Development and Performance of Kyoto's X-ray Astronomical SOI pixel sensor

T.G.Tsuru (tsuru@cr.scphys.kyoto-u.ac.jp)

S.G. Ryu, S.Nakashima (Kyoto), A.Takeda, Y.Arai (KEK), + SOIPIX group

T. Imamura, A. Iwata, T. Ohmoto, T. Maeda (A-R-Tec) for Chip Design

M. Bautz, G.Y.Prigozhin, S.E.Kissel, B.LaMarr, R.F.Foster (MIT)
for experiment of XRPIX1b-CZ-FI/BI

H. Nakajima, H.Tsunemi (Osaka) J.P.Doty (Noqsi) for design of ADC

Ryu et al.	IEEE NSS 2010, Conf. Record	XRPIX1-CZ -FI
Ryu et al.	IEEE TNS 58, 2528 (2011)	XRPIX1-CZ-FI
Tsuru et al.	IEEE NSS 2011	Review
Ryu et al.	IEEE NSS 2011, Conf. Record	Trigger Readout system
Nakashima et al.	IEEE NSS 2011, Conf. Record	XRPIX-ADC1
Nakashima et al.	NIM A Accepted (2012)	XRPIX1-FZ-FI
Ryu et al.	IEEE TNS Accepted (2012)	XRPIX1b-CZ-FI, Inter-pixel cross-talk
Takeda et al.	IEEE TNS Accepted (2012)	Trigger Readout with XRPIX1b-CZ-FI
Tsuru et al.	SPIE Astro2012	Review
Nakashima et al.	NIM A, Submitted (Pixel 2012)	XRPIX2

内容

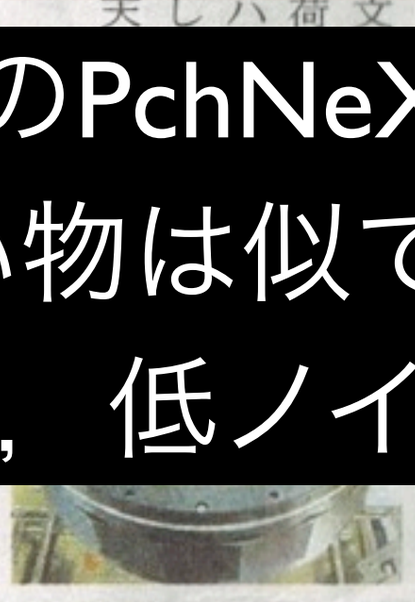
- SOI / SOIPIX とは？
- X線SOIPIX検出器
- 現在の開発状況，到達点
  - ゲイン，ノイズ，エネルギー分解能
  - トリガ読み出し
  - 空乏層厚み，裏面不感層，暗電流
- 今後

はじめに... 2008年11月20日 - 京都新聞(夕刊) -

京都新聞（夕刊） 2008年(平成20年)11月20日 木曜日 7版 8
第3種郵便物認可

開発したCCDは、波長の長いエックス線から波長の短いエックス線まで幅広くとらえることができ、二〇一三年の打ち上げを目指している次期エックス線天文衛星「Astro-H」への搭載を予定している。

グループの鶴剛京大理学研究科准教授（高エネルギー天体物理学）は「波長の短いエックス線を放つと考えられている誕生したてのブラックホールを見つけ、銀河中心にあるブラックホールへの成長などの謎に迫りたい」と期待している。

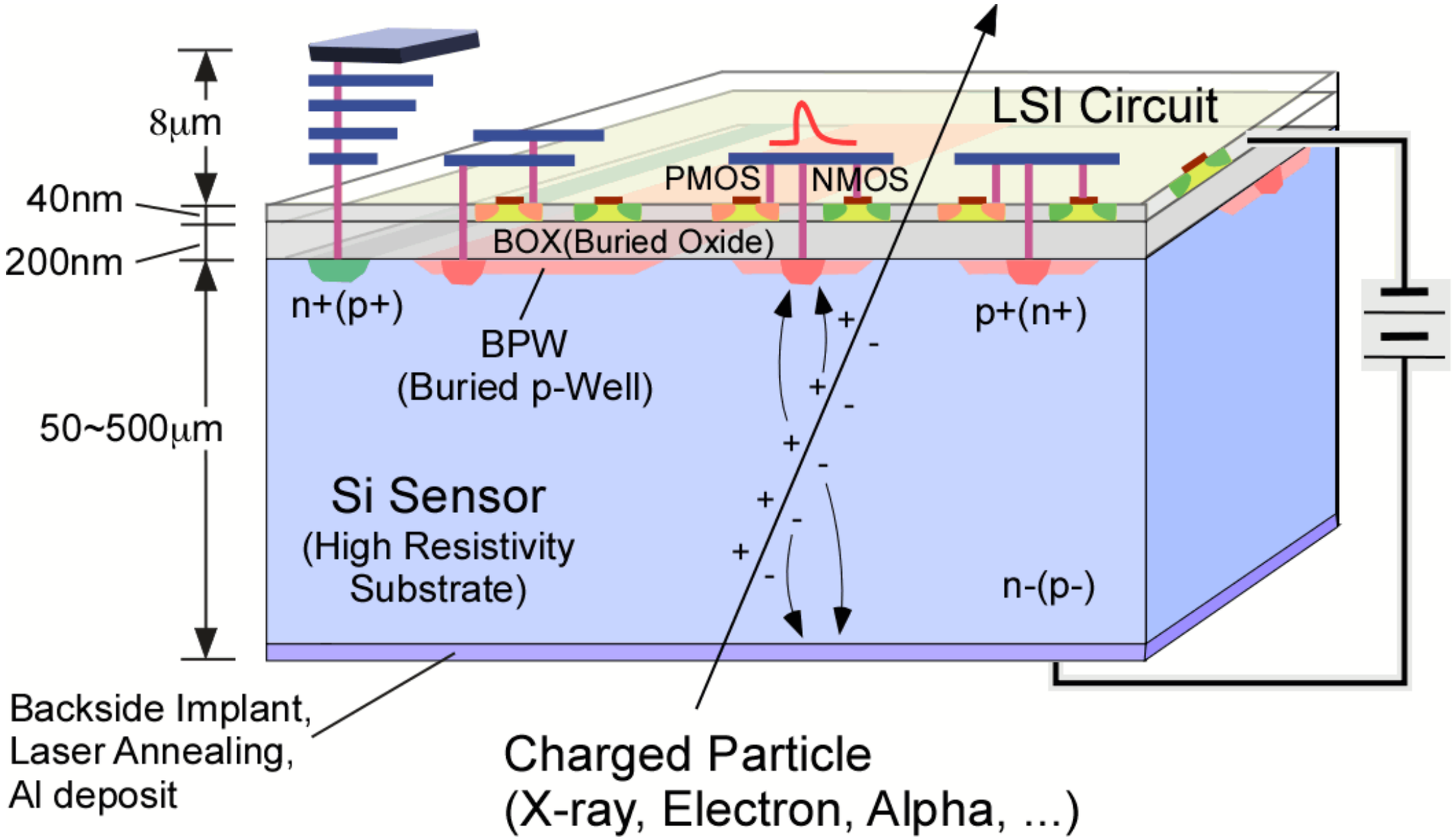


HSCの2k4kBICCDとASTRO-HのPchNeXT4は兄弟

光赤外とX線 ⇒ 実は欲しい物は似ている.

(裏面照射，厚い空乏層，低ノイズ)

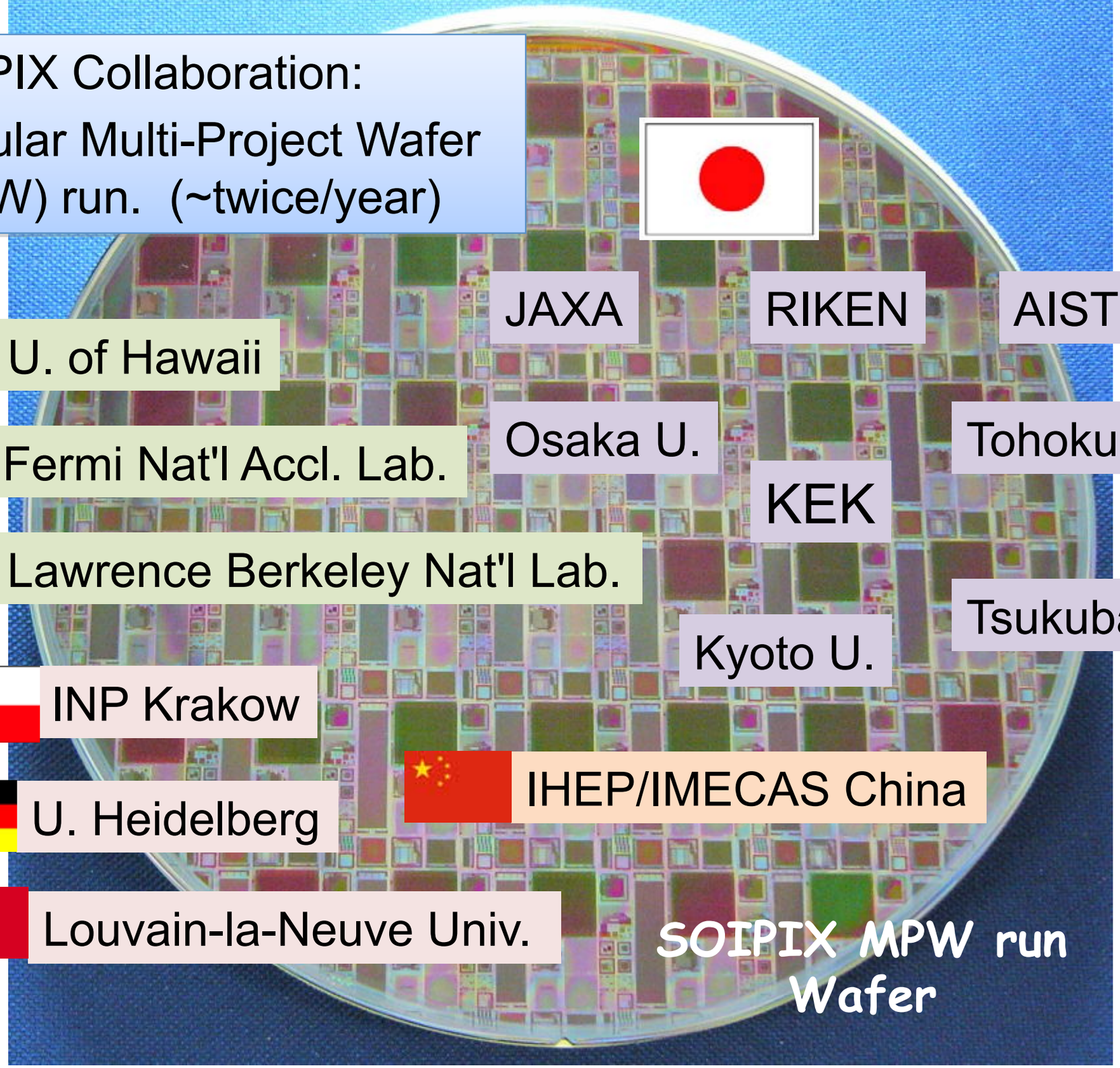
What is SOI pixel sensor ?



- Monolithic Detector using Bonded wafer (SOI: Silicon On Insulator)
- Thick Depletion Layer in the high resistivity Si substrate.
- Standard CMOS circuits can be build in the low resistivity Si.
- Seamless connection between the two layers → No bump bonding.
- Based on Industrial Standard Technology → Stable
- No latch Up & High Radiation Tolerance.

SOIPIX Collaboration:

Regular Multi-Project Wafer (MPW) run. (~twice/year)



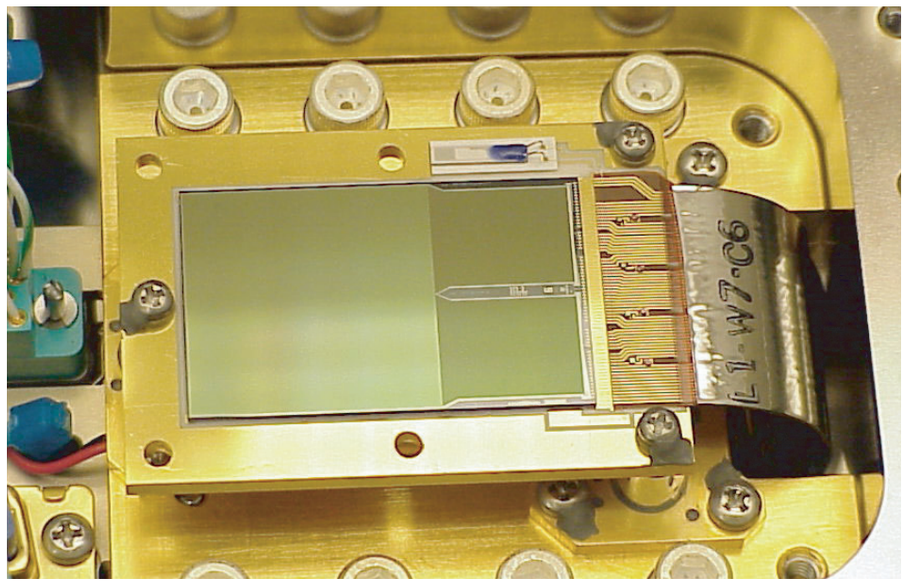
- PI=Prof.Y.Arai @ KEK, 2005.10~
- With OKI semiconductor → Lapis semiconductor
- Kyoto joins the collaboration in 2008.

SOIPIX Applications

- INTPIX : 汎用積分型（高精細X線透過像撮影）
- CNTPIX : 汎用計数型（高S/N計測）
- SOPHIAS : XFEL用（高ダイナミックレンジ）
- PIXOR : 素粒子実験（崩壊点検出）
- XRPIX : X線衛星搭載用(低ノイズ）
- MALPIX : 投影型質量分析装置用(時間計測）
- TDIPIX : X線異物検査装置用
- STJPIX :超伝導体光検出器（赤外線1光子分光）
- . . .

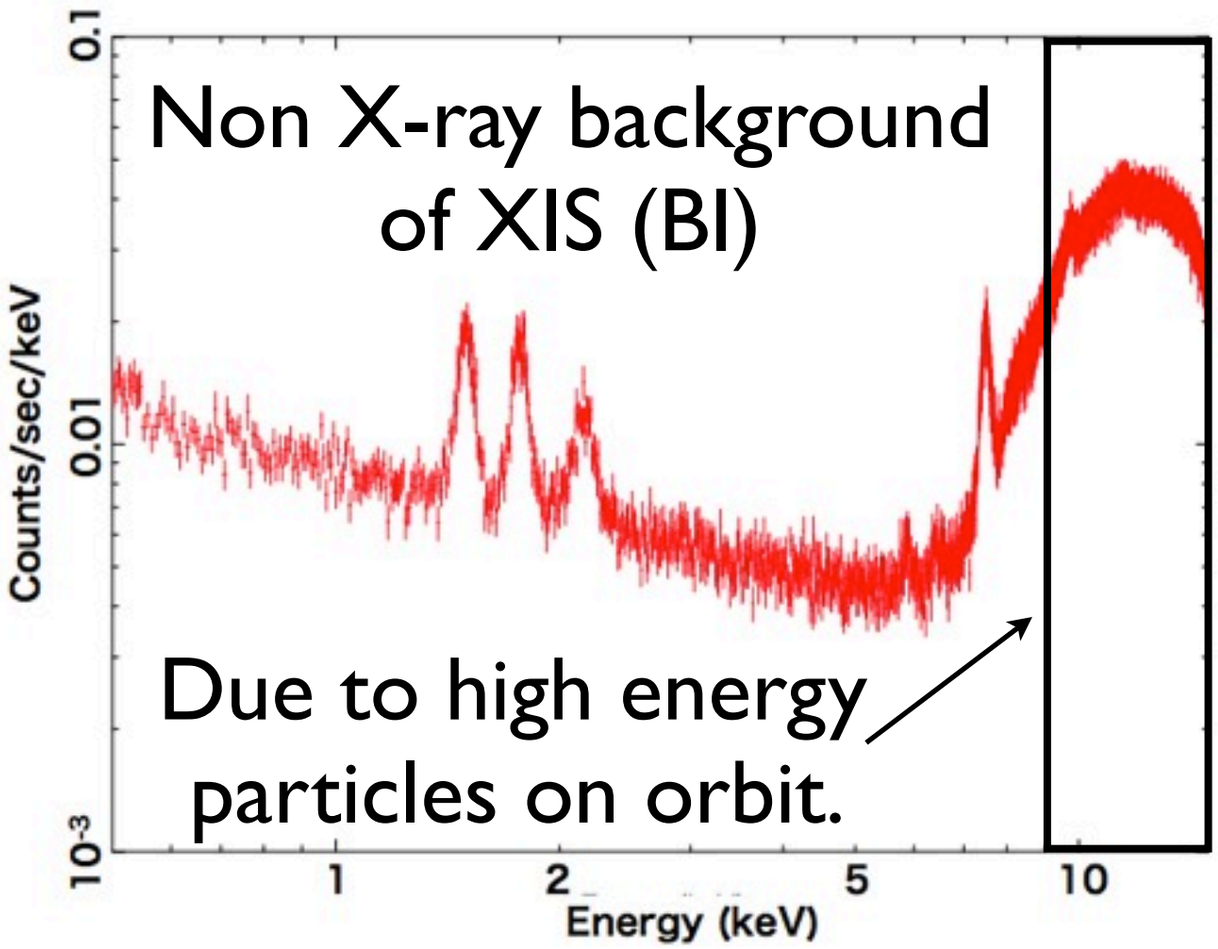
The standard Imaging Spectrometer of modern X-ray astronomical satellites → X-ray CCD

Suzaku 「すざく」 XIS



- Fano limited spectroscopy with the readout noise ~3e- (rms).
- Wide and fine imaging with the sensor size of ~20-30mm pixel size of ~30μm□

- Non X-ray background above 10keV is too high to study faint sources.
- The time resolution is too poor (~ sec) to make fast timing obervation of time variable sources.

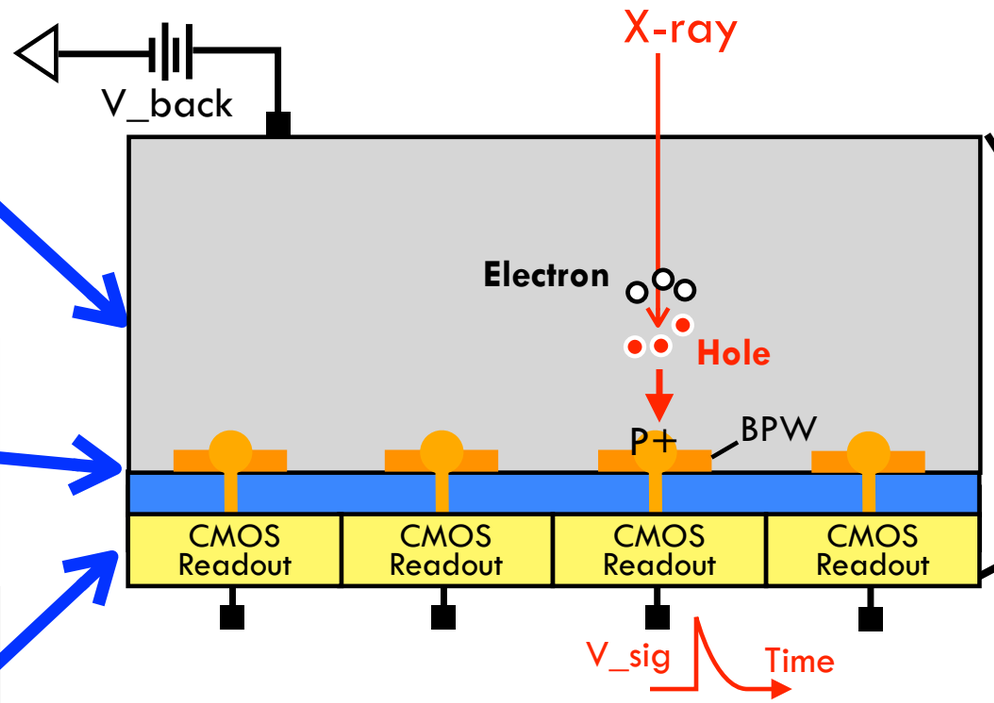


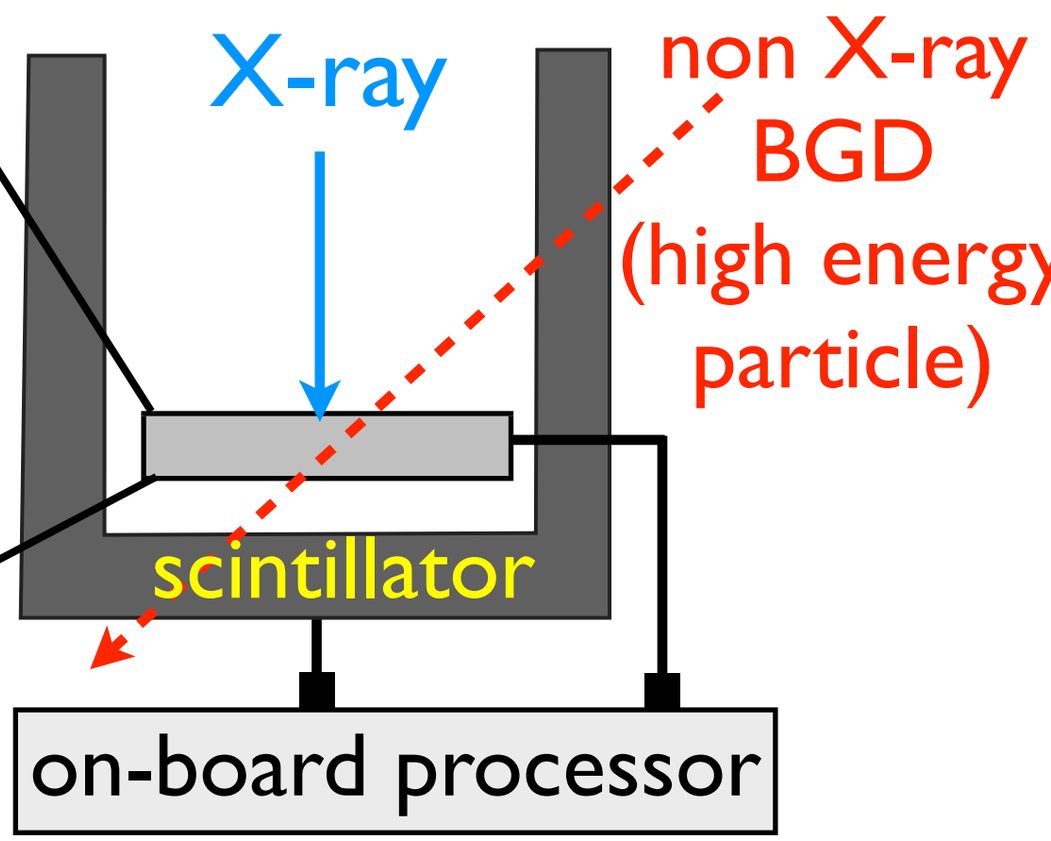
"XRPIX" = **Monolithic** SOI pixel sensor for future X-ray astronomical satellites

Sensor (high ρ, depleted Si)

Insulator (SiO2)

Fast CMOS (low ρ Si)





Our SOIPIX (XRPIX)

Each pixel has its own trigger and analogue readout CMOS circuit.

Realize Very Low BGD by Anti-coincidence

Target Specification

Imaging	area > 25x25mm2, pixel ~ 30-60μm□ (1" @ F=9m)
Energy Band	0.3-40keV with BI, and thick depletion (>300μm)
Spectroscopy	ΔE < 140eV @ 6keV, Fano limit (<10e-)
Timing	<1μsec
Dark Current	<1pA/cm2
Function	Trigger signal & pixel address output, built-in ADC
Non X-ray BGD	5e-5 c/s/keV/10x10mm2 at 20keV (1/100 of CCD)

Applications for X-ray Astronomy

X線CCDと明確に違う点

（同じ完全空乏・裏面照射，解像度，素子大きさ，ノイズ性能を持った上で）

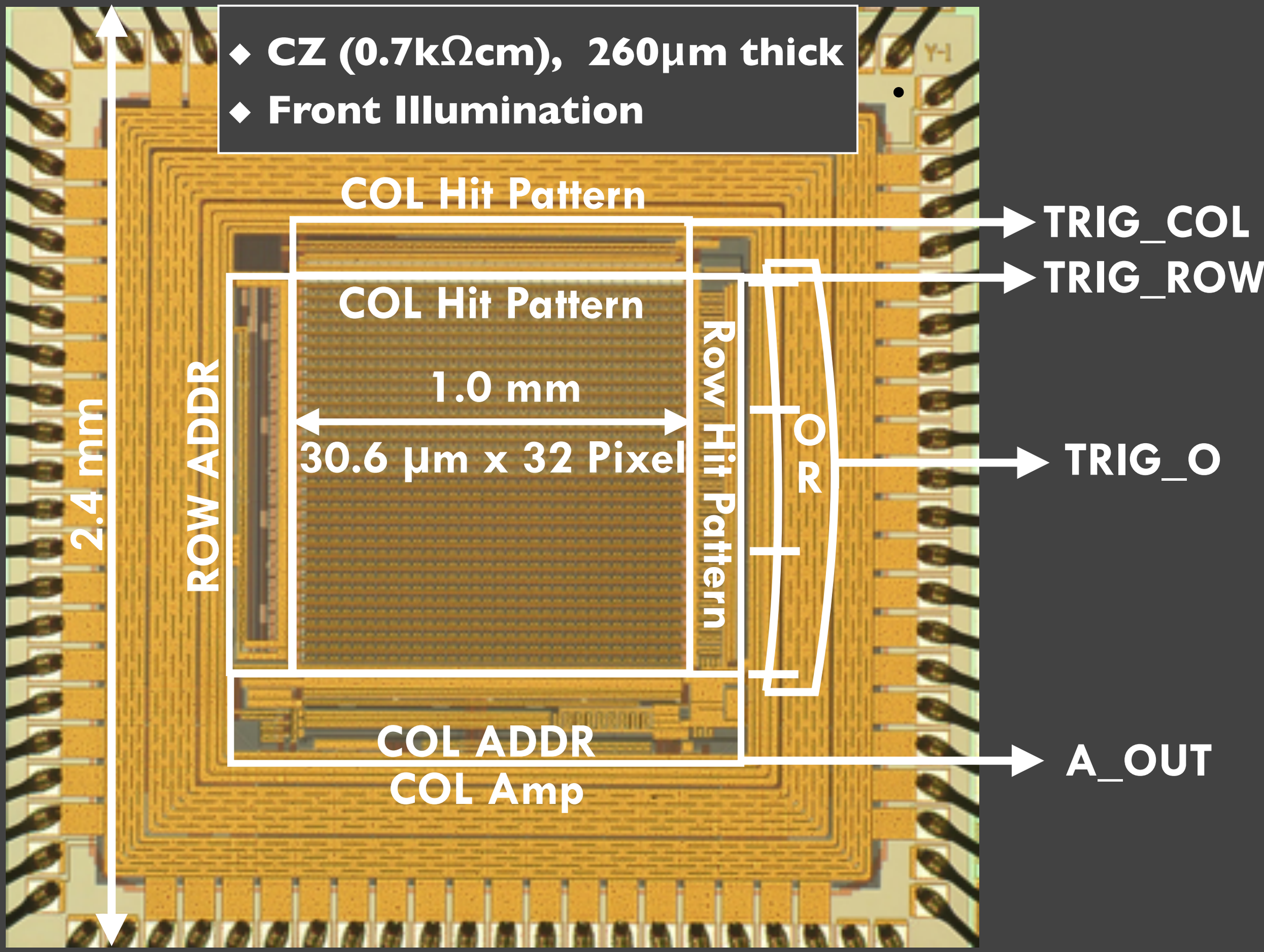
- デジタル(FPGA)だけの簡単な駆動・読み出し回路
- 高度なアナログ・デジタル処理機能
- トリガ出力可能，高速読み出し，高時間分解能(~μsec)
- 反同時計数法による低い非X線バックグラウンド(1/100 @ 20keV)
- 高い耐放射線性能

考えられるアプリケーション

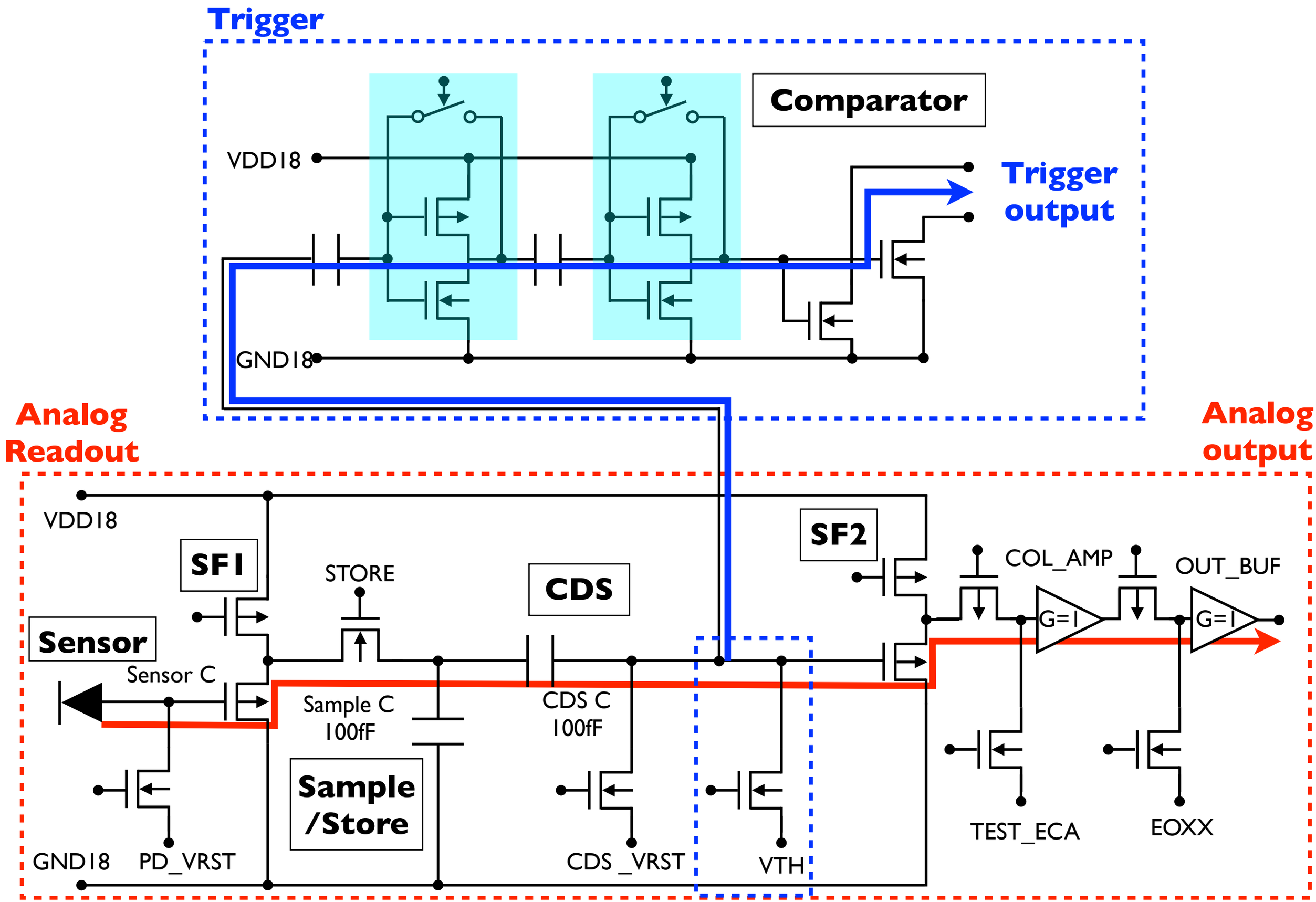
- ASTRO-Hに続く次期中型・大型Ｘ線衛星の焦点面検出器
- 全天X線監視モニター，γ線バーストモニター（MAXI, Swift）
- 偏光Ｘ線撮像分光器
- 惑星探査用X線検出器（高い耐放射線性能）

など...

XRPIX1-CZ (X-Ray PIXel detector - CZochralski)

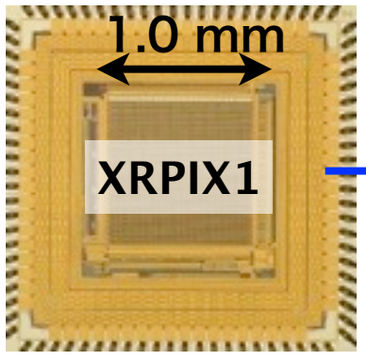


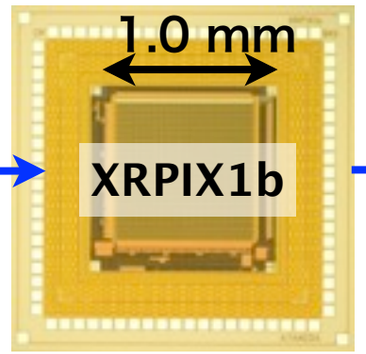
XRPIX1: Pixel Circuit



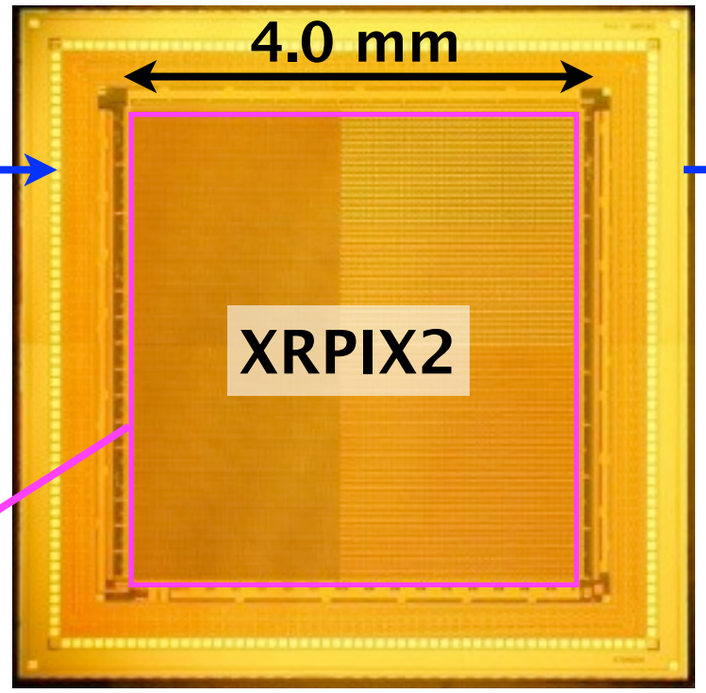
XRPIX Series – Road Map –

2010 2011 2012 2013



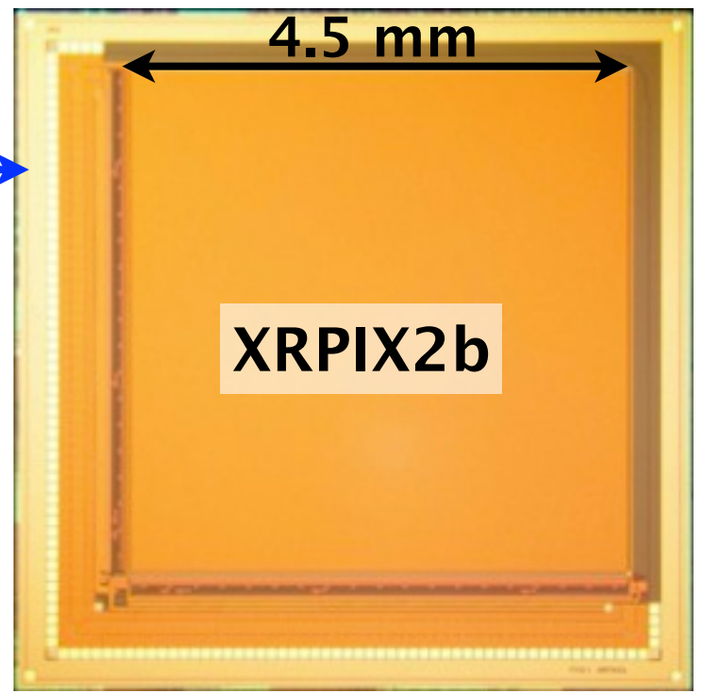


2.4 mm 2.4 mm



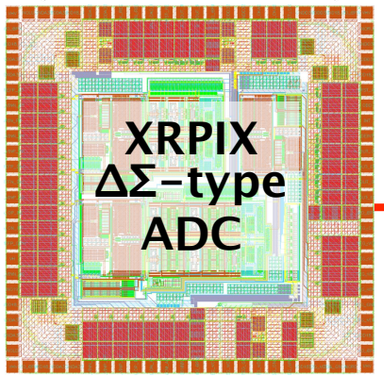
6.0 mm

X-ray imaging area

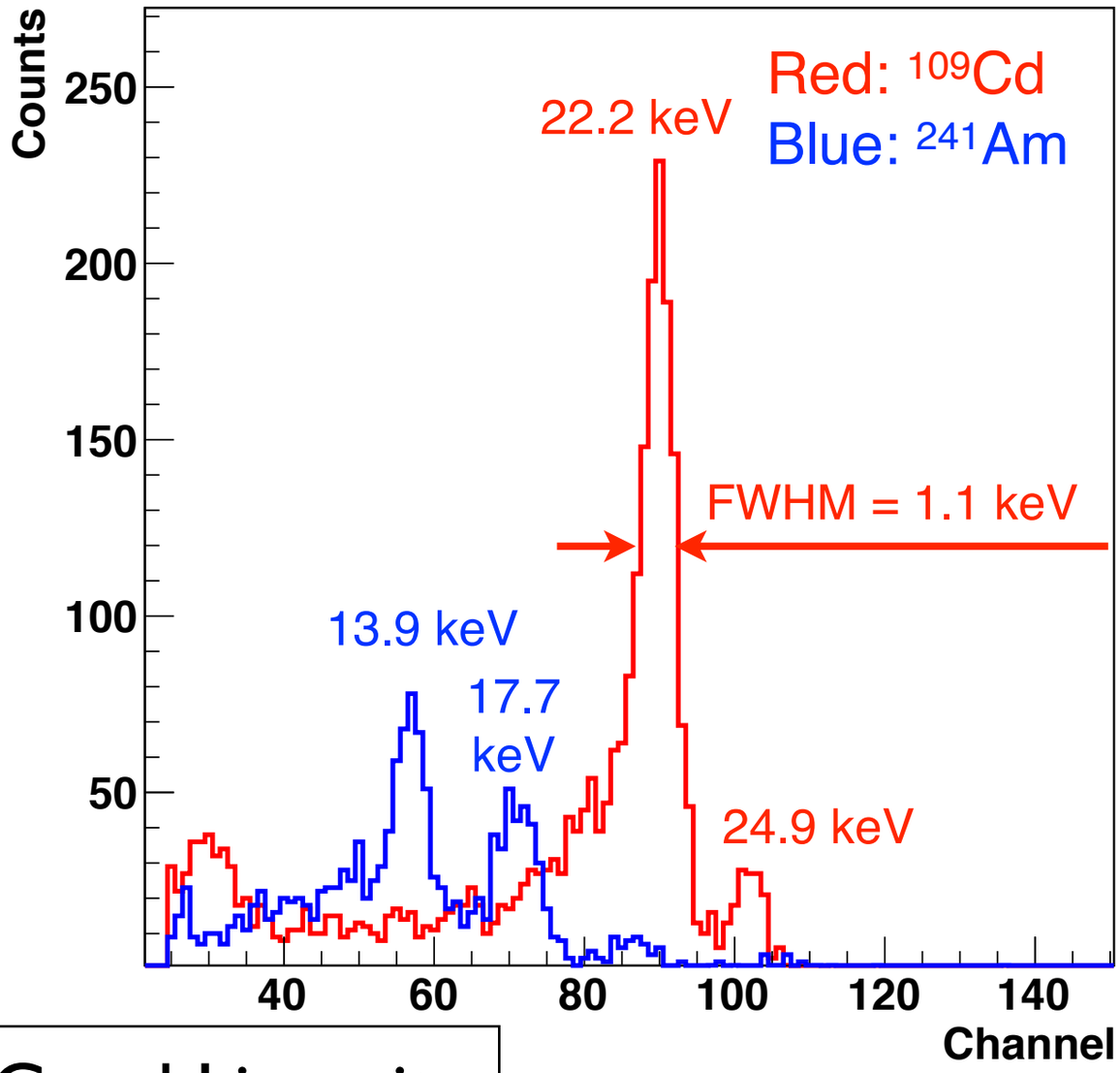


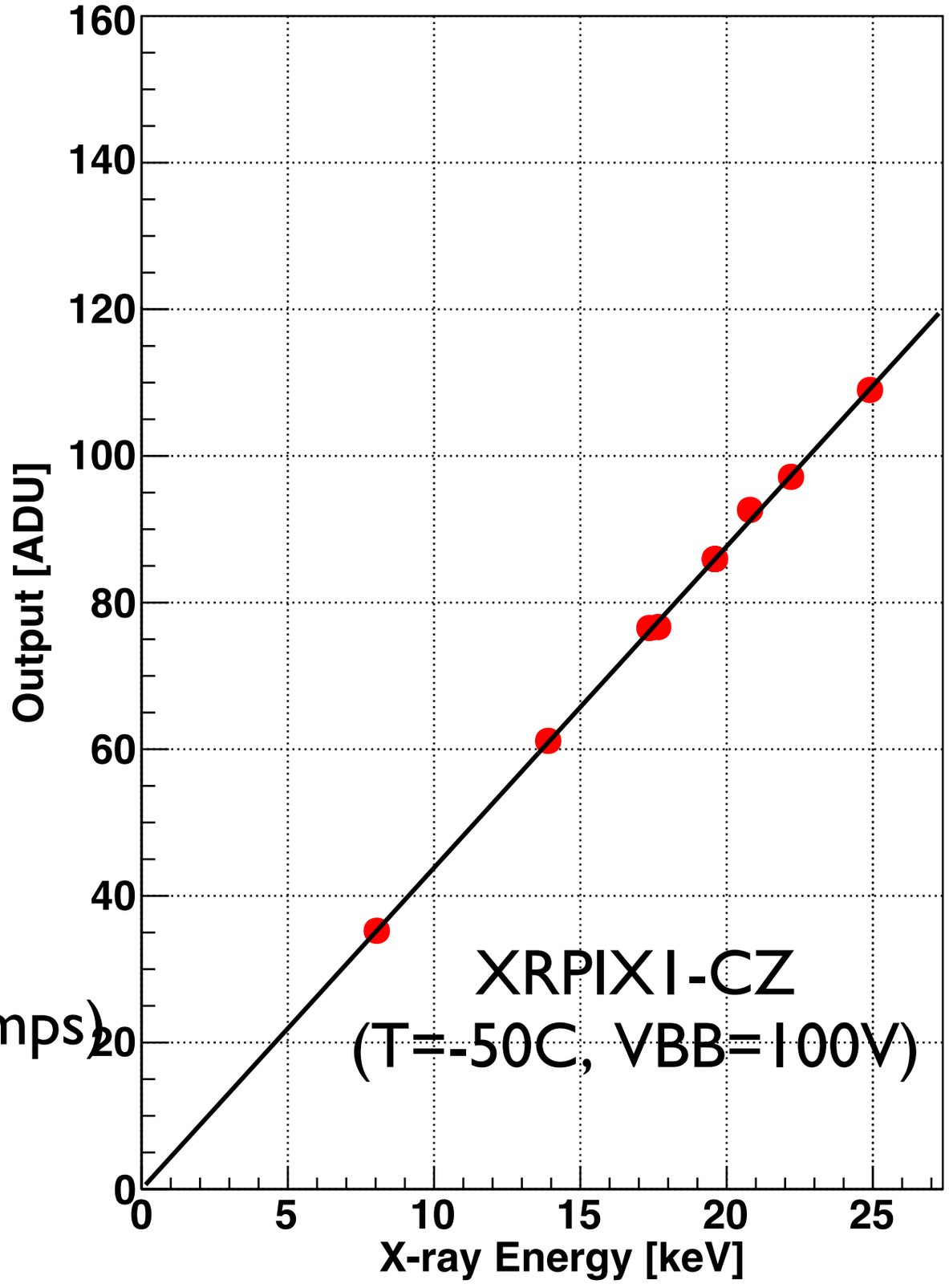
6.0 mm

2.4 mm



XRPIX1-CZ : X-ray Spectra in the frame mode





Good Linearity

Sensitivity = 4.0 μV/e- (including SF, amps)
Sensor C = 34 fF

Energy Resolution

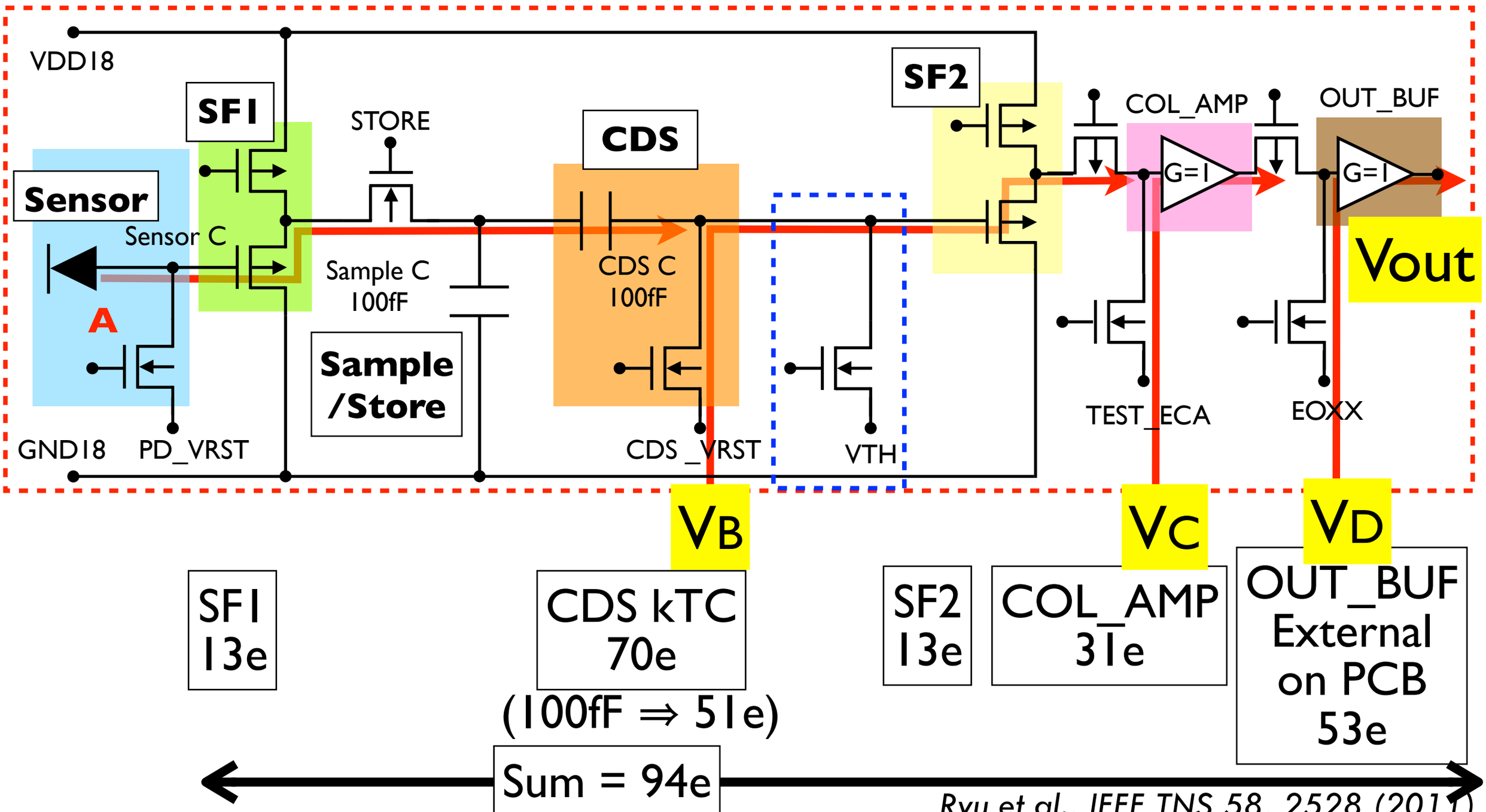
ΔE = 1.1-1.2keV (FWHM) » Fano limit
Readout Noise = 100e- (rms)

Ryu et al., IEEE TNS 58, 2528 (2011)

XRPIX1-CZ : Readout Noise

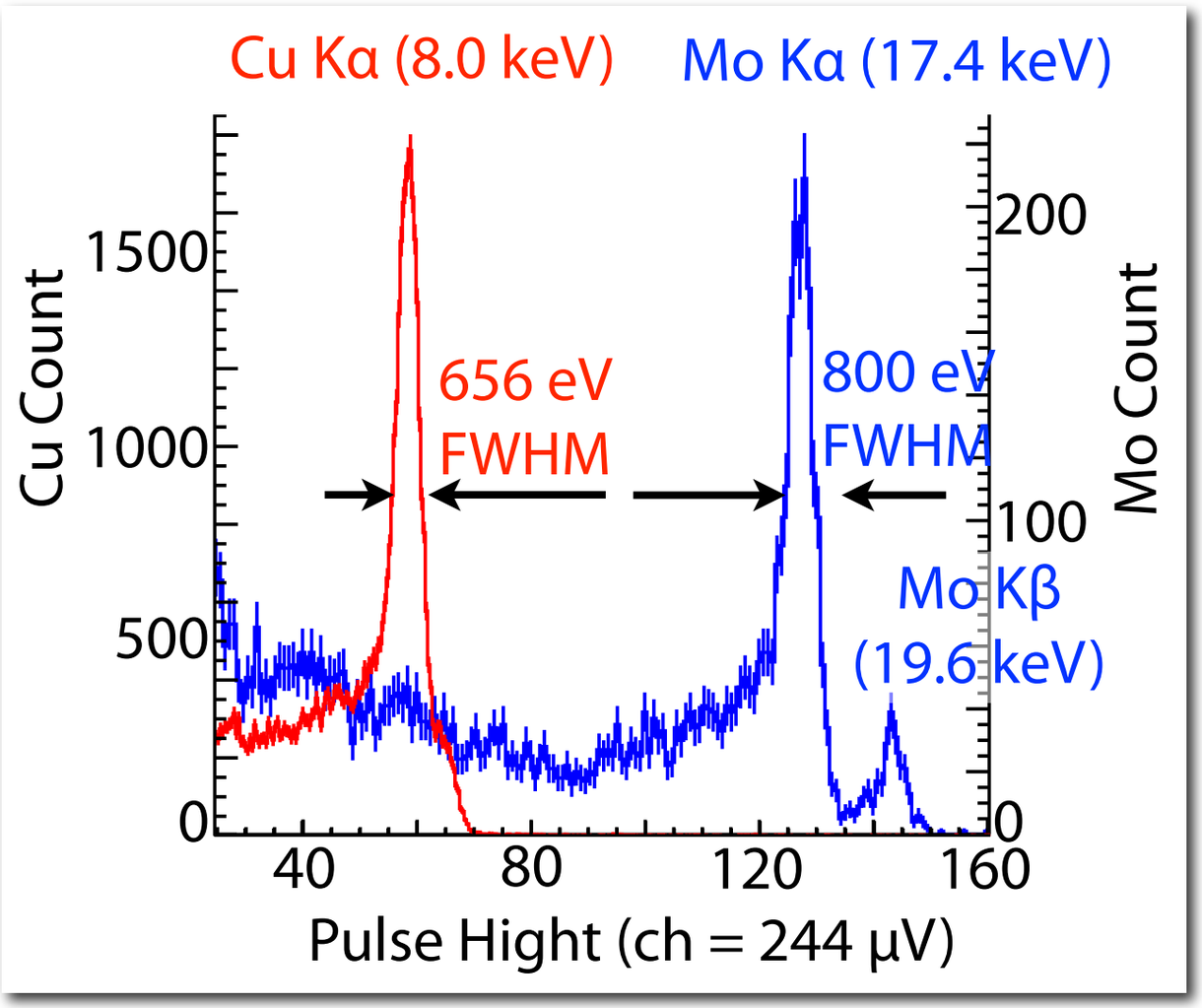
- See whether the readout noise of 100e- (rms) is explained by the sum of circuit noises or not.
- Measure the noise of individual circuit element through several DC voltage input points.

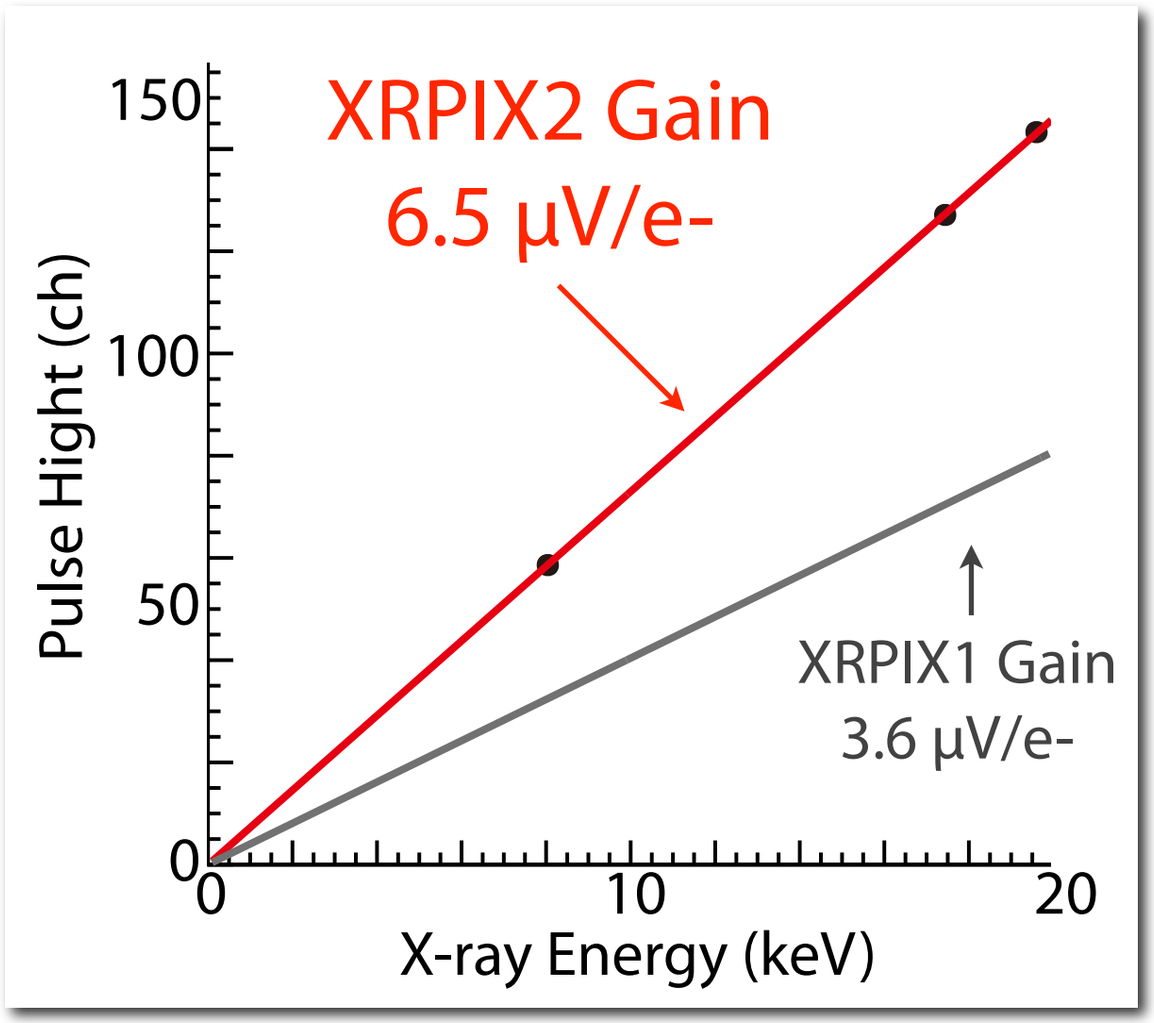
The sum of these noises is almost consistent with the observed readout noise of 100e.



Ryu et al., IEEE TNS 58, 2528 (2011)

XRPIX2-CZ-FI (Small Pixel) : Spectrum



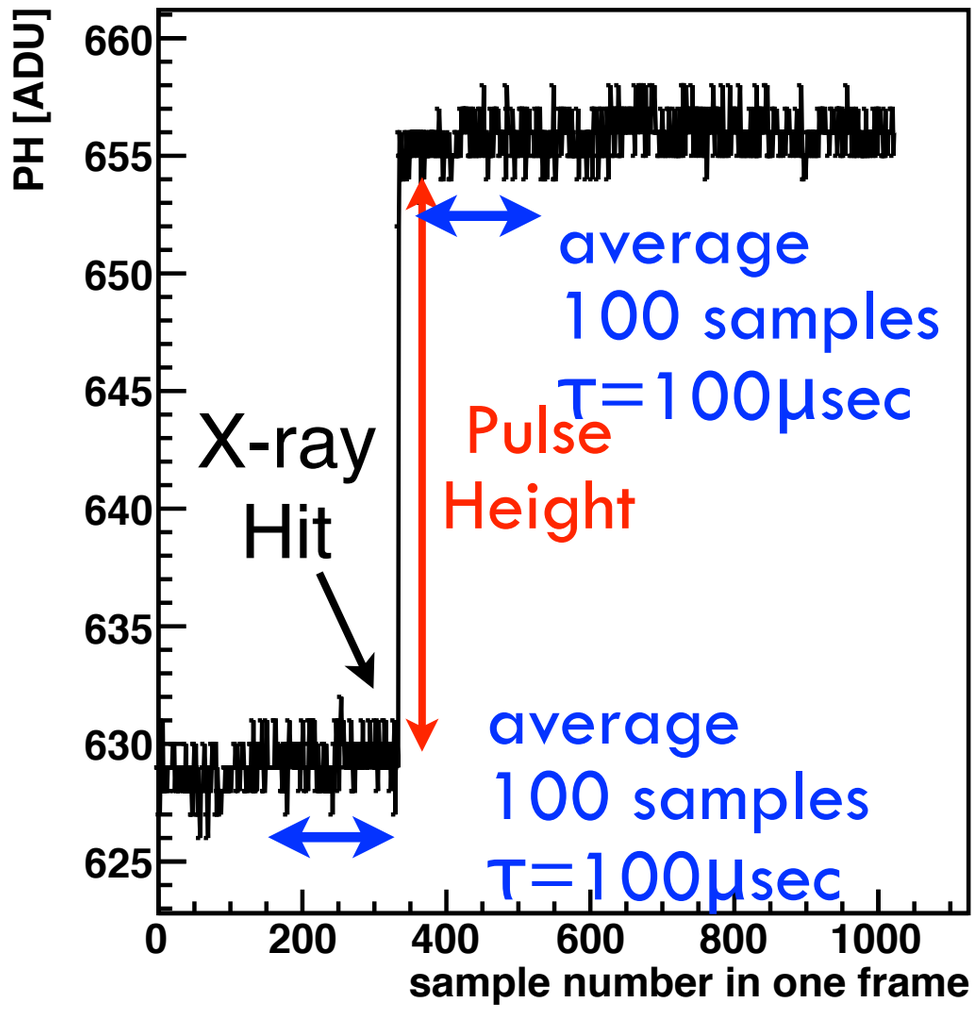


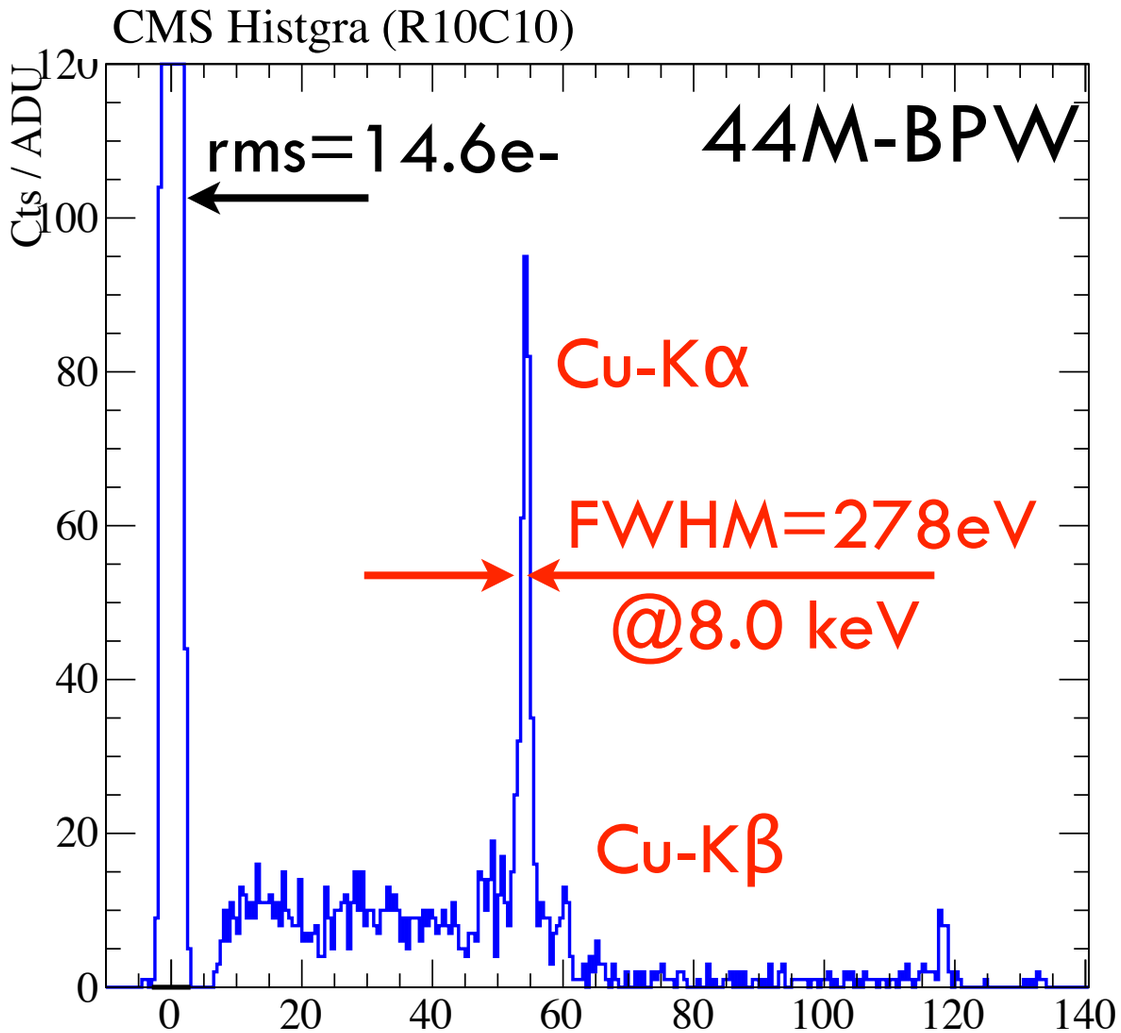
	Observed	Readout Noise	Fano Noise	Pixel-Pixel Gain Dispersion 1%	Sum
Cu Kα	656 eV	548 eV (FWHM) 64 e-(rms)	139 eV	255 eV	620 eV
Mo Kα	800 eV		205 eV	553 eV	805 eV

Nakashima et al., 2012, NIM A submitted

XRPIX1b-CZ : Single Pixel Readout

- In order to study the limit of the spectroscopic performance.
- Observe the waveform of analogue output from a single pixel by fixing the readout address without clocking (Single Pixel Readout like a SSD).
- Detect an X-ray as a "step" and measure the pulse height. → X-ray spectrum.
- No reset during the measurement → Free from the reset noise
- Reduce noises other than the reset noise by introducing LPF.
  high_v(100 samples average) - low_v(100 samples average) → LPF with τ=100μs

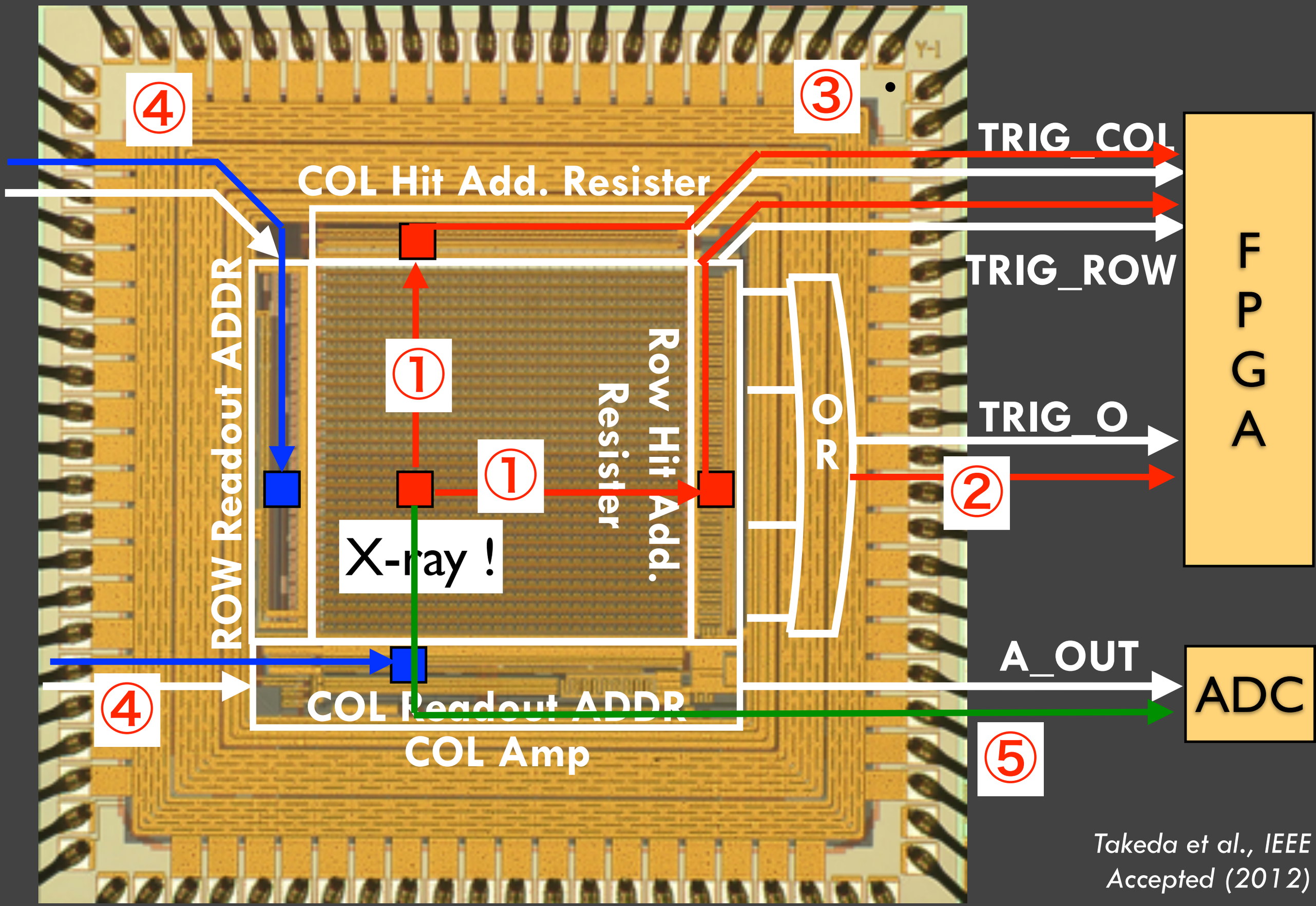




ΔE = 278eV @ 8.0keV (FWHM), readout noise = 14.6e (rms)

Nakashima et al., 2012, NIM A accepted

XRPIX1b-CZ : Trigger Driven Readout



Takeda et al., IEEE Accepted (2012)

XRPIX1b-CZ : Trigger-driven Readout of X-ray Events

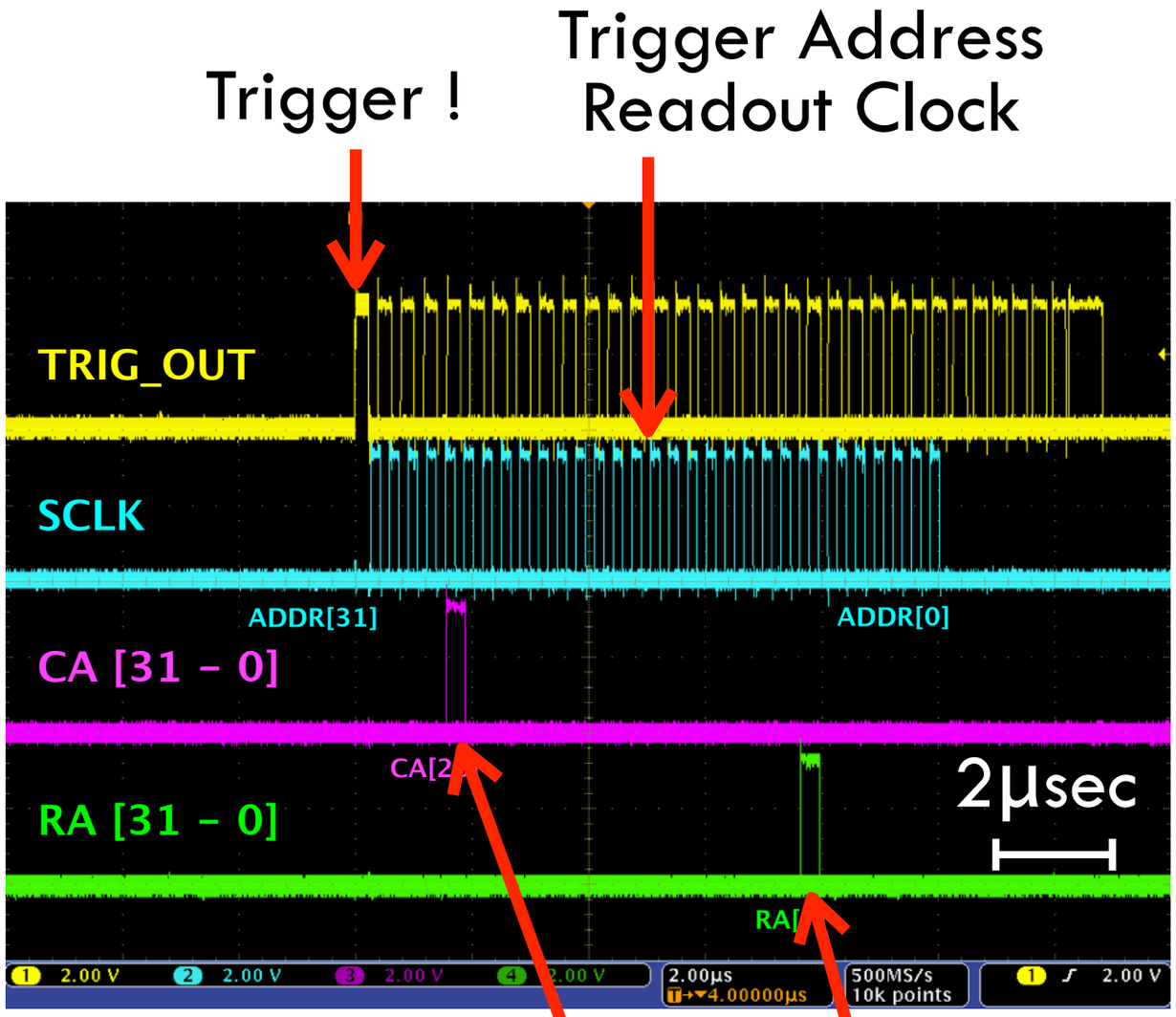
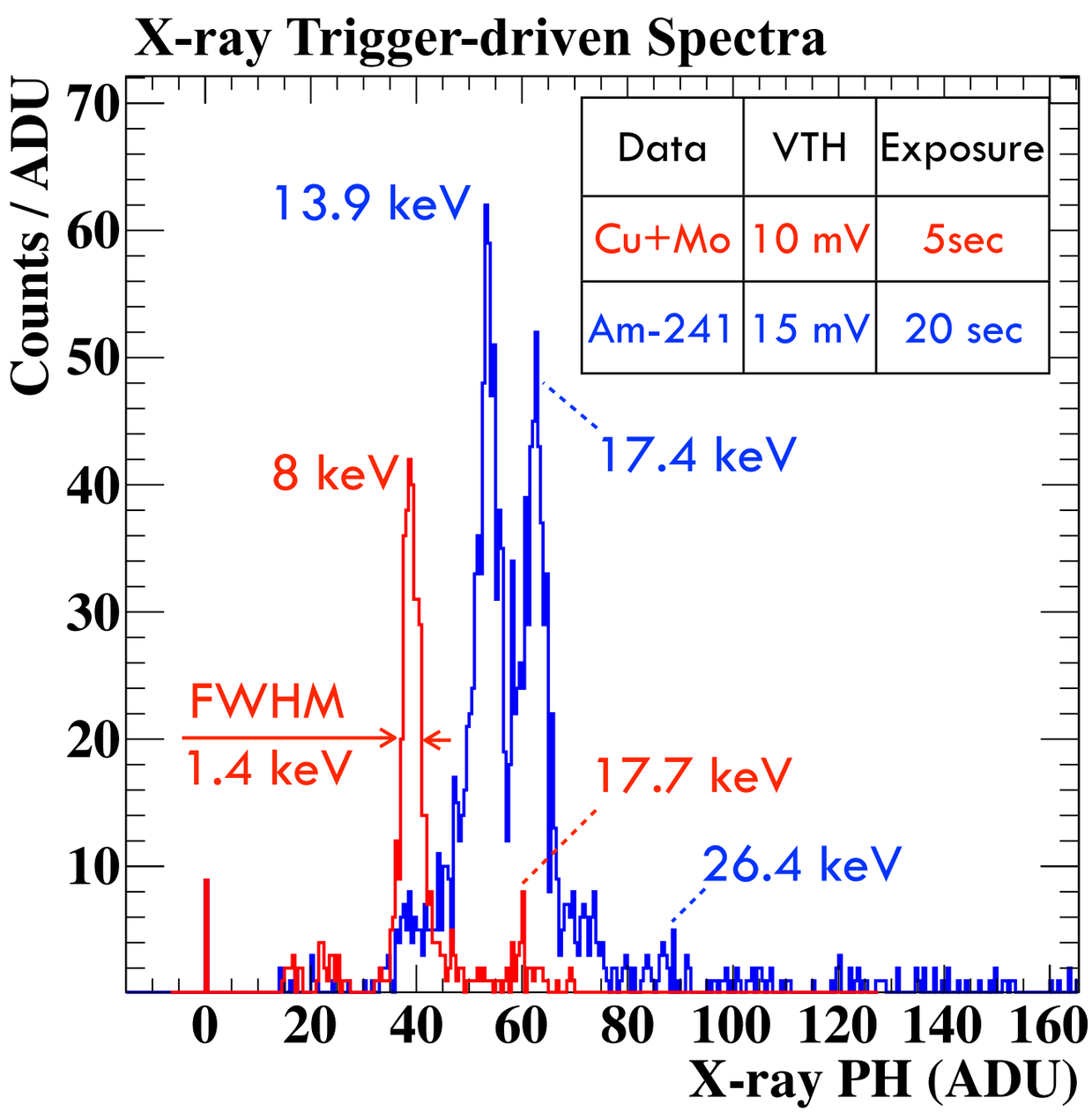


Fig. 12. Raw X-ray trigger signals recorded by the oscilloscope (c.f., Fig. 9).

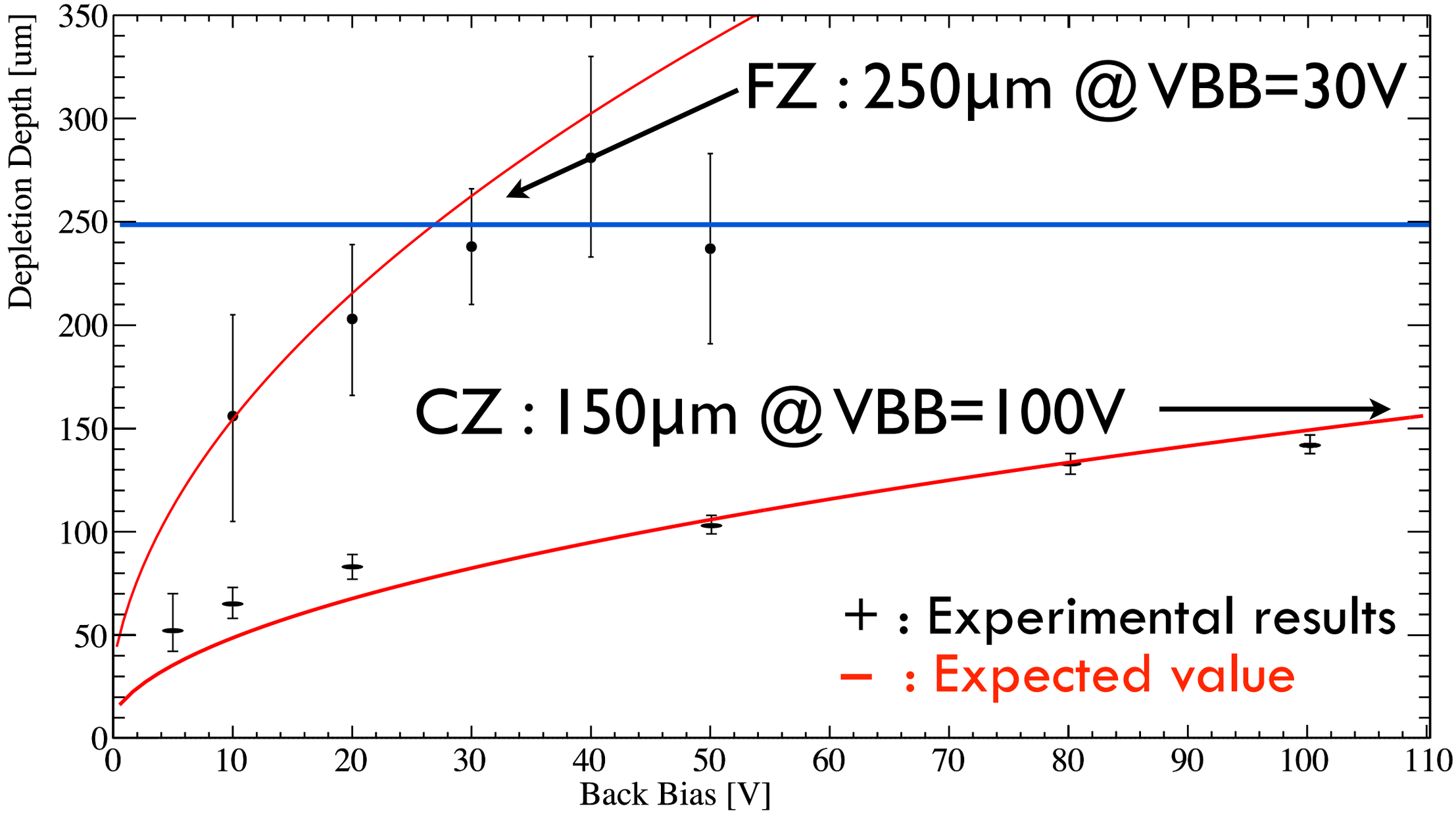


- Trigger-driven mode basically operates as designed.

- The gain is different from that of the frame mode.
- We are now investigating.

Takeda et al., IEEE Accepted (2012)

XRPIX1-FZ (7kΩcm): Depletion Depth



- The X-ray measured thickness of the depletion layer of XRPIX1-FZ reaches ~250μm at 30V and stops its growth there.
- The 250μm is nearly equal to the hi-ρ Si thickness (260μm).
- Full depletion is achieved at VBB=30V.

Nakashima et al., 2012, NIM A accepted

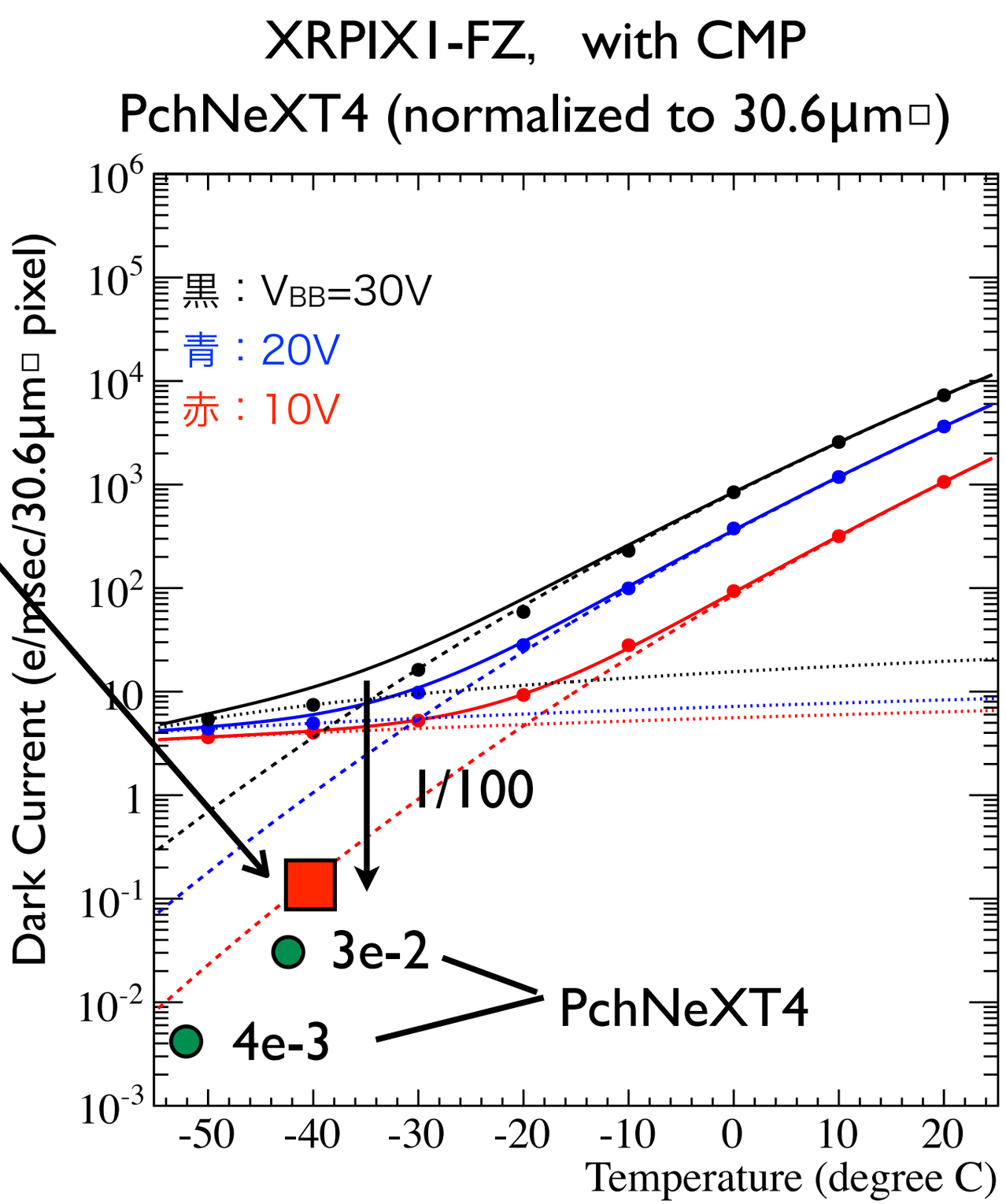
XRPIX1-FZ-FI (7kΩcm) : Dark (Leak) Current

Requierment at -40C

= 0.1e/msec/30.6μm□ pix

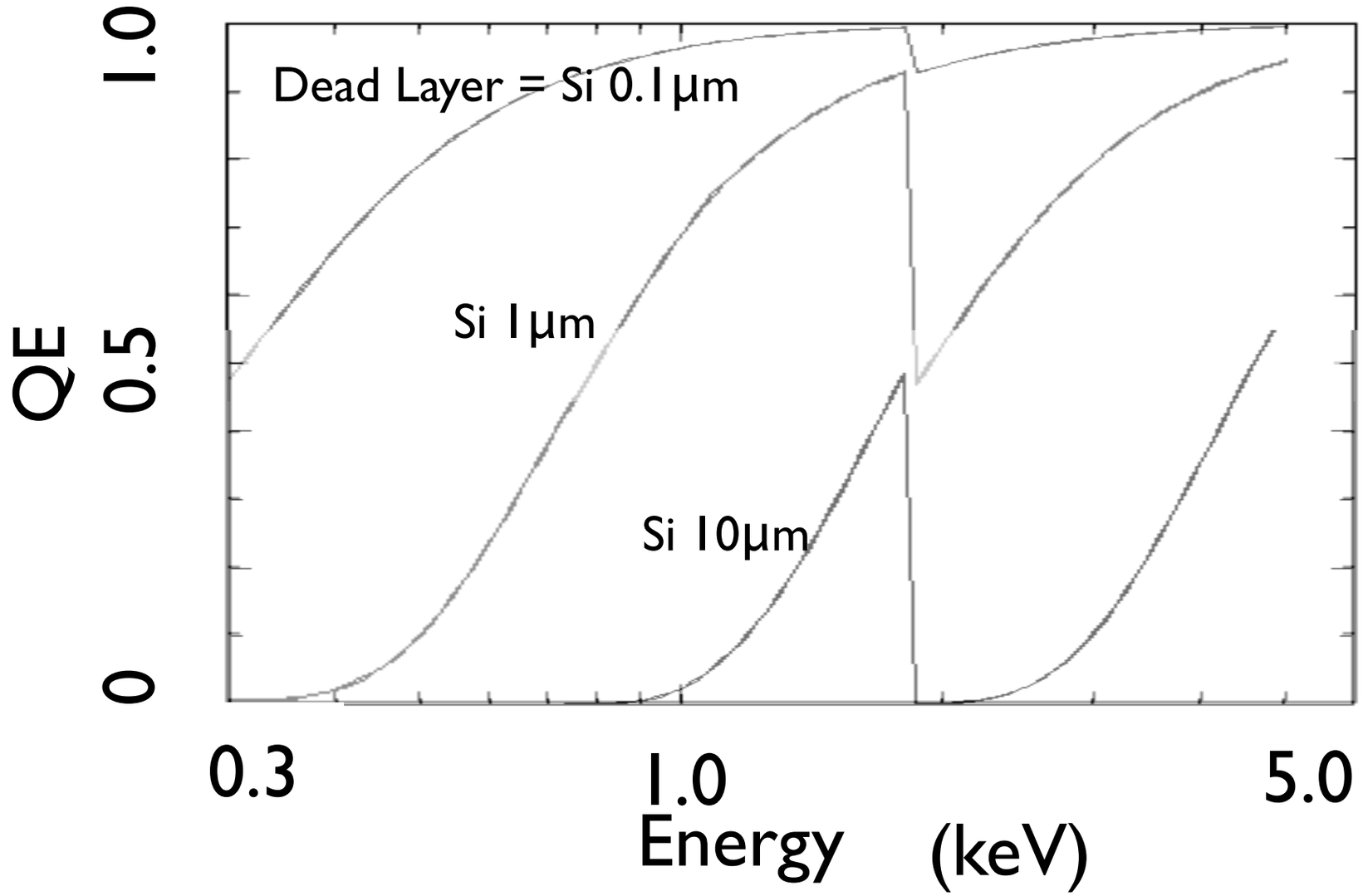
(depletion = 250μm)

= 2pA/cm2



From 20110516_OKImeeting_SOI_Dark_v5

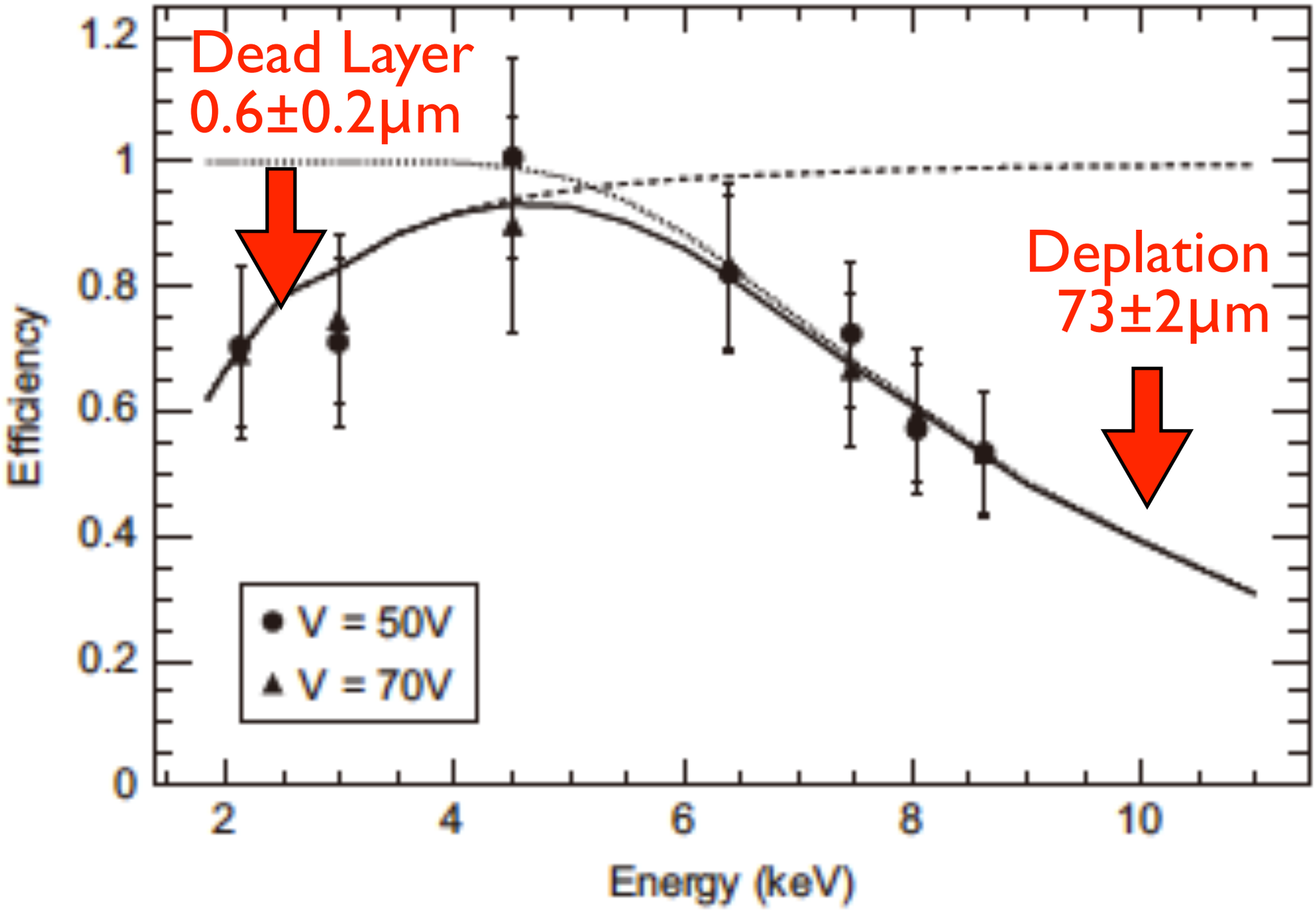
Back Illumination is Essential



- Scientific Target : observe C-Kα X-ray line at 0.3keV.
- The front side of SOIPIX has a circuit-layer of 10μm thickness. (Note: XIS FI-CCD~1μm, BI-CCD~0.07μm)
- Difficult to detect Soft X-rays with FI.
- Difficult to reduce the thickness of the circuit layer.

→ BI is essential

QE of LBNL's BI-SOIPIX / SOImager-2-CZ-BI



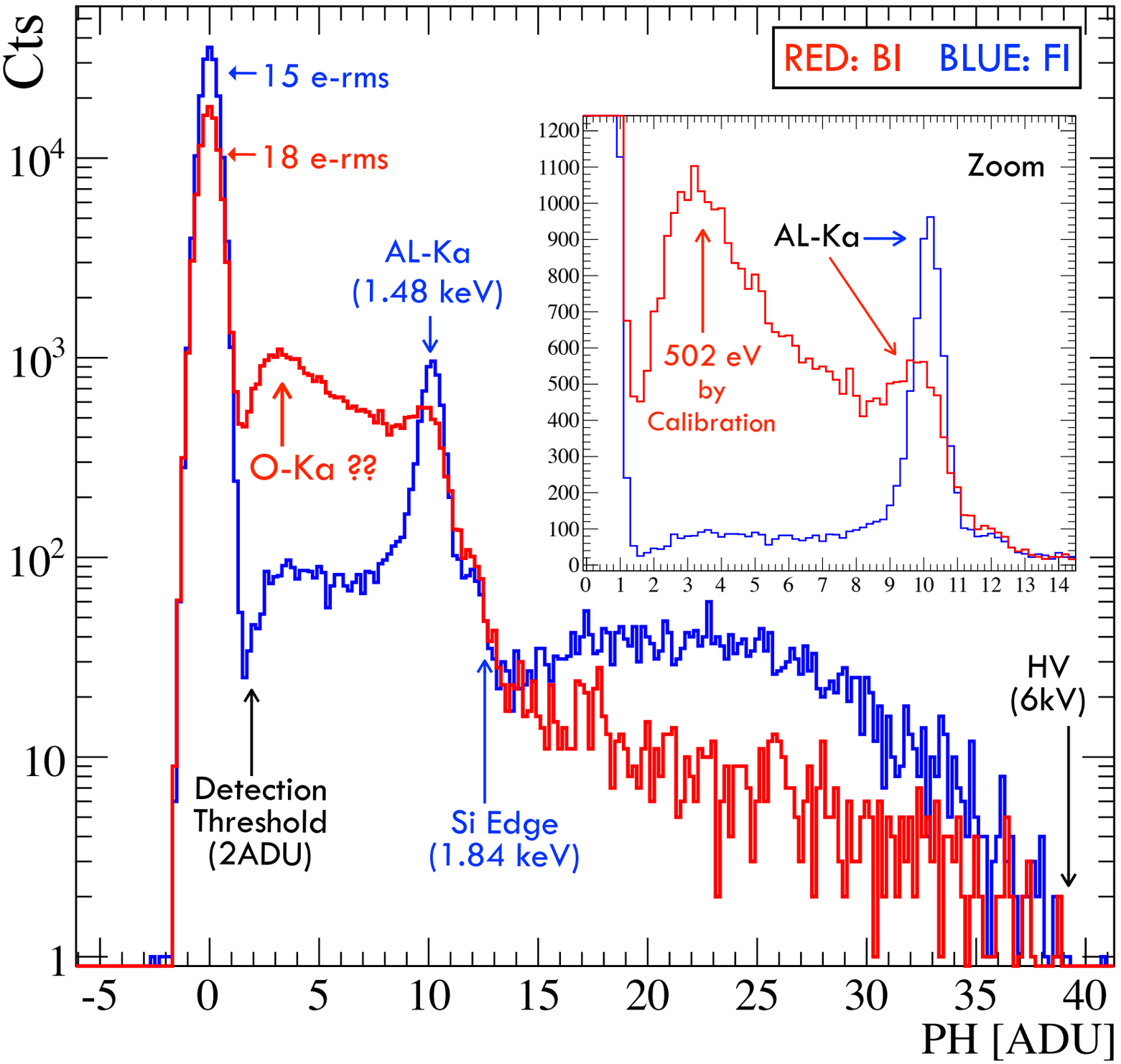
- CZ-BI with Back-thinned to 70μm.
- A thin phosphor layer is implanted.

Battaglia+12 NIM-A

※ これは我々の素子ではなく，同じウェハを使用した別の素子です.

XRPIX1b-CZ-FI/BI (100μm): Spectra in Single Pixel Readout (2011.11.22)

Target= Al_2O_3 , Front-I, Back-I, V_tube=6 kV,
V_bais = 100V, Temp=–50°C, Hit Threshold= 2 ADU, Exposure=400 sec, PIX=R10C10, 2us_sample, 300 μs_ave



- Back illumination type.
- X-ray generator (target = Al, 6kV).
- Al-K + Bremss
  (+O-K from Al2O3?)
- ΔE (FI) = 188eV,
  ΔE (BI) = 351eV (if line)

Results on FI : Ryu et al., IEEE Accepted (2012)

XRPIX3 and after

Spectral Performance

- 全てのピクセルにチャージアンプを持つ
- ノイズ性能の改善，エネルギー分解能の改善

Backside

- 裏面プロセスの改良
- 暗電流の削減とデットレイヤーを薄く

→以上の要素技術の合体

System

- 反同時計数システムの試作
- 非Ｘ線BGDの減少の実証
- 外部回路のノイズ削減

Conclusion

- X線天文衛星用のX線SOIピクセル検出器(XRPIX)を開発.
- 反同時計数による低非X線BGDを目指し，トリガ機能を持つ.
- 4.5mm角の素子の開発に成功
- 空乏層厚み~250μm，裏面不感層~0.6μm
- 読み出しノイズ64e-(rms)，ΔE=656eV @ 8.0keV (FWHM)
- トリガ読み出しに成功
- 今後，読み出しノイズ，裏面不感層，反同時計数の実証を行う

A-R-Tec
Analog and RF Technologies