Trigger-Output Event-Driven SOI pixel sensor for X-ray Astronomy

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Abstract We are developing monolithic active pixel sensors, called X-ray SOIPIXs. These sensors are based on a Silicon-On-Insulator (SOI) CMOS technology and are intended for use on future X-ray astronomy satellites (e.g., Tsuru+18, Proc. SPIE, 10709, doi: 10.1117/12.2312098). Each pixel has an event trigger output function which allows for an immediate readout of only the pixels hit by an X-ray with its high time resolution better than ~10 µs. This paper presents the introduction of the X-ray SOIPIX and its current achievements.

Keywords: SOI pixel sensor, X-ray, imaging, spectroscopy

1. X-ray Astronomy

X-ray astronomy is the study of celestial objects at X-ray wavelengths. Since X-rays from celestial objects are absorbed by the atmosphere, it is necessary to develop satellites equipped with X-ray instruments to observe celestial objects. The current standard X-ray instruments are imaging spectroscopy systems combining a Wolter-I type X-ray telescope and an X-ray CCD imager [1]. We operate the X-ray CCD in single photon counting mode to obtain the position on the CCD (direction of arrival), energy and arrival times of each incident X-ray.

2. Limitation of X-ray CCD

X-ray CCDs have high performance in terms of imaging and spectroscopy [2, 3]. However, the current time resolution of X-ray CCDs cannot keep up with the improved performance of X-ray telescopes. As the X-ray collecting area of the telescope increases and the angular resolution improves, the probability of multiple X-ray photons hitting the same pixel during single exposure increases, making it impossible to measure the X-ray energy (pile-up). Also, fast time variability, such as black holes, cannot be observed. High temporal resolution and fast readout are therefore required for the next generation of X-ray imagers.

3. Trigger-Output Event-Driven SOI pixel sensor

We are developing a Trigger-Output Event-Driven SOI pixel sensor (X-ray SOIPIX) for the next generation of X-ray imager [4]. An SOI pixel sensor is monolithic using bonded wafer of high resistivity depleted Si layers for X-ray detection, SiO2 insulator and low resistivity Si for CMOS circuits [5, 6]. In the X-ray SOIPIX, each pixel has an event trigger output function that allows immediate readout of only those pixels hit by an X-ray with its high time resolution better than ~10 µs. Bulk CMOS image sensors can also be equipped with the function. However, the depletion thickness of bulk CMOS image sensors is too thin to detect high energy X-rays. Then, we adopt SOI pixel sensor technology.

Since 2010, we have been developing X-ray SOIPIXs using Lapis Semiconductor's 0.2 µm FD-SOI CMOS technology [7]. The development of the sensor focuses on three main aspects: pixel circuits, device structures and on-chip functions.

4. Pixel circuit and Device Structure

A pixel circuit consists of an analog readout circuit and a comparator circuit. The analog readout circuit consists of a charge sensitive amplifier, CDS sampling, source follower. We use an inverter chopper type comparator.

The device structure was the most challenging part of the development. A small capacitance at the readout node is required to reduce the readout noise. The back gate effect of the circuit due to the electric field from the back bias is needs to be avoided [6]. The dark current from the interface between the sensor layer and the BOX layer needs to be reduced. Interference between the readout node and the circuit is necessary to be avoided. Signal charges generated at the pixel boundaries are required to also be collected without loss [8, 9]. Together with the Kawahito group at Shizuoka University, we have successfully developed a PDD (Pinned Depleted Diode) structure to meet this requirement [10, 11, 12].

5. Performances

From the above developments, the required performance has now been achieved: observations with a temporal resolution better than 10 µs at an event rate higher than ~500 Hz can be made without pile-up. The quantum efficiency already meets the requirements for the high energy band above 6 keV, which is determined by the depletion layer thickness [13]. The one in the low energy band below 1 keV still has room for improvement. We will develop it in the future. Energy resolution is the most difficult performance item, but the requirements are met [11, 13, 14]. However, there is still room for performance improvement. This will also be developed in the future. In terms of radiation resistance, the probability of the SEU is very low thanks to its SOI structure [15], and the TID has also been experimentally proven to meet the required performance over the observation period [16, 17].

6. On-chip function and "Digital X-ray SOIPIX"

We are developing various on-chip functions to increase practicality and broaden the range of applications. One is on-chip pattern processing and particle species identification [18]. X-rays produce compact clouds of signal charges, while high-energy charged particles produce tracks. Using this property, we have implemented an on-chip function to discriminate between the two.

On-chip ADCs, DACs, and BGRs (bandgap reference) are also being developed: a 14-bit 1-stage cyclic ADC and a 12-bit DAC have been developed, and test devices have been processed. Imaging spectroscopy using the ADCs has been successfully performed [19]. We are now developing a function to generate the clock to drive the sensor to simplify the interface and readout circuitry.

7. Applications other than X-ray astronomy

We are implementing scientific applications of the X-ray SOIPIX. We are developing the electron-track Compton gamma-ray camera [20, 21, 22], preparing a solar axion search experiment [23], a Lunar and planetary X-ray fluorescence mapping camera, and neutron TOF imaging spectroscopy.

The X-ray SOIPIX collaboration: M.Nobukawa (Nara Edu.), Y.Uchida, Y.Sbhimizu, F.Shiga, S.Fujita, T.Kohmura (Tokyo Sci.), K.Shimazoe, S.Sato, H.Matsuhashi, K.Hagino, Y.Onuki, K.Nagai (Tokyo), M.Uenomachi (Tokyo I. Tech.), H.Odaka (Osaka), M.Kagaya (Sendai Nct.), R.Azuma, N.Terano,

T.Tanaka (Konan), Y.Fukazawa, M.Hashizume, Y.Suda (Hiroshima), T.Kishimoto, K.Nobukawa, Y.Nishimura, S.Kuwano, R.Matsui (Kindai), M.Matsuda, T.Narita, H.Uchida, Y.Komura, H.Uebayashi, T.Tsuru (Kyoto), K.Mori, Y.Fuchita, M.Indo, K.Kadoya, S.Kamada, E.Kurogi, M.Kimura, H.Mitani, S.Nagayama, Y.Nishioka, Y.Saito, Y.Sasaki, N.Shigematsu, A.Shiokawa, K.Sugimoto, R.Takagi, A.Takeda, T.Tanaka, T.Sakamoto, T.Yoshida, M.Yukumoto (Miyazaki), H.Nakajima (Kanto Gakuin), H.Katagiri (Ibaraki), Y.Arai, T.Ikeda, T.Takayanagi (KEK), H.Suzuki (ISAS), I.Kurachi (D&S)

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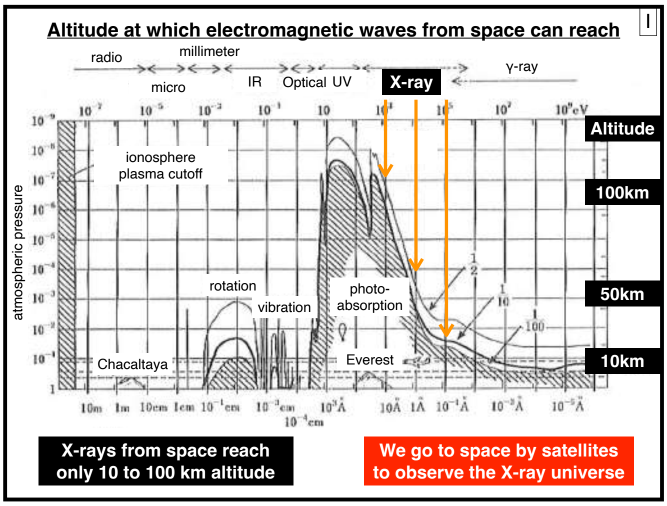
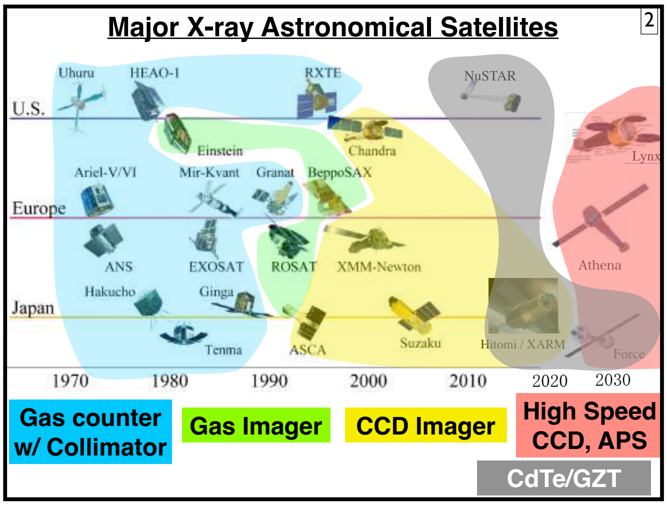
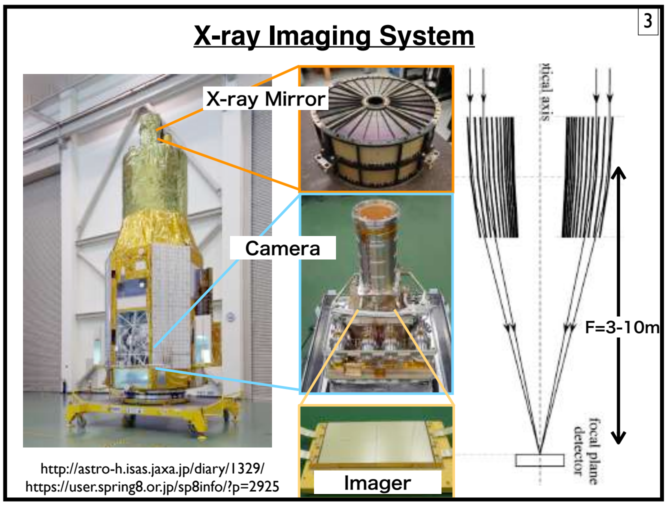
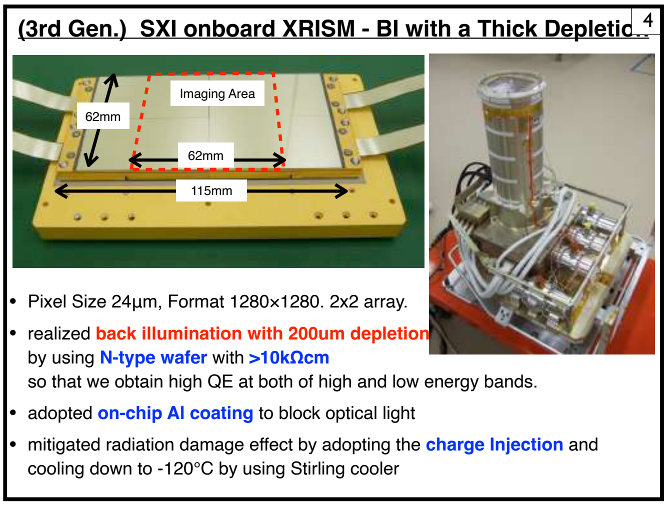
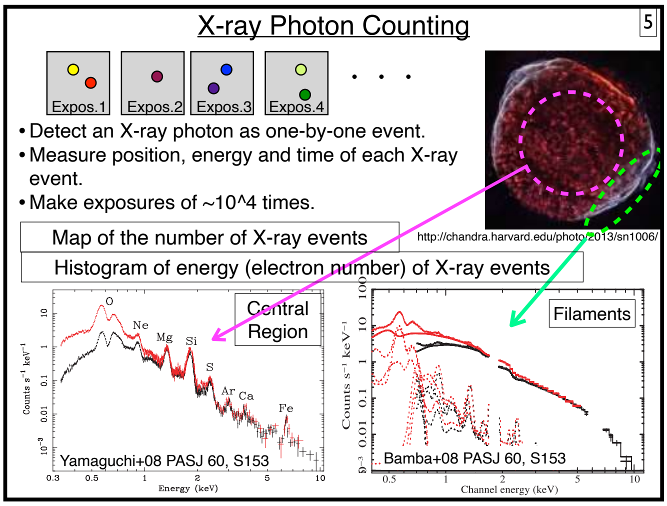
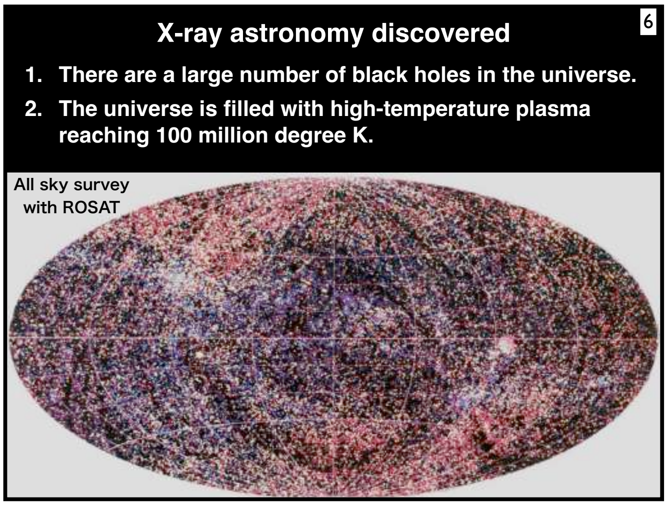

Altitude at which electromagnetic waves from space can reach
1
radio
millimeter
micro
IR
Optical
UV
X-ray
γ-ray
Altitude
100km
50km
10km
atmospheric pressure
ionosphere
plasma cutoff
rotation
vibration
photo-
absorption
Chacaltaya
Everest
X-rays from space reach
only 10 to 100 km altitude
We go to space by satellites
to observe the X-ray universe

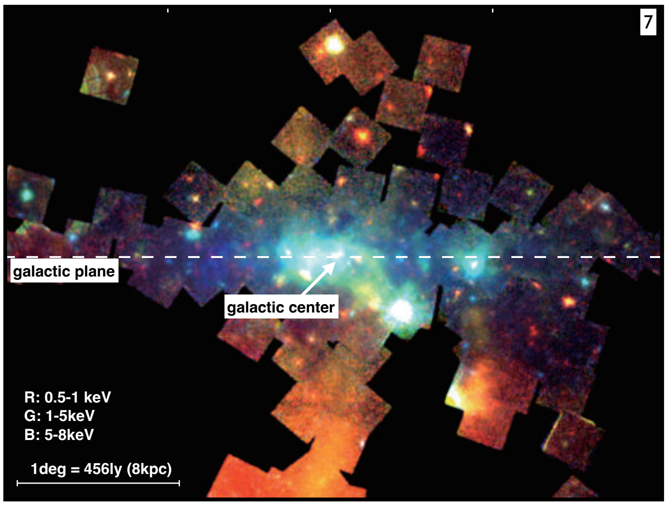

Major X-ray Astronomical Satellites
2
U.S.
Europe
Japan
Uhuru
HEAO-1
RXTE
NuSTAR
Einstein
Chandra
Lynx
Ariel-V/VI
Mir-Kvant
Granat
BeppoSAX
ANS
EXOSAT
ROSAT
XMM-Newton
Athena
Hakucho
Ginga
Tenma
ASCA
Suzaku
Hitomi / XARM
Force
1970
1980
1990
2000
2010
2020
2030
Gas counter
w/ Collimator
Gas Imager
CCD Imager
High Speed
CCD, APS
CdTe/GZT

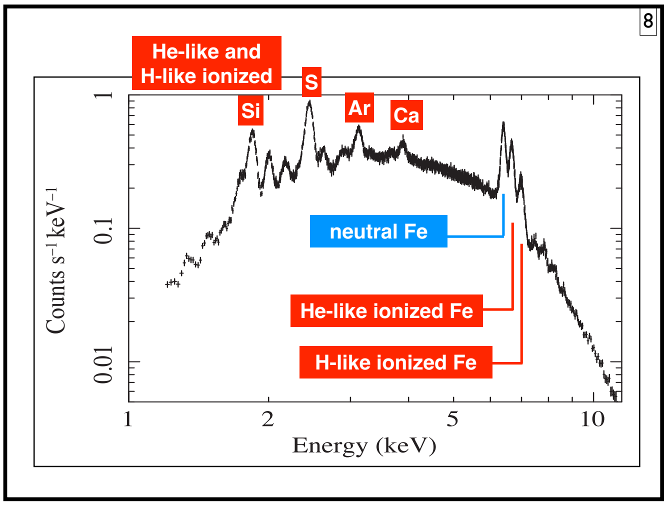

X-ray Imaging System
3
X-ray Mirror
Camera
Imager
F=3-10m
optical axis
focal plane
detector
http://astro-h.isas.jaxa.jp/diary/1329/
https://user.spring8.or.jp/sp8info/?p=2925


(3rd Gen.) SXI onboard XRISM - BI with a Thick Depletio...
4
Imaging Area
62mm
62mm
115mm
• Pixel Size 24μm, Format 1280×1280. 2x2 array.
• realized back illumination with 200um depletion
by using N-type wafer with >10kΩcm
so that we obtain high QE at both of high and low energy bands.
• adopted on-chip Al coating to block optical light
• mitigated radiation damage effect by adopting the charge Injection and
cooling down to -120°C by using Stirling cooler


X-ray Photon Counting
5
Expos.1
Expos.2
Expos.3
Expos.4
• Detect an X-ray photon as one-by-one event.
• Measure position, energy and time of each X-ray
event.
• Make exposures of ~10^4 times.
Map of the number of X-ray events
http://chandra.harvard.edu/photo/2013/sn1006/
Histogram of energy (electron number) of X-ray events
Central
Region
Filaments
Yamaguchi+08 PASJ 60, S153
Bamba+08 PASJ 60, S153
Energy (keV)
Channel energy (keV)

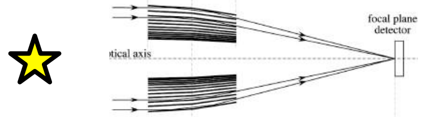

X-ray astronomy discovered
6
1. There are a large number of black holes in the universe.
2. The universe is filled with high-temperature plasma
reaching 100 million degree K.
All sky survey
with ROSAT


7
galactic plane
galactic center
R: 0.5-1 keV
G: 1-5keV
B: 5-8keV
1deg = 456ly (8kpc)


8
He-like and
H-like ionized
Si
S
Ar
Ca
neutral Fe
He-like ionized Fe
H-like ionized Fe
Counts s⁻¹ keV⁻¹
Energy (keV)

Limitation due to low time resolution of CCD (~1sec)   9

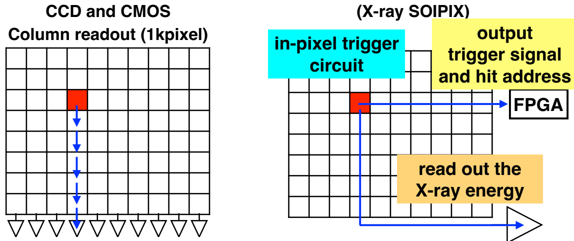
- Unable to take advantage of the performance of the latest X-ray mirrors that provide large X-ray collecting area and high angular resolution.
  - Event pileup occurs due to slow readout. Photon counting is impossible.



- Unable to resolve fast variability of compact objects such as blackholes and neutron stars, which requires better than 30μsec (=10km/c).
- Unable to apply anti-coincidence technique using anti-counter
  - Unable to make use of the excellent performance of Si in the band above 10 keV due to the high detector background
  - The technique requires time resolution better than 10μsec.

High time resolution better than 10μsec is Key to the next generation of X-ray Astronomy

Trigger Output Event-Driven Readout   10

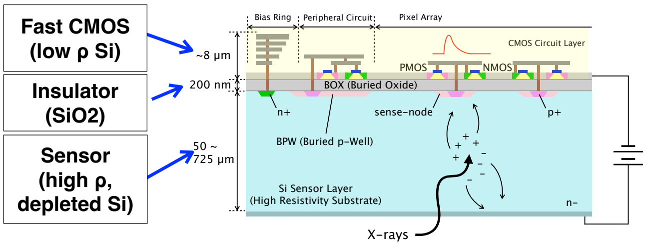


- time resolution 1msec. dose not meet.
- only a few pixels have X-ray events
- almost all the pixels are empty
- However, must read out all the pixels
- data rate = pixel readout rate ⇒ reaches 1GHz

- read out X-ray hit pixels only
- time resolution better than 10μsec
- data rate = X-ray event rate ⇒ 1kHz at the maximum

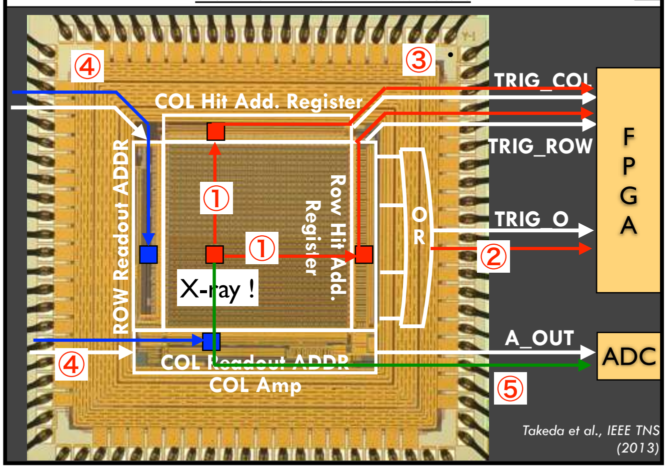
- **Power consumption at post-stage date processing ∝ data rate**
- **Event Driven readout reduces power cost**

SOI-CMOS image sensor (SOIPIX)   11



- **fine imaging (small pixel size ~20μm, large size > 20mm)**
- **low noise (< 10e rms),**
- **on-chip signal processing (high speed CMOS)**
- **wide-band, high quantum efficiency (thick depletion max 500μm, backside < 1μm)**

Event Driven Readout   12

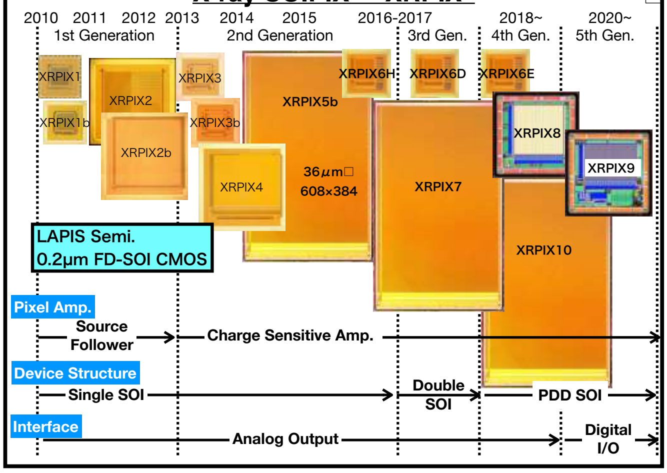


Takeda et al., IEEE TNS (2013)

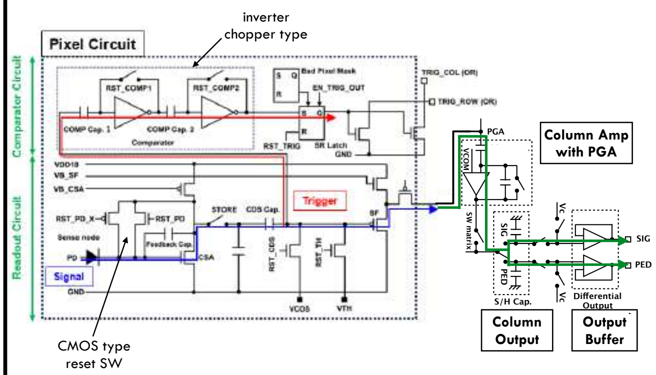
Target Specification of the Device   13

Imaging	pixel ~ 36μm□ — same performance as CCD area: Req. ~15x22mm², Goal ~15x44mm² 3side-buttable
Energy Band	Req. 1-40 keV, Goal 0.5-40 keV Backside Illumination Req. <1μm, Goal 0.1μm Full Depletion Req. >250μm
Spectroscopy	ΔE : Req. < 300eV, Goal < 140eV @ 6keV ENC: Req. <10e-, Goal < 3e- ← **Most Difficult**
Time Resolution	< 10μsec — new features with X-ray SOIPIX
Max Count Rate	> 2kHz / sensor for observation of bright X-ray sources

X-ray SOIPIX - "XRPIX"   14

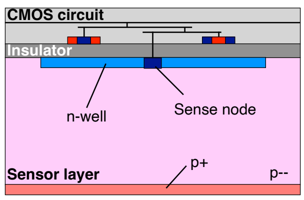


XRPIX: Pixel and Readout Circuits   15



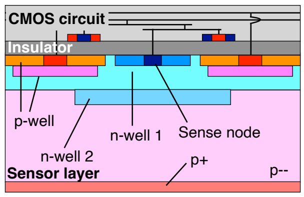
Yukumoto et al., in prep. (2024)

PDD (Pinned Depleted Diode) Structure   16



Conventional Single SOI

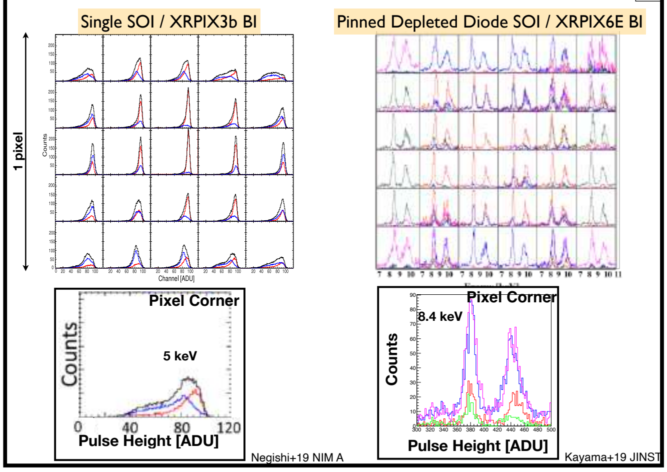
- large n-well connected to the sense node to collect signal charge
- a large sense node capacitance (C_{sense}) → not easy to achieve low readout noise
- causes capacitive coupling and interference between pixel circuit and sensor layer → degrade spectroscopy performance



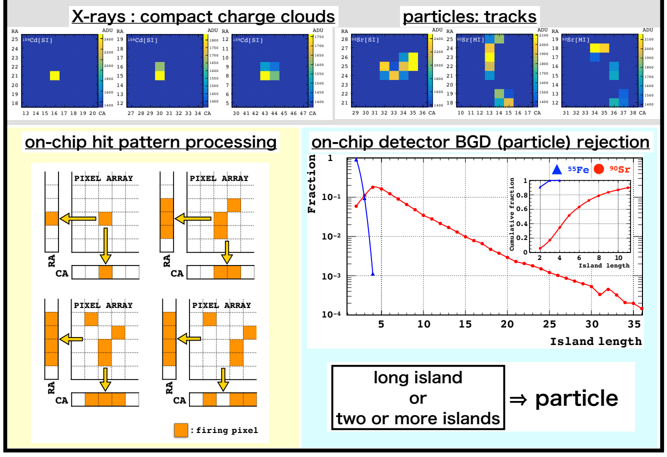
Pinned Depleted Diode (Kamehama+18)

- pinned p-well is formed under the interface of insulator and sensor layers
- the pinned p-well suppresses
  - interference between pixel circuit and sensor layers
  - dark current from the interface between the sensor and insulator layers
- small sense node capacitance (C_{sense}) → easier to achieve low readout noise

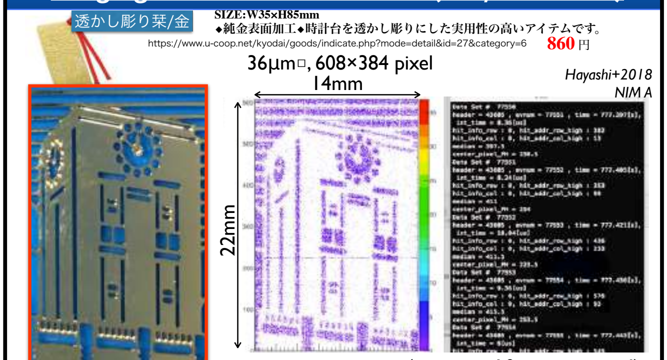
Subpixel Response in 2G (Single SOI) and 4G (PDD) 17



on-chip pattern processing : X-ray or non-X-ray 21



Imaging in Event-Driven Mode (2G / XRPIX5b) 18



Cd-109, Vbb=10V, Room Temp.

(movie in 10 times speed)

Capability of event rate > 500Hz

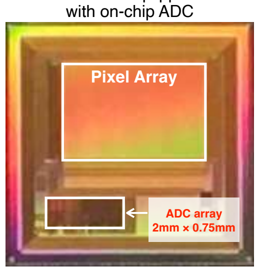
Trigger delay and time resolution better than 10us using laser.

on-chip ADC for "digital XRPIX" 22

14-bit 1-stage Cyclic ADC

- Small Size: 20 μm × 2 mm width/1ch
- Fast Conversion : 5.96 μsec
- Low Current Consumption : 125 μA / 1ADC
- Voltage Range : 0.4 - 1.5V (67 μV / LSB)

XRPIX9 equipped with on-chip ADC



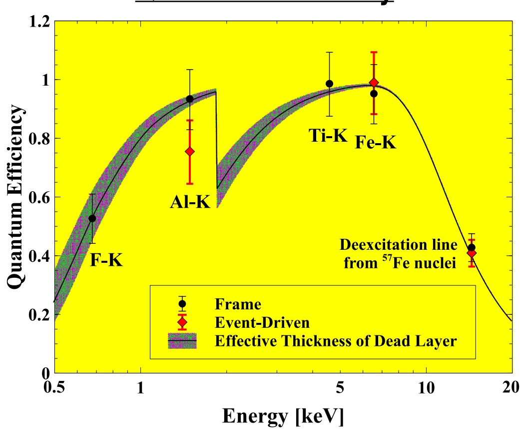
Equipped with a total of 16 ADCs

- We have two gain outputs.
  - Low gain (x1) : Range 0 - 80 keV
  - High gain (x4) : Range 0 - 20 keV where there are many astronomically important emission lines.

- We output pulse heights of 8x8 pixels for an X-ray event
- We perform simultaneous 8-column conversion of 8x8 pixels

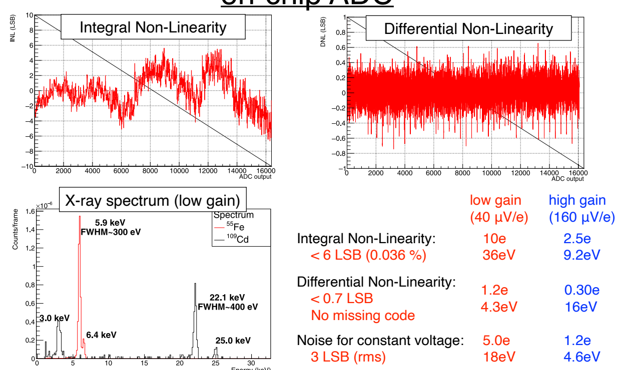
⇒ 16 ADCs in total

Quantum Efficiency 19



Kodama+21 (NIM A)

on-chip ADC 23

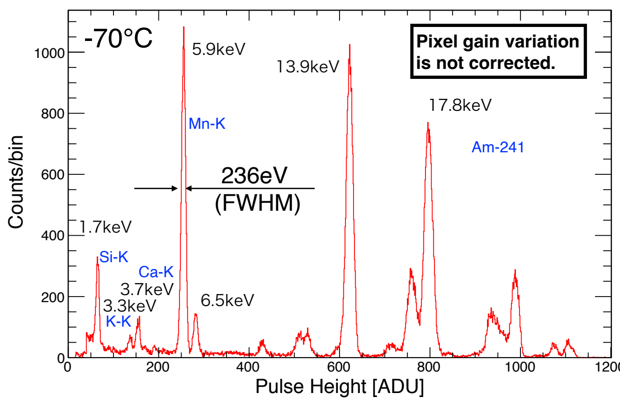


	low gain (40 μV/e)	high gain (160 μV/e)
Integral Non-Linearity: < 6 LSB (0.036 %)	10e 36eV	2.5e 9.2eV
Differential Non-Linearity: < 0.7 LSB No missing code	1.2e 4.3eV	0.30e 16eV
Noise for constant voltage: 3 LSB (rms)	5.0e 18eV	1.2e 4.6eV

- We successfully demonstrated 300 eV FWHM at 6 keV (the energy resolution requirement)
- The jumps in INL may be a issue for the X-ray energy calibration.
- For the 20 keV range, the jumps are effectively reduced to 1/4 by adopting the high gain output.

Matsuhashi, Hagino +24, NIM A

XR8.5 Spectral Performance (8x8 frame mode) 20



XRPIX8.5 / VBB=-300V / BI / Frame mode / Integration Time = 100us /
8x8 pixel out of 94x94 pixels / h_onepix_event / pixel gain correction not applied

Doi+

Application of X-ray SOIPIX 24