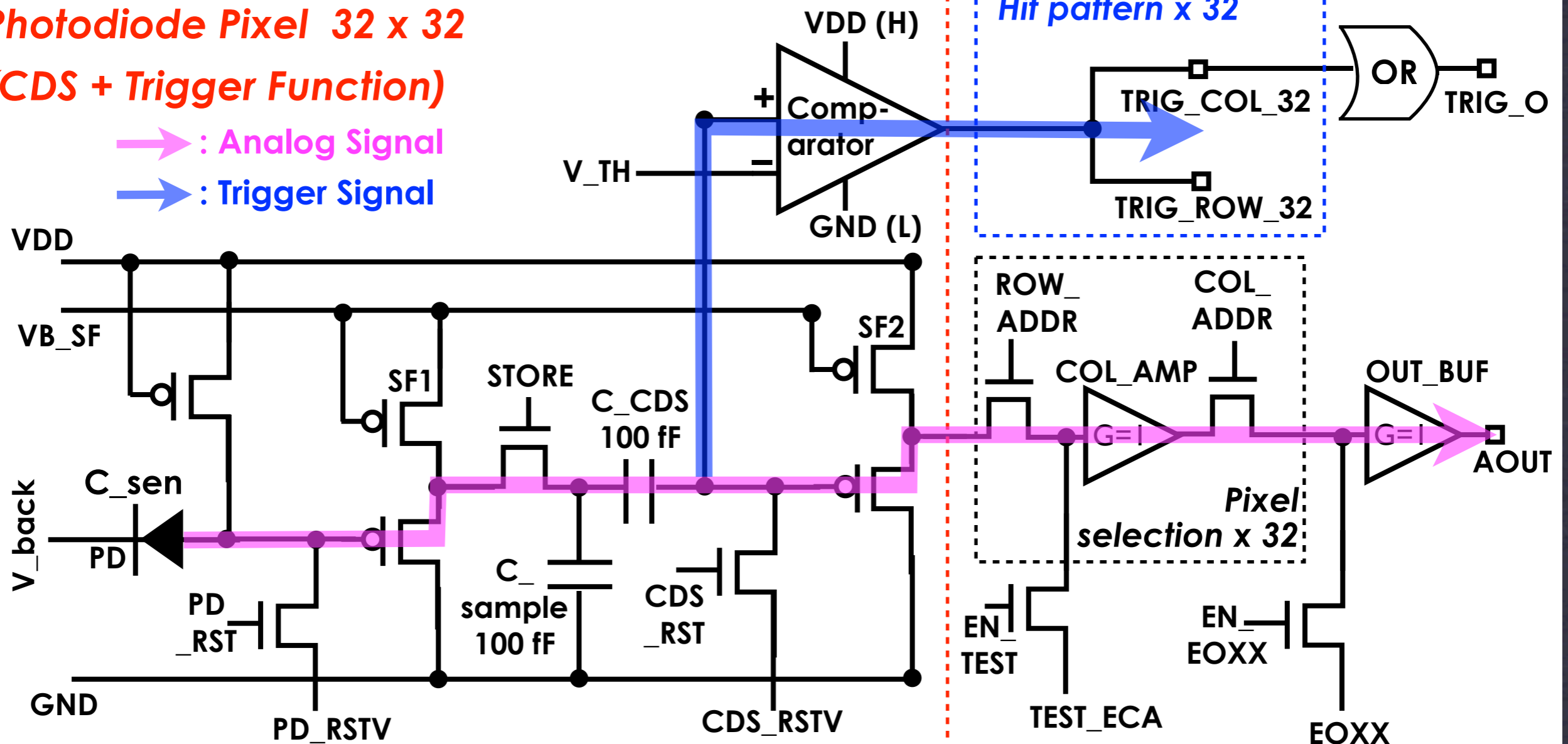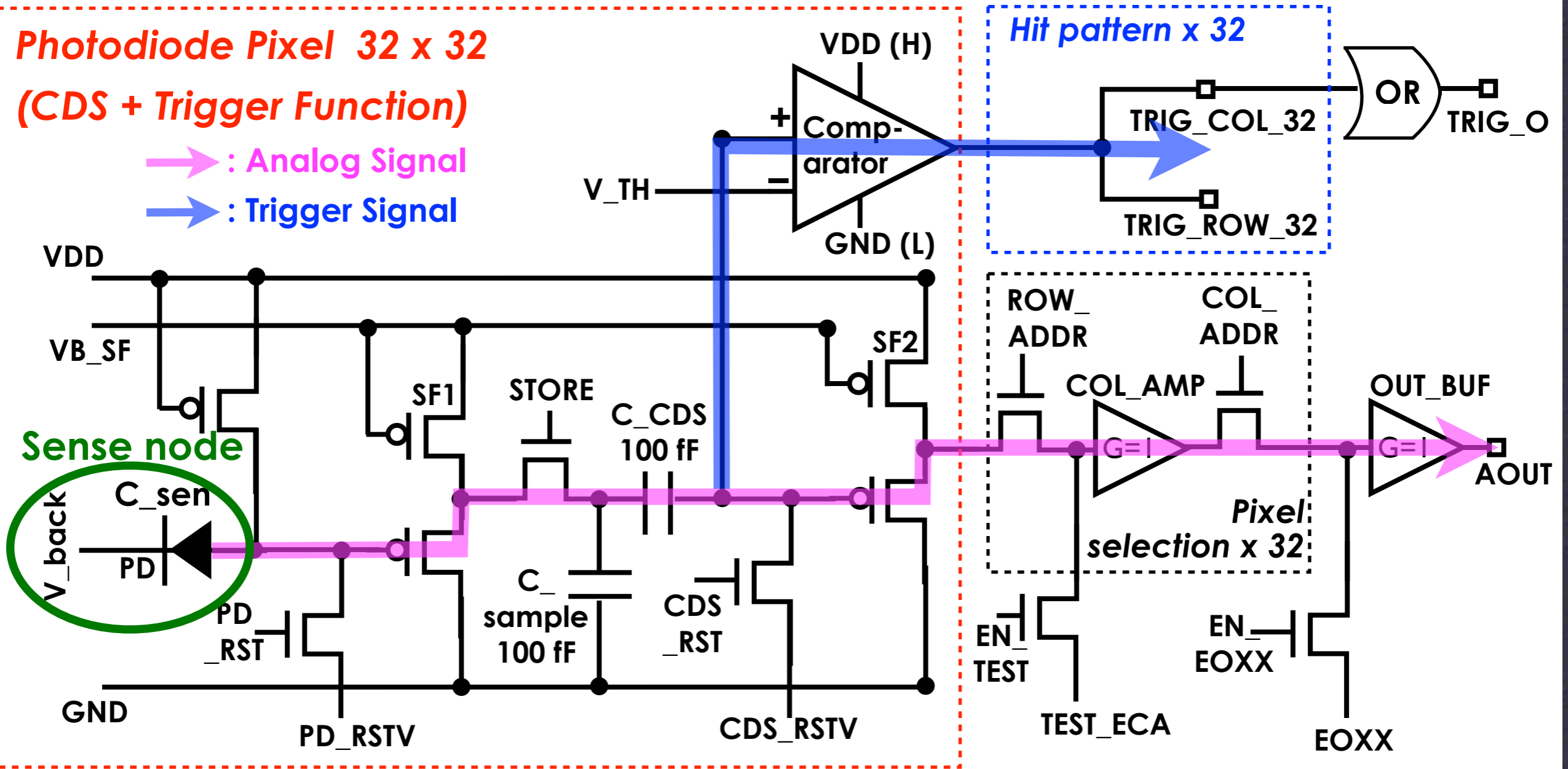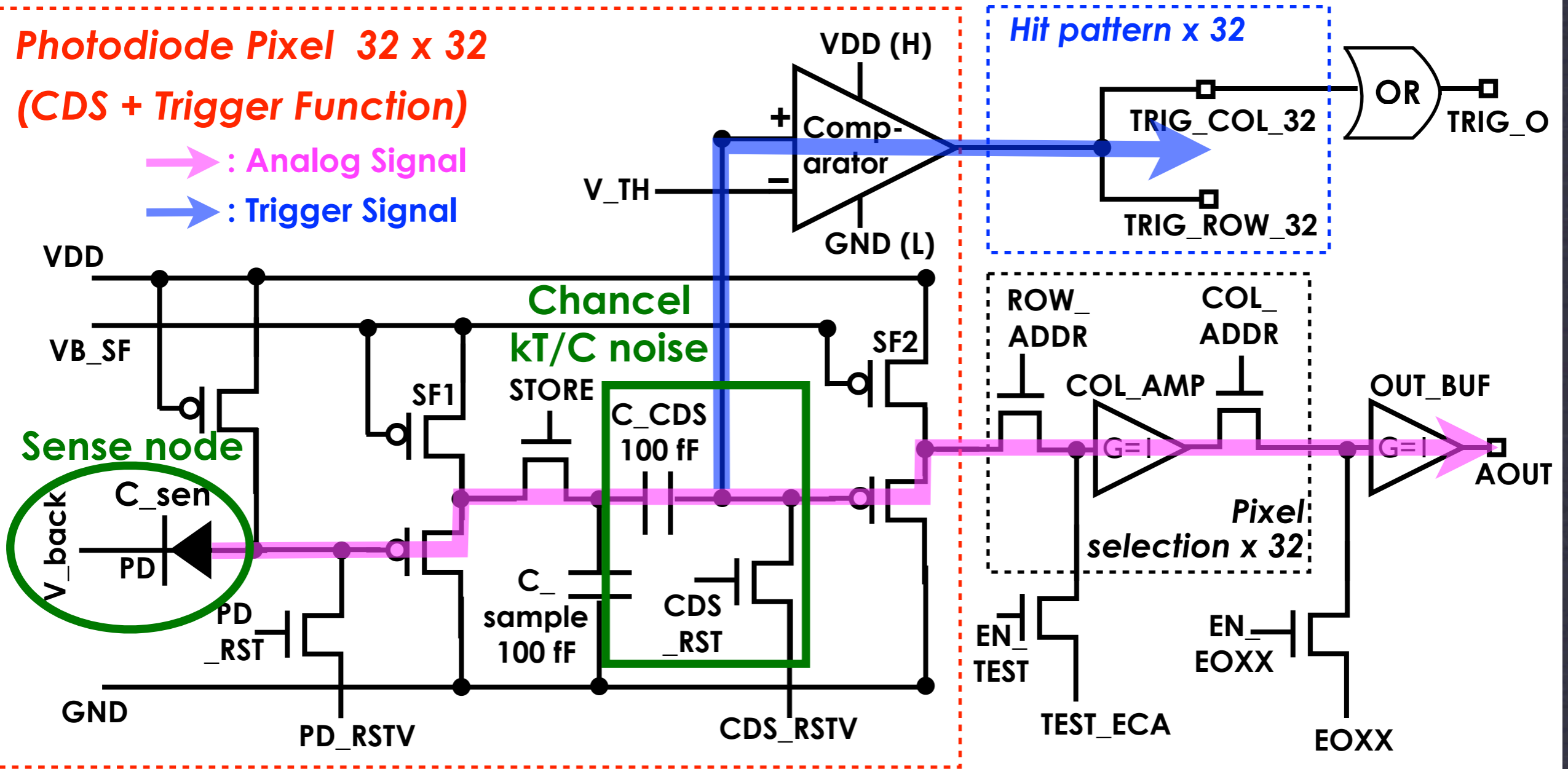
CMOS Circuit of XRPIX1-FZ

Photodiode Pixel 32 x 32
(CDS + Trigger Function)

→ : Analog Signal
→ : Trigger Signal

VDD (H)

Hit pattern x 32

TRIG_COL_32

OR

TRIG_O

+
Comp-
arator
−

V_TH

TRIG_ROW_32

GND (L)

VDD

VB_SF

SF1

STORE

C_CDS
100 fF

SF2

ROW_
ADDR

COL_
ADDR

COL_AMP

OUT_BUF

Sense node

C_sen

V_back

PD

G=1

G=1

AOUT

*Pixel
selection x 32*

PD
_RST

C_
sample
100 fF

CDS
_RST

EN_
TEST

EN_
EOXX

GND

PD_RSTV

CDS_RSTV

TEST_ECA

EOXX

- The design of the circuit is same as that of XRPIX1
- Trigger function -> OFF in this test

CMOS Circuit of XRPIX1-FZ


Photodiode Pixel 32 x 32 (CDS + Trigger Function)

→ : Analog Signal
→ : Trigger Signal

Hit pattern x 32

VDD (H)
+ Comp-arator
V_TH −
GND (L)

OR
TRIG_COL_32
TRIG_ROW_32
TRIG_O

VDD
VB_SF
Sense node
V_back C_sen PD
PD _RST
GND
PD_RSTV

SF1
STORE
Channel kT/C noise
C_CDS 100 fF
C_sample 100 fF
CDS _RST
CDS_RSTV

SF2

ROW_ADDR   COL_ADDR
COL_AMP
G=1
Pixel selection x 32
EN_TEST
TEST_ECA

OUT_BUF
G=1
AOUT
EN_EOXX
EOXX

- The design of the circuit is same as that of XRPIX1
- Trigger function -> OFF in this test

Experimental Setup
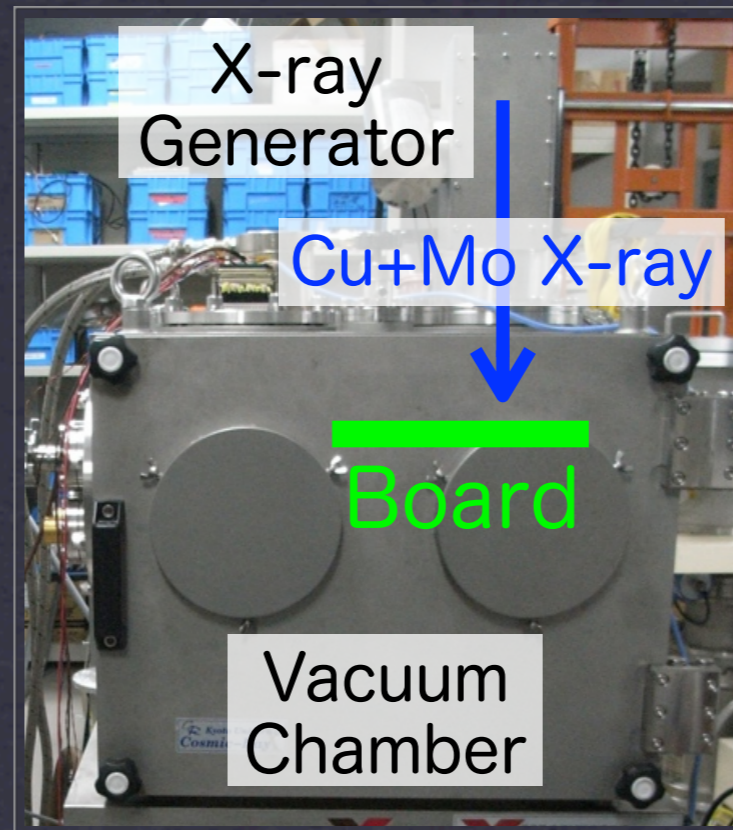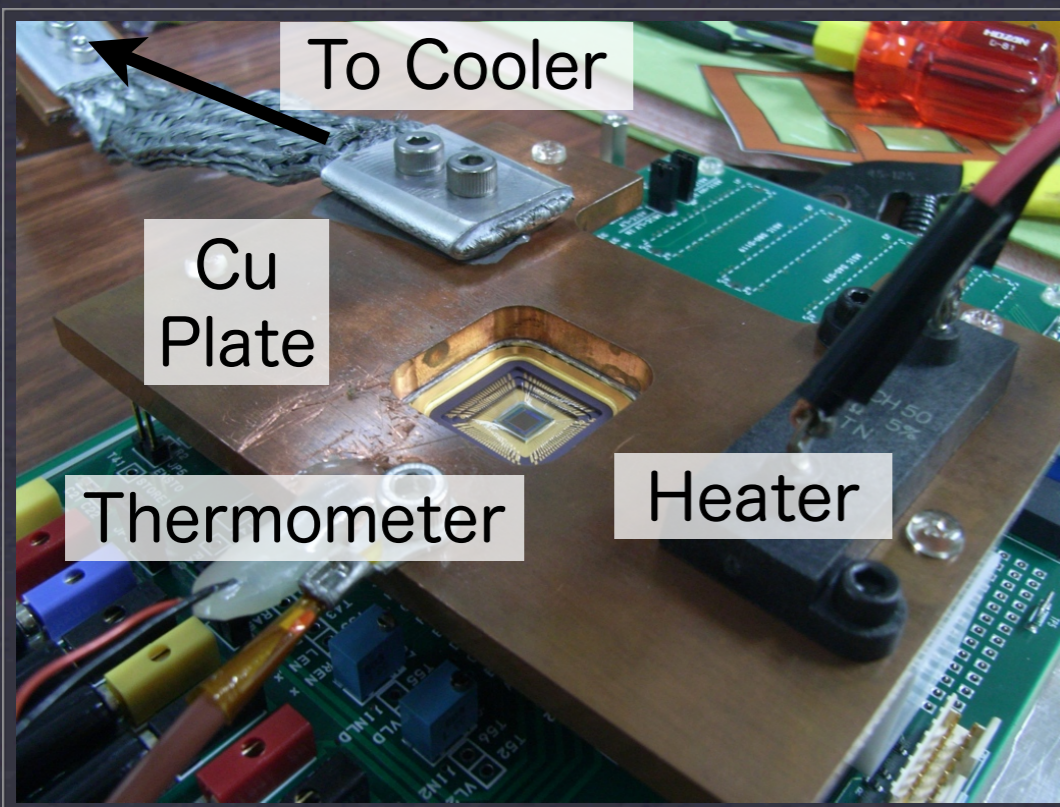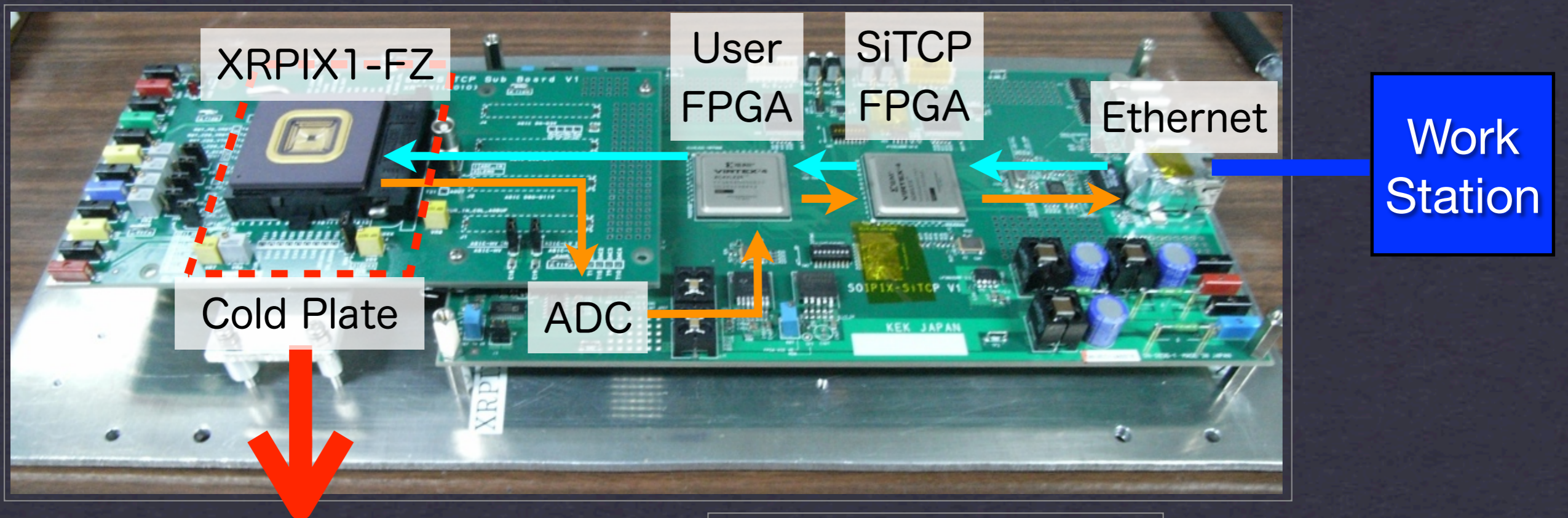
Dark Current

- X-ray is NOT irradiated
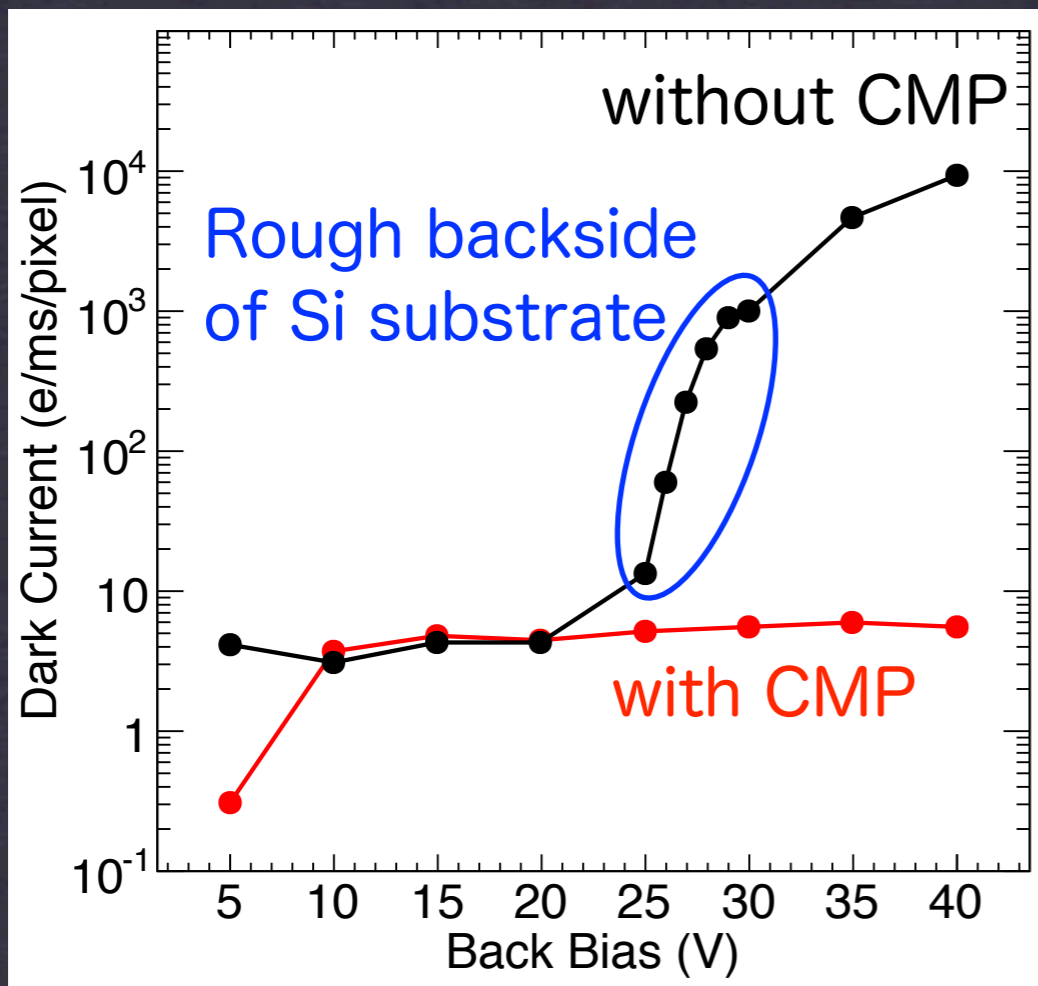- Output voltage ∝ exposure time
- -> Slope = dark current

measure slope

Output

Exposure Time
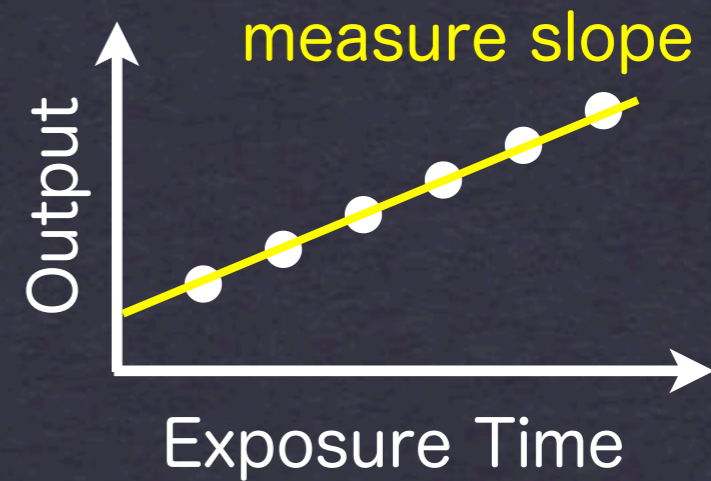
Back Bias v.s. Dark Current @-50℃

without CMP

Rough backside of Si substrate

with CMP

Dark Current (e/ms/pixel)

Back Bias (V)

Temperature v.s. Dark Current
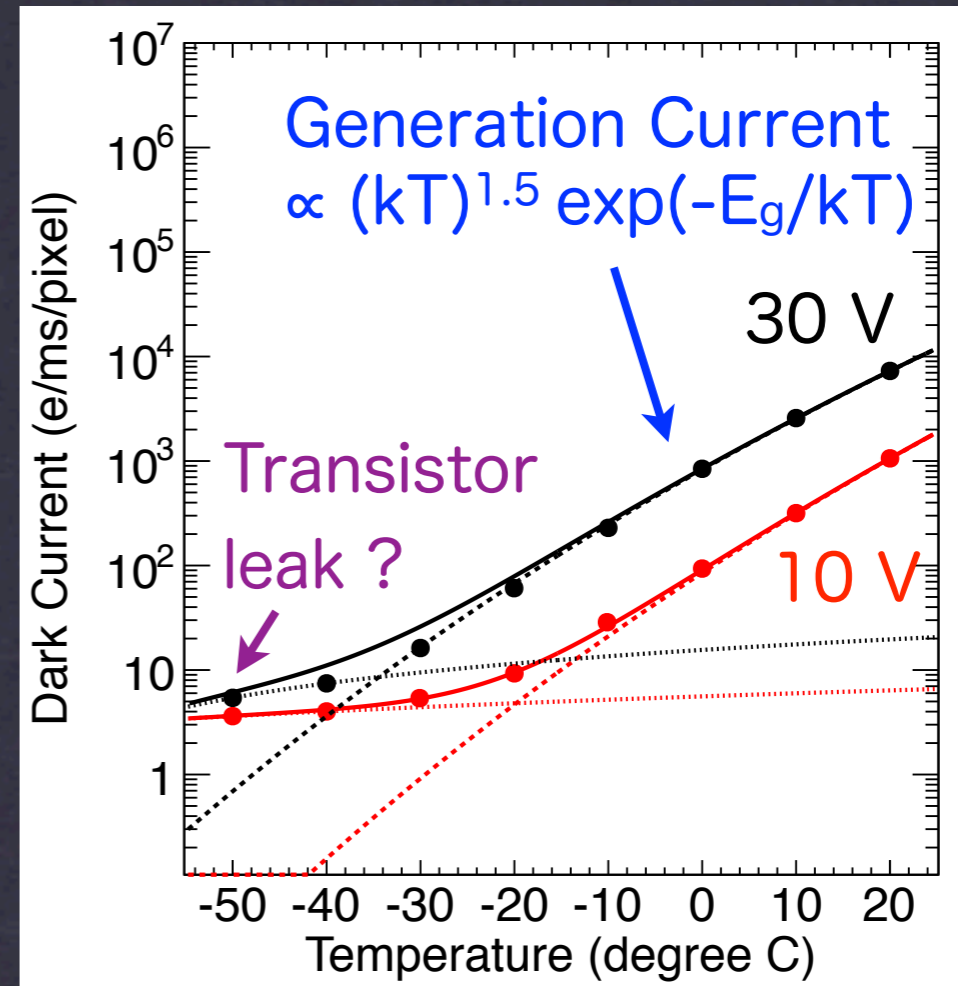
Generation Current ∝ $(kT)^{1.5} \exp(-E_g/kT)$

30 V

Transistor leak ?

10 V

Dark Current (e/ms/pixel)
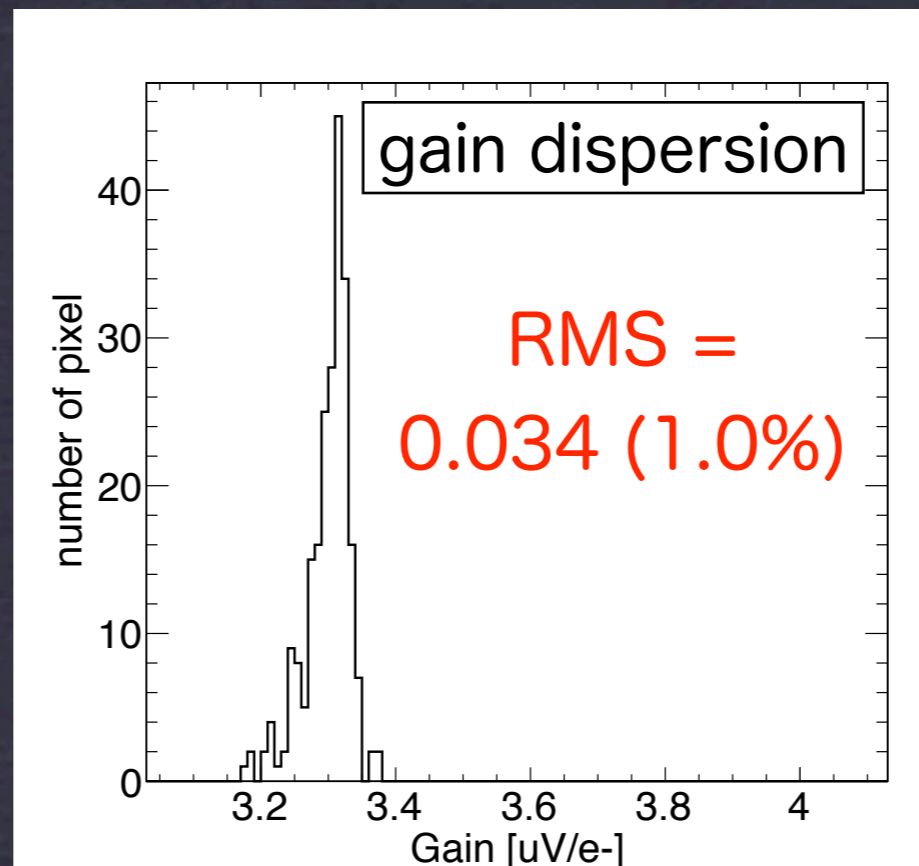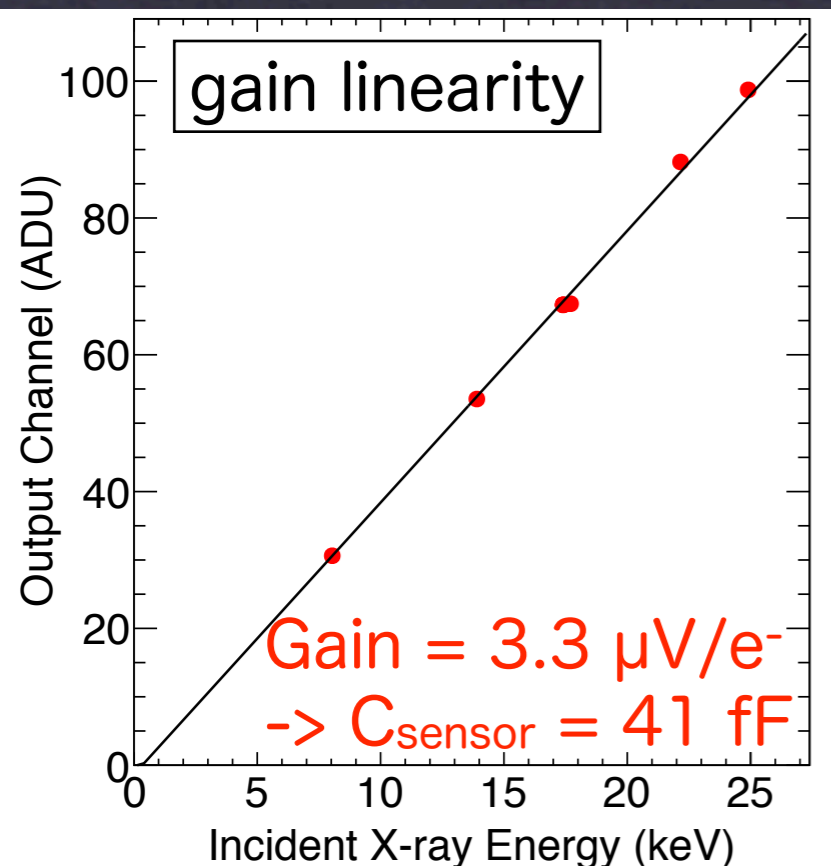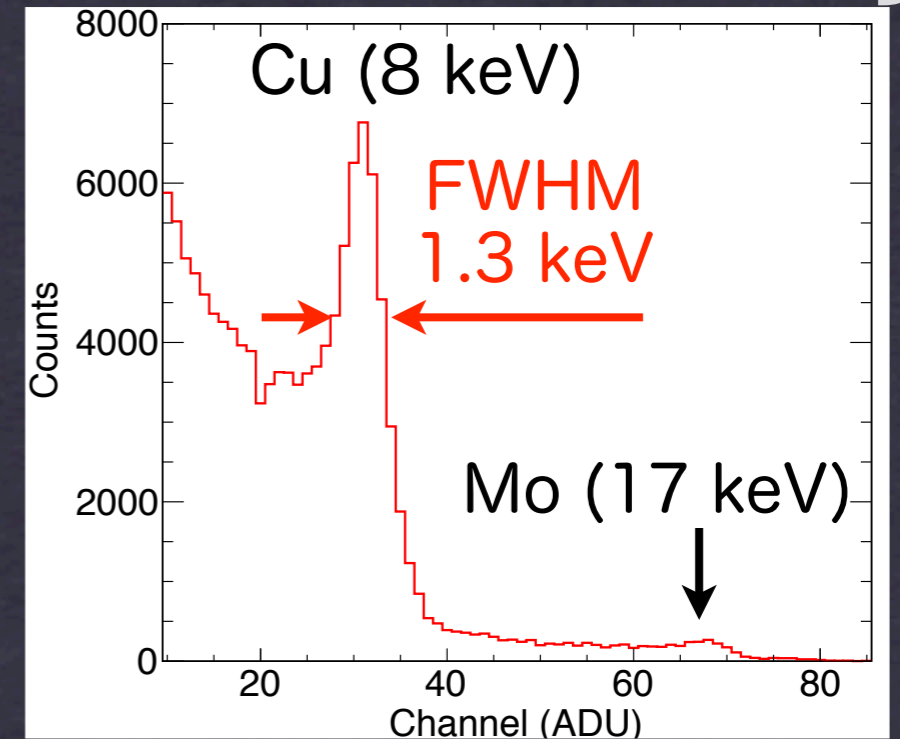
Temperature (degree C)
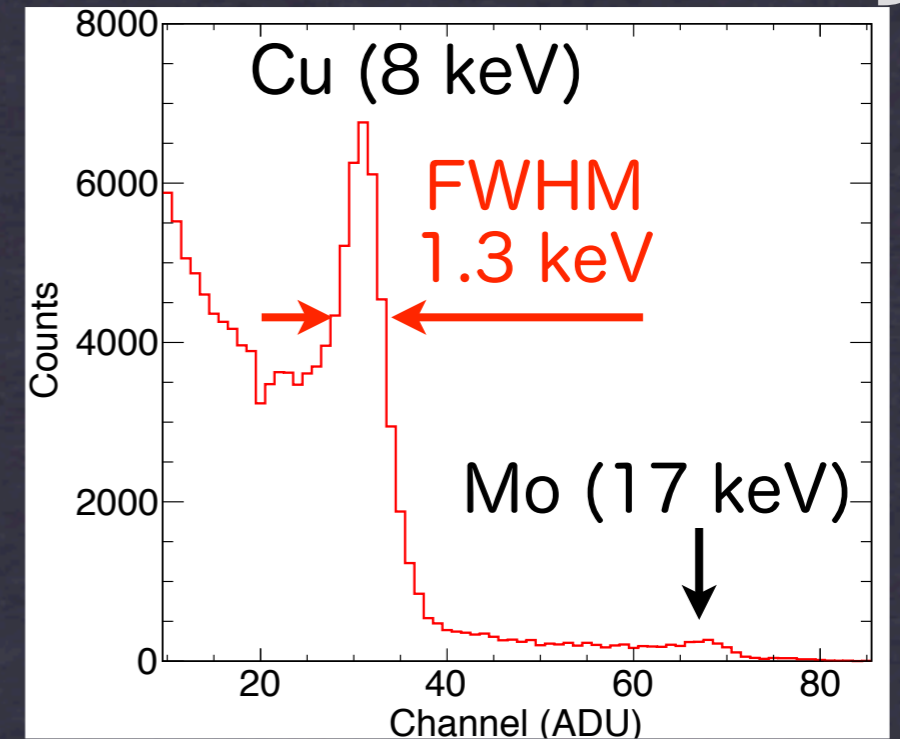
X-ray Spectrum and Sensitivity

- Reset all pixels to constant voltage
- Wait for X-ray injection in 1 ms
- Read all pixels (1 sample/pixel)
- Repeat the above step
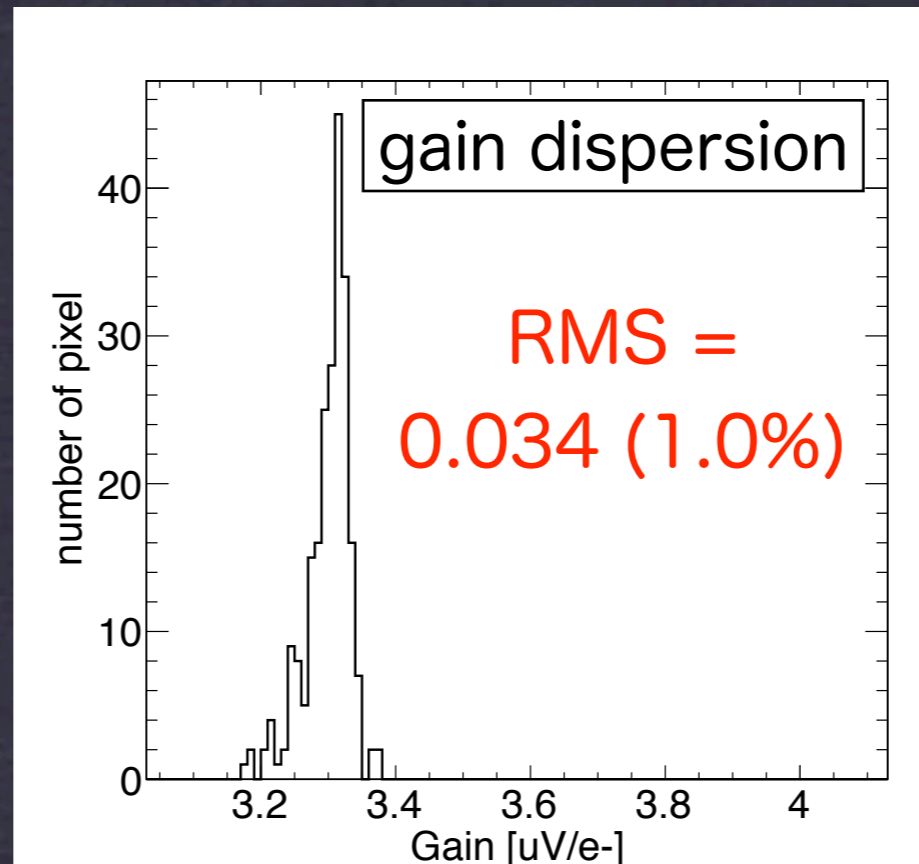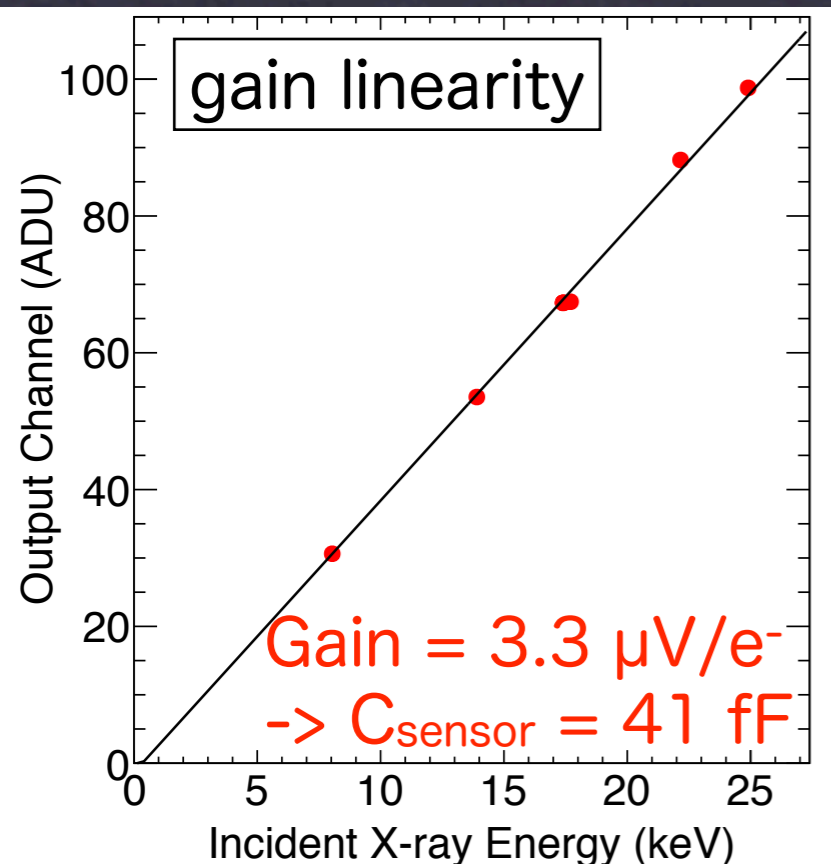
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- Repeat the above step

Cu (8 keV)

FWHM 1.3 keV

Mo (17 keV)

Counts

Channel (ADU)

gain linearity

Output Channel (ADU)

Incident X-ray Energy (keV)

Gain = 3.3 μV/e⁻
-> C_{sensor} = 41 fF

gain dispersion
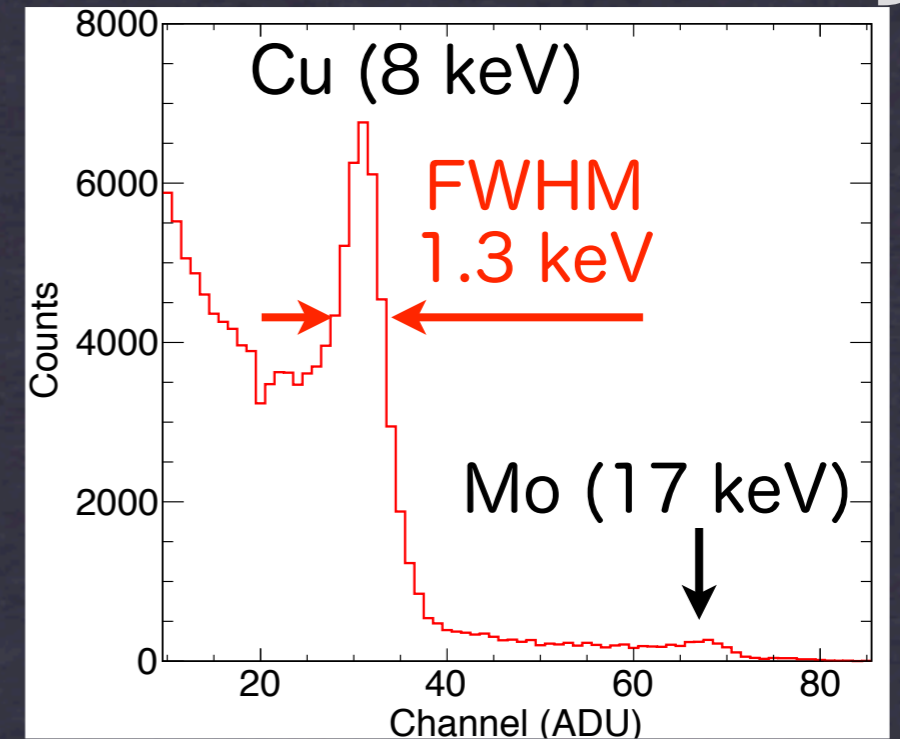
number of pixel

Gain [uV/e-]

RMS = 0.034 (1.0%)

X-ray Spectrum and Sensitivity

- Reset all pixels to constant voltage
- Wait for X-ray injection in 1 ms
- Read all pixels (1 sample/pixel)
- Repeat the above step

Cu (8 keV)
FWHM 1.3 keV
Mo (17 keV)

gain linearity

Gain = 3.3 µV/e⁻
-> C$_{sensor}$ = 41 fF

gain dispersion

RMS = 0.034 (1.0%)

Readout noise = 100 e⁻
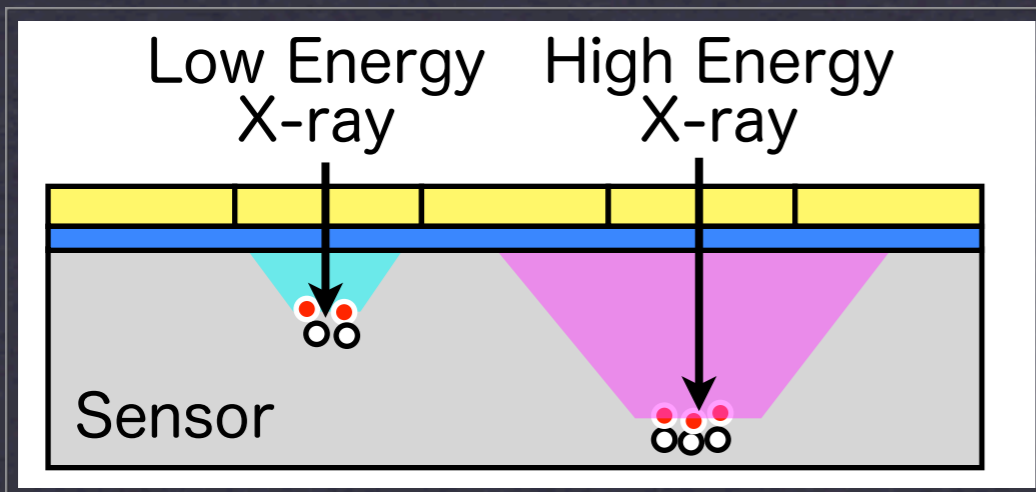→ very large considering our goal (~ 10 e⁻)

1 Pixel Readout Method

- Use only 1 pixel to redunoce readout noise and investigate the limit of the performance (cf. Prigozhin et al. 2009)
- Sample the signal of a particular pixel many times
- Analyze in off-line and search X-ray hit point
- Incident X-ray energy = Signal level - Base level

signal-time profile
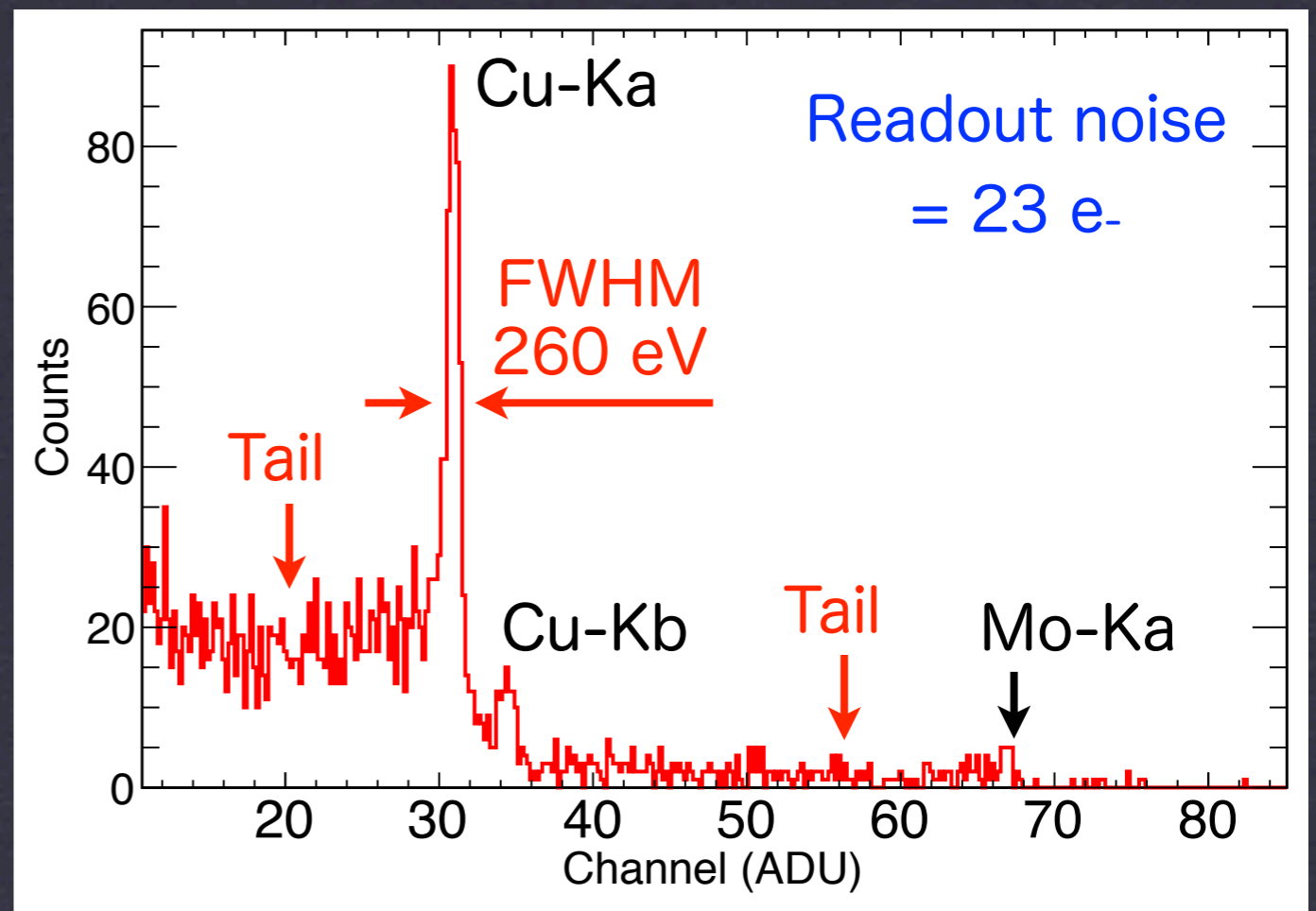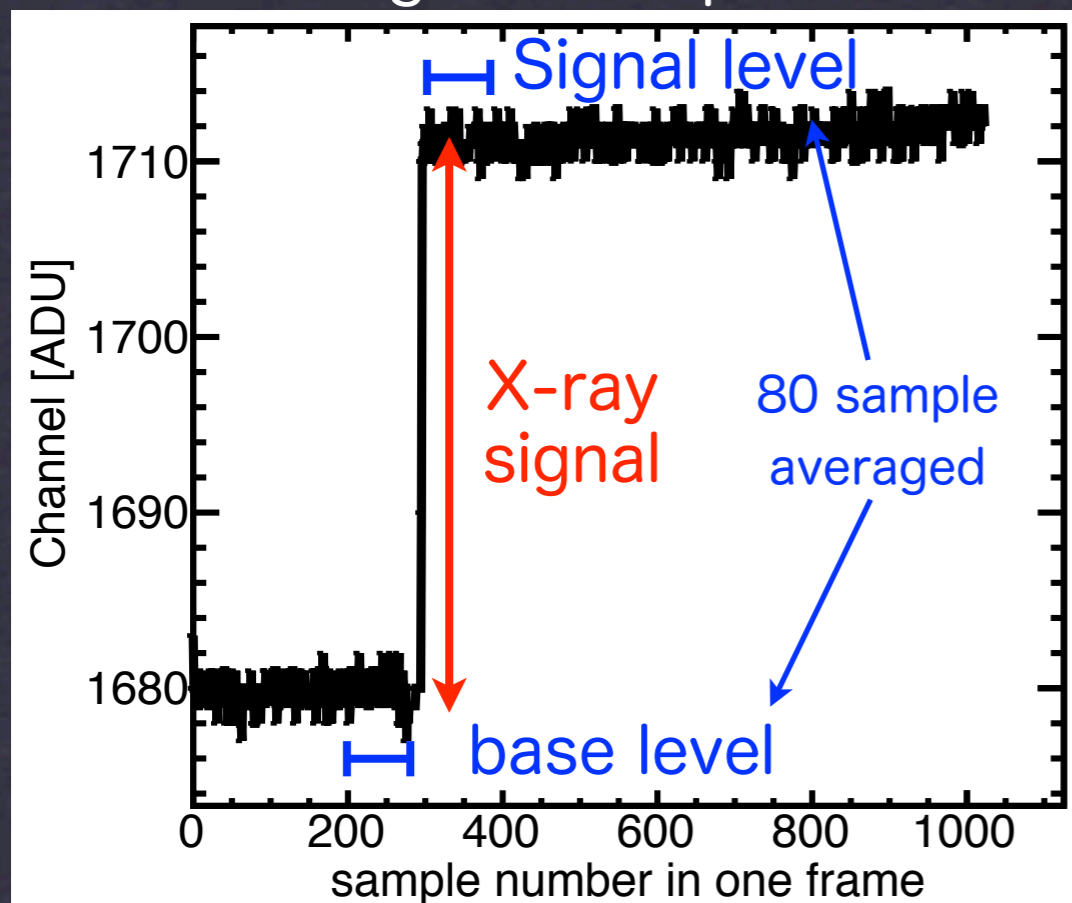
3 x 3 Pixels Readout Method

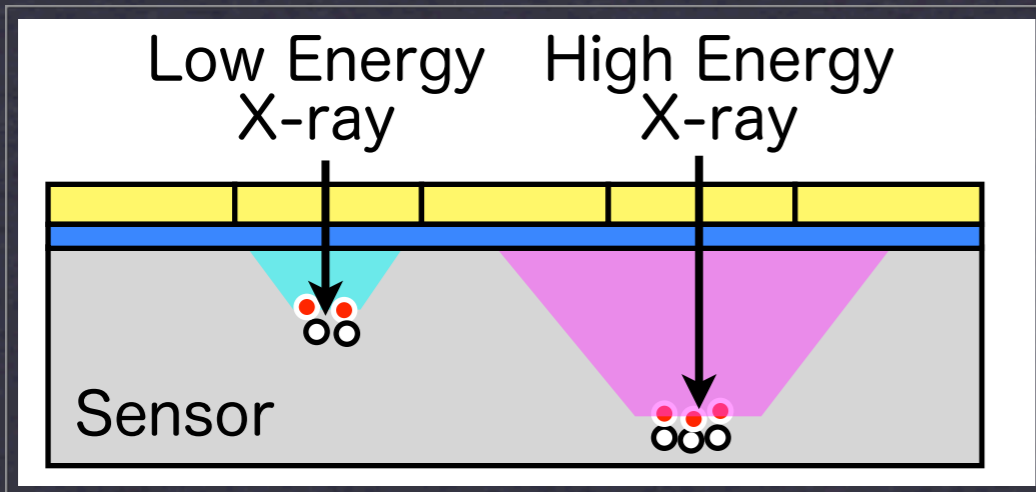Low Energy X-ray   High Energy X-ray

Sensor

Signal charges of high energy X-rays generated in the deep depletion layer

⬇

Charges spread over several pixels

1 pixel readout method can not treat the split event...

3 x 3 Pixels Readout Method

Low Energy X-ray   High Energy X-ray
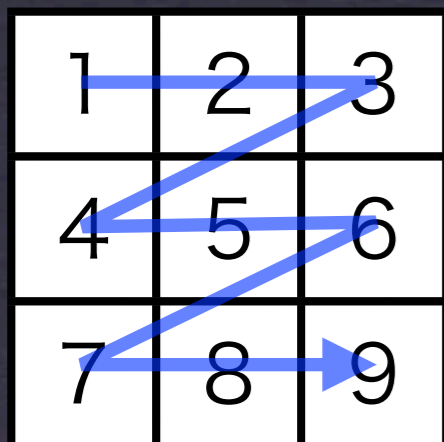
Sensor

Signal charges of high energy X-rays generated in the deep depletion layer

⬇

Charges spread over several pixels

1 pixel readout method can not treat the split event...

⬇

1	2	3
4	5	6
7	8	9

- Use 3 x 3 pixels cluster
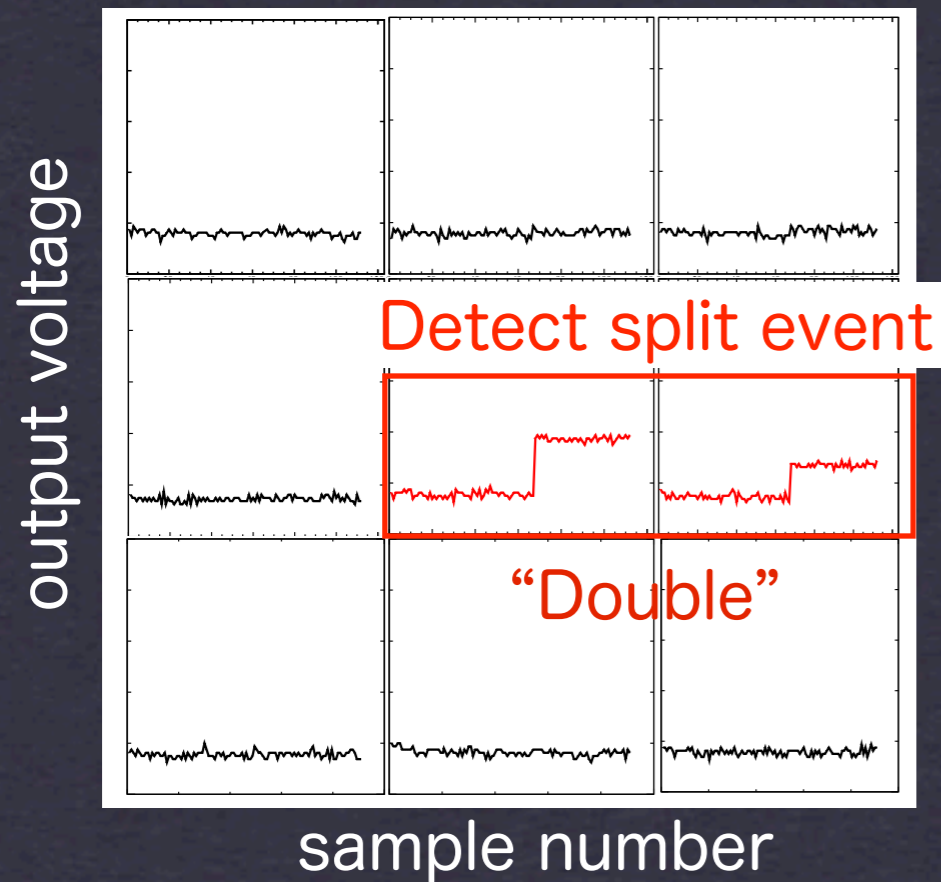- Read in series and cyclically during expousure

  1 -> 2 -> ... -> 9 -> 1 ->2 -> .....->9

  1 Cycle   Repeat during exposure

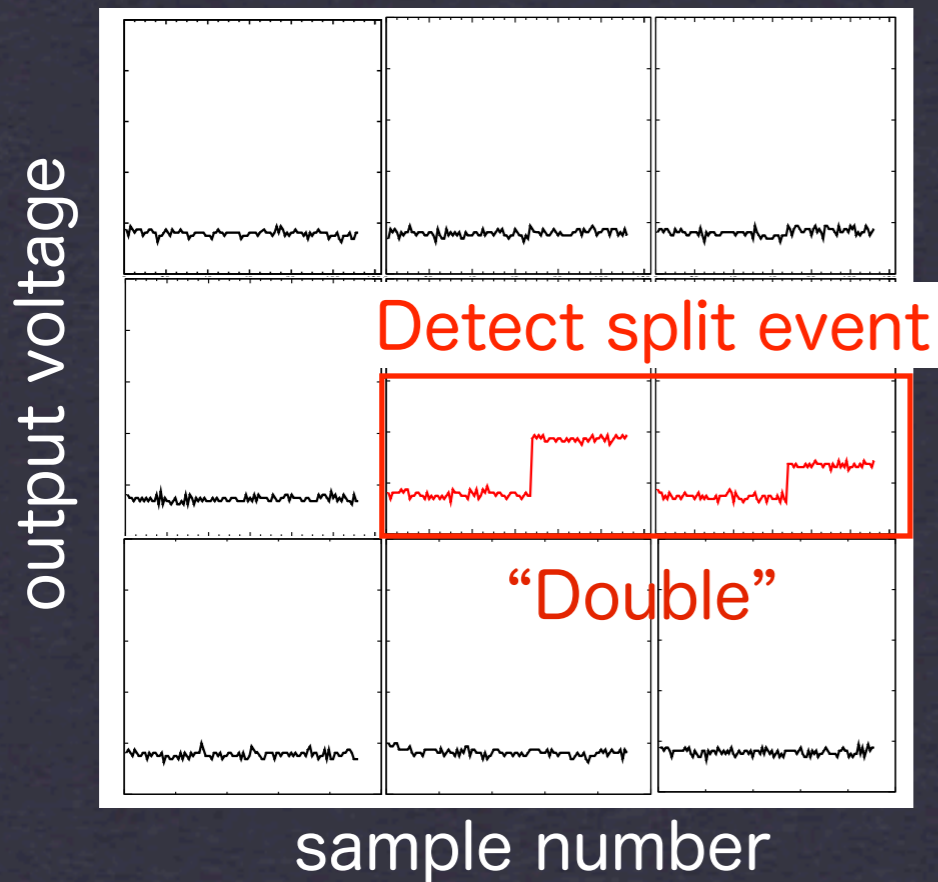- Analyze as same as 1 pixel readout method

Spectrum of 3 x 3 Pixels

output voltage

Detect split event

"Double"

sample number

- Use the event selection method (like CCDs)

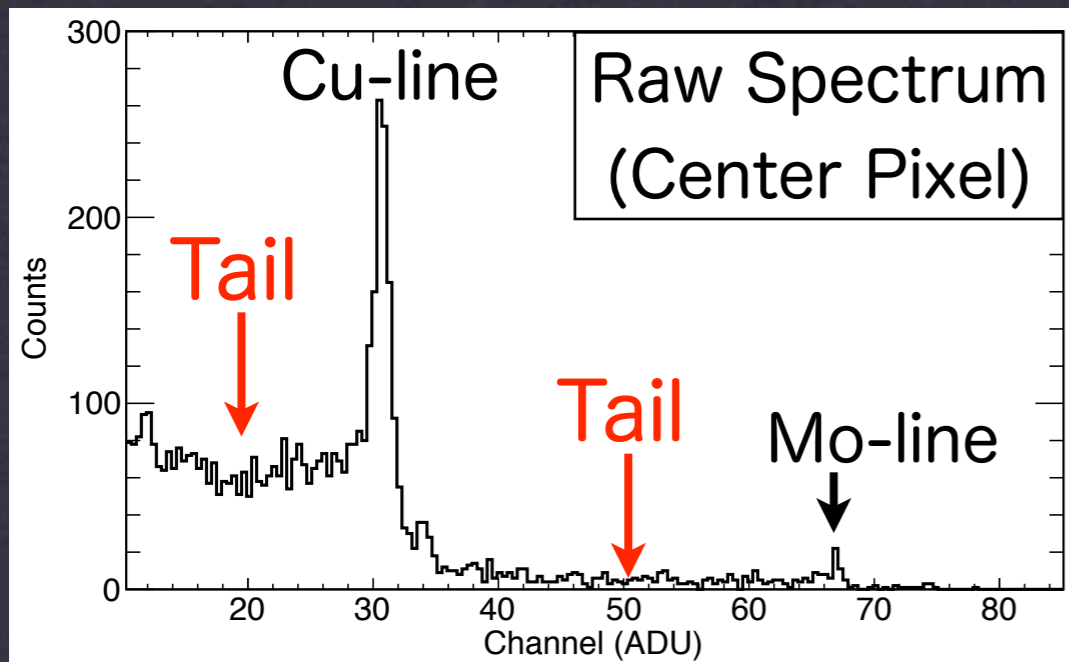 Single   Double   Triple

  etc...
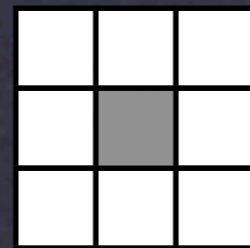
- Sum up the all split signals

Spectrum of 3 x 3 Pixels

output voltage

Detect split event

"Double"

sample number

Use the event selection method (like CCDs)

Single   Double   Triple

etc...

Sum up the all split signals


Cu-line

Raw Spectrum
(Center Pixel)

Counts

Tail

Tail

Mo-line

Channel (ADU)

event
selection

➡

summing
up
process

Cu-line

FWHM
510 eV

Mo counts
increase

Cu-Kb
shoulder

Counts

Channel (ADU)

Depletion Depth

Incident X-ray

Cu (8 keV) + Mo (17 keV)

Attenuation Length

Cu -> 71 μm

Mo -> 678 μm

XRPIX1-FZ

almost absorbed

partially absorbed
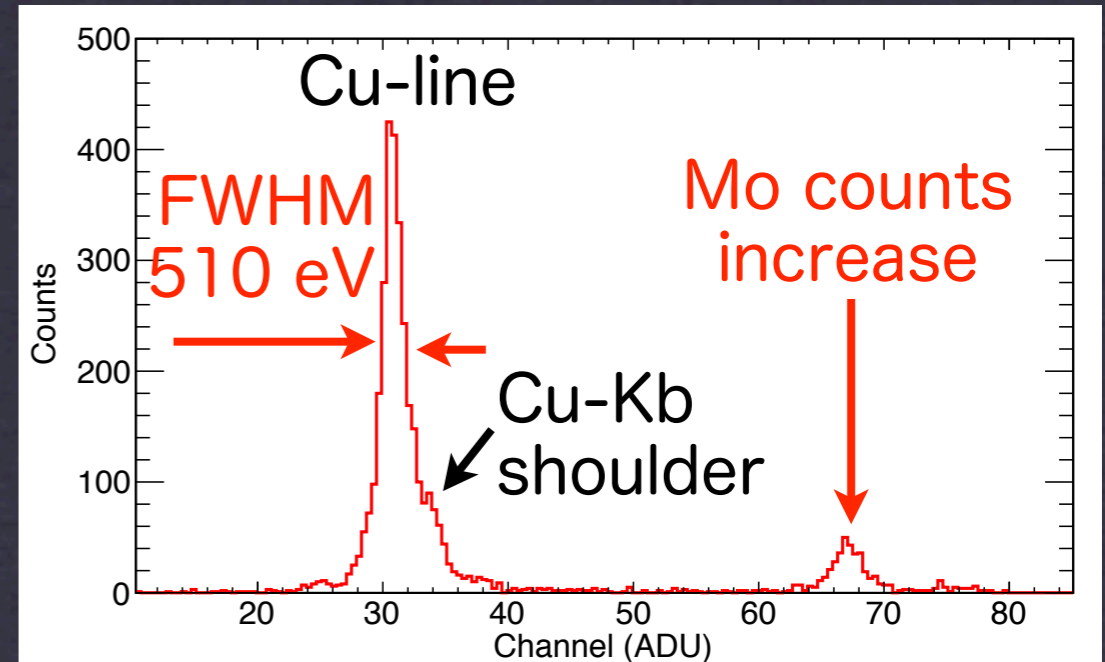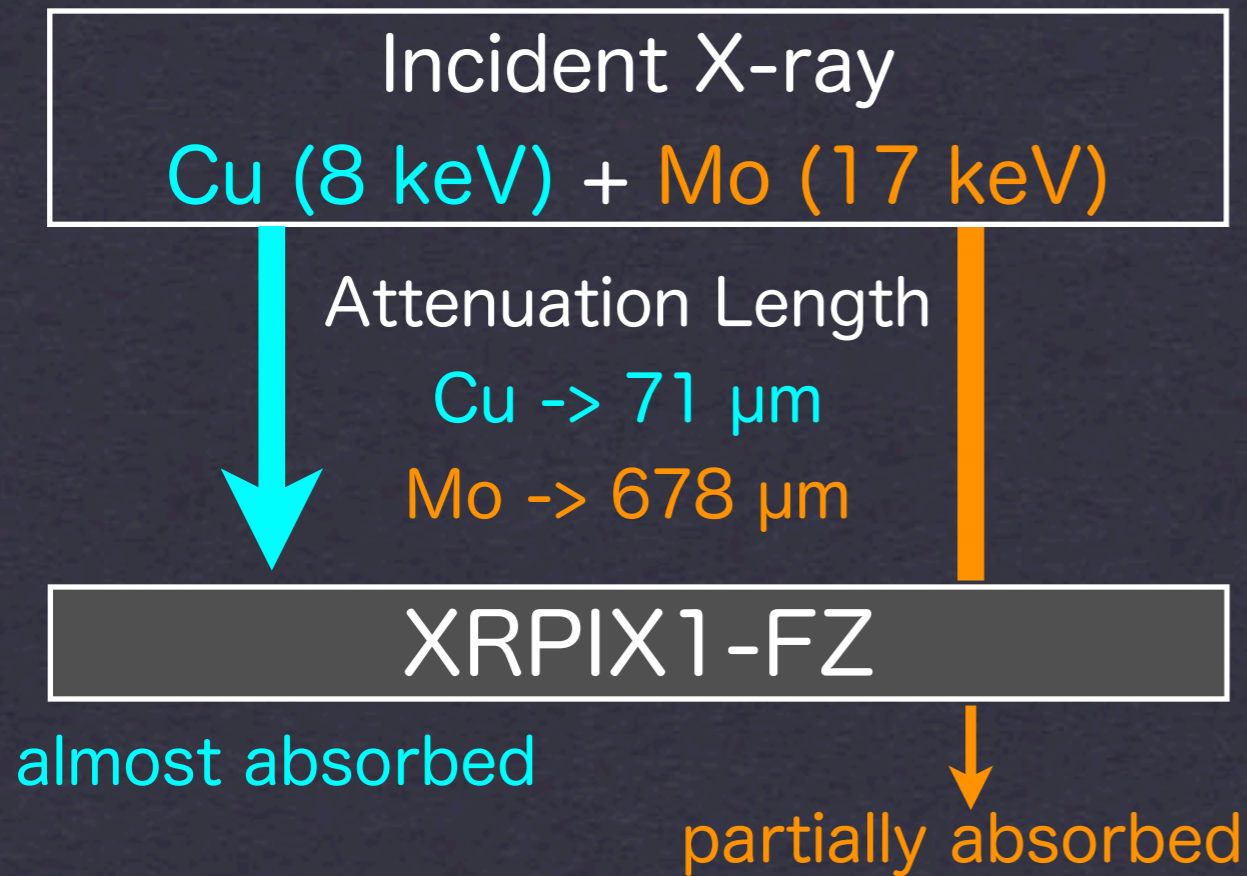
Detected counts ratio Mo/Cu

∝ Depletion Depth

(compare to incident ratio of Mo/Cu

obtained by CdTe detector)

Preliminary !

250 μm
Sensor layer

full depletion !

Depletion Depth [um]

Back Bias [V]
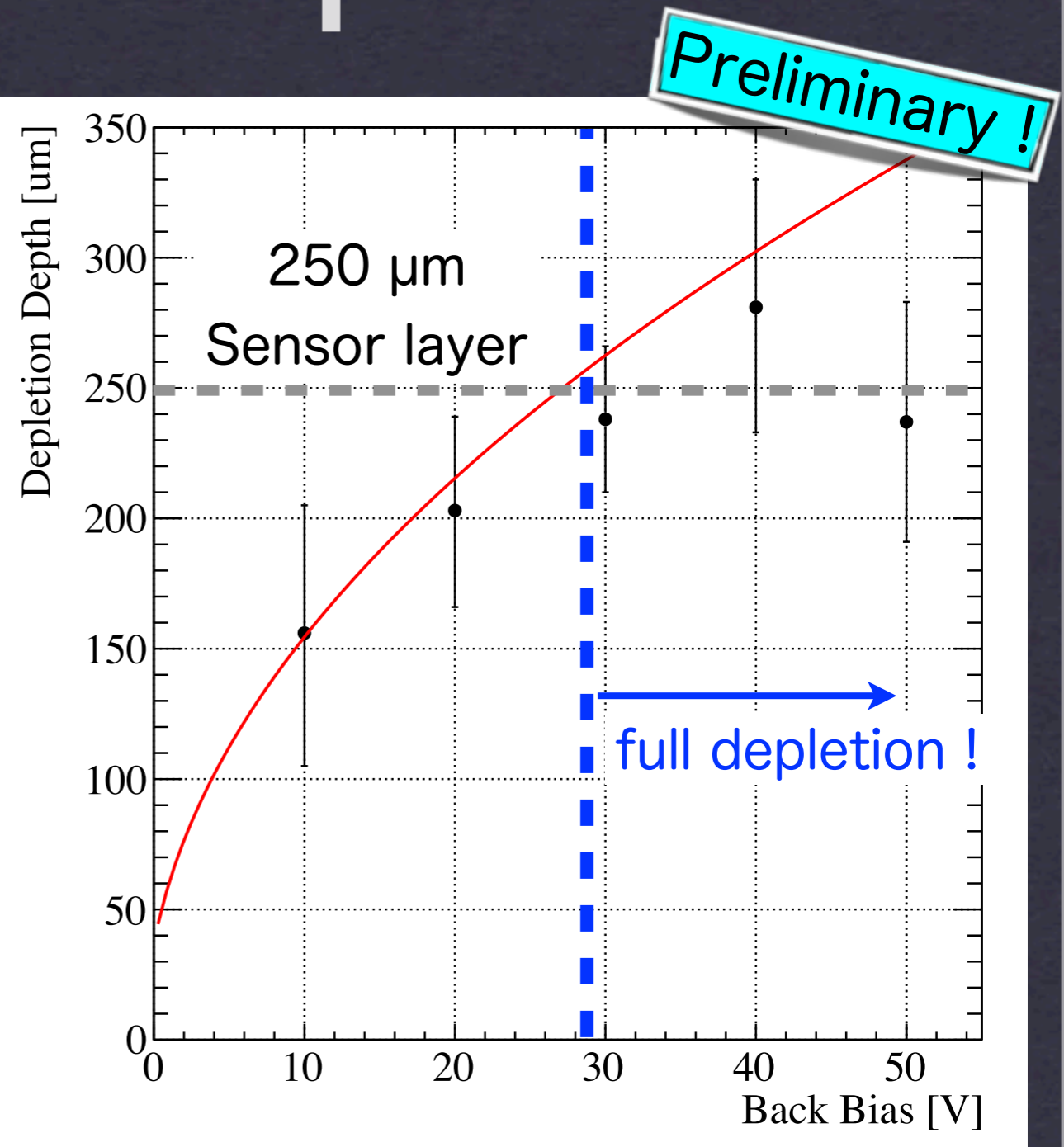
Consistent with calculated value
QE = 97% @8 keV, 32% @ 17 keV

Summary

- We developed XRPIX1-FZ with high resistivity (~ 7 kΩcm)

- CMP treatment of backside reduce dark current

- XRPIX1 has

  - Non-uniformity of gain ~ 1.0 %

  - Energy resolution ~ 260 eV FWHM @8 keV in 1 pixel readout method

  - Full depletion of 250 μm