High Resolution X-ray Imaging Sensor with SOI CMOS Technology

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Outline

I. Introduction of the SOI Pixel Detector

II. Design of INTPIX4
   i. Specifications
   ii. Circuit
   iii. DAQ System

III. Device Performance Tests
   i. Noise Measurement & Effect of CDS Circuit
   ii. Energy Resolution
   iii. Spatial Resolution

IV. Summary

Introduction of the SOI Pixel Detector

- A monolithic pixel detector with Silicon-On-Insulator (SOI) CMOS Technology **-> 0.2 μm fully-depleted (FD) - SOI pixel process**
  - SOI Pixel Detector (SOIPIX) : Processed by OKI Semi. Co. Ltd.

SOIPIX Advantages

- **No mechanical bump bonding**
  - **-> High Density, Low material budget**
  - **-> Low Parasitic Capacitance, High Sensitivity**
- **Standard CMOS circuits can be built**
- **Based on Industrial standard technology**

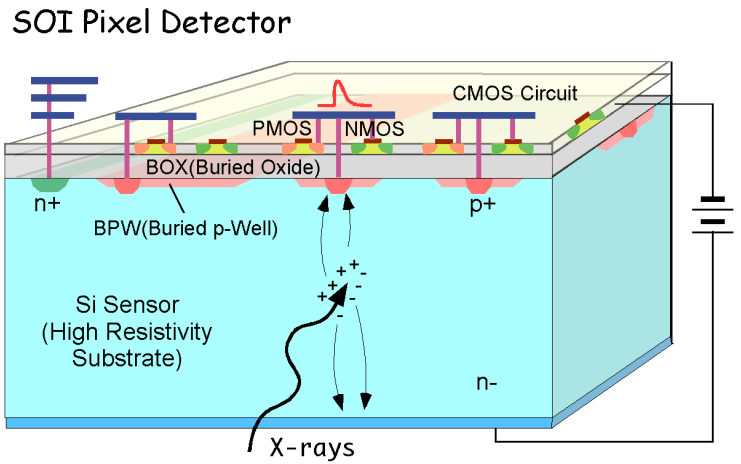
Circuit Layer : ~40 nm
Buried Oxide (BOX) Layer : 200 nm
Sensor Layer : 100 - 725 μm

More details

-> Dr. Miyoshi's talk (Mon 13, 14:20)

SOI Pixel Process

New Process to make pixel detector with SOI technology. Joint development with OKI Semi. Co. Ltd.



Cross section of the SOI Pixel Detector

INTPIX4 Specifications

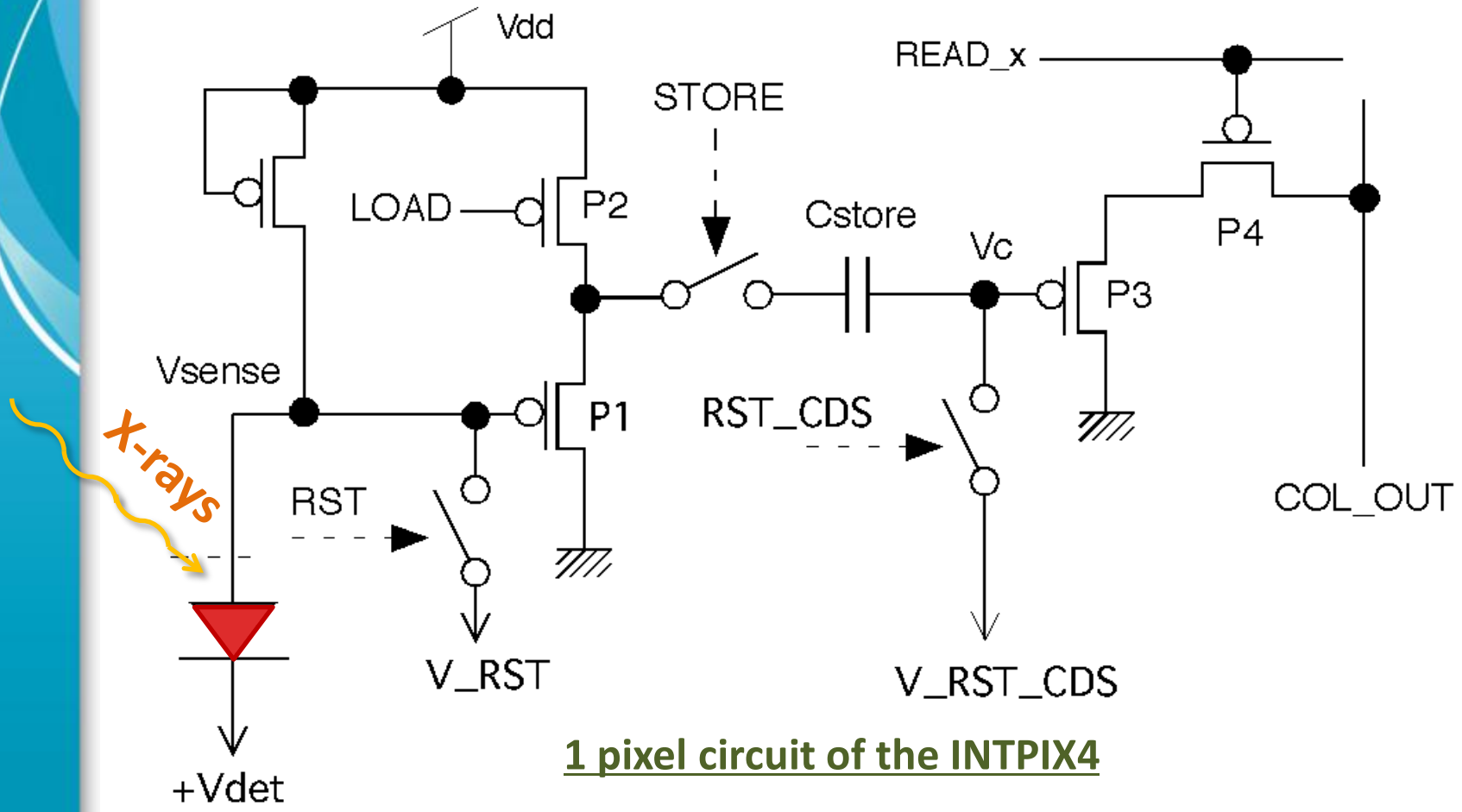
- Integration Type SOIPIX Detector
- Chip Area : 10.3 x 15.5 mm^2 (Effective Area : 8.7 x 14.1 mm^2)
- Number of Pixels : 512 x 832 (= 425, 984)
- Pixel Size : 17 x 17 μm^2
- Correlate Double Sampling (CDS) Circuit in each pixel.
- 13 Analog Out
- Sensor thinned to 260 μm
- Sensor Wafer Type
  - Czochralski (CZ) - SOI : 700 Ω cm
  - Floating Zone (FZ) - SOI : 7 kΩ cm
- **Fully-depleted by FZ-SOI wafer**
- **Back-illumination**

This presentation treat only CZ-SOI wafer.

INTPIX4 Chip Photo

INTPIX4 Circuit

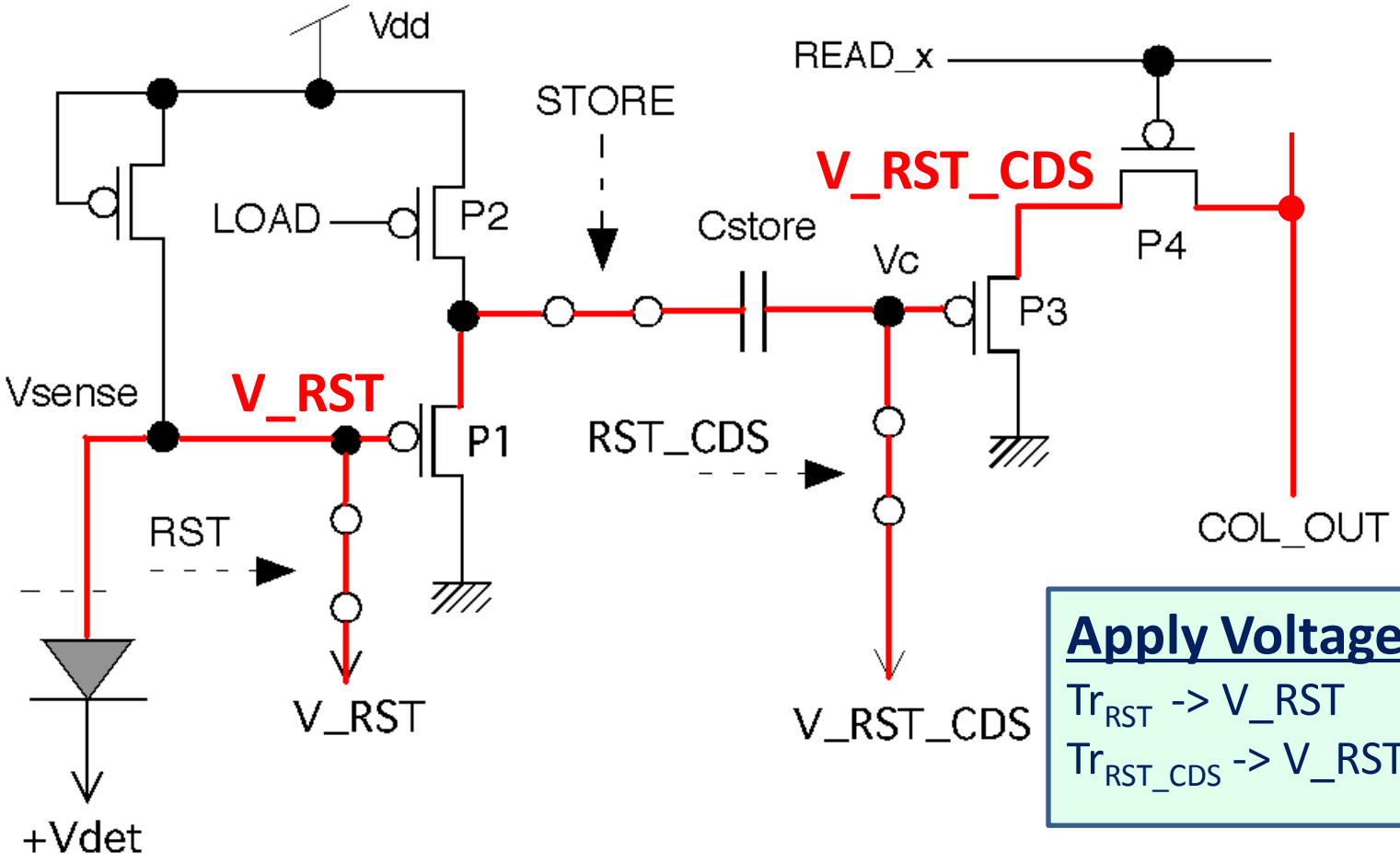
- CDS Circuit : CDS Cap. -> Cstore, Reset Tr. -> RST & RST_CDS
- Stored Signal read out from COL_OUT.



1 pixel circuit of the INTPIX4

How to Suppress Reset Noise

1. Reset state.
   - Apply voltage to each reset Tr (RST & RST_CDS).



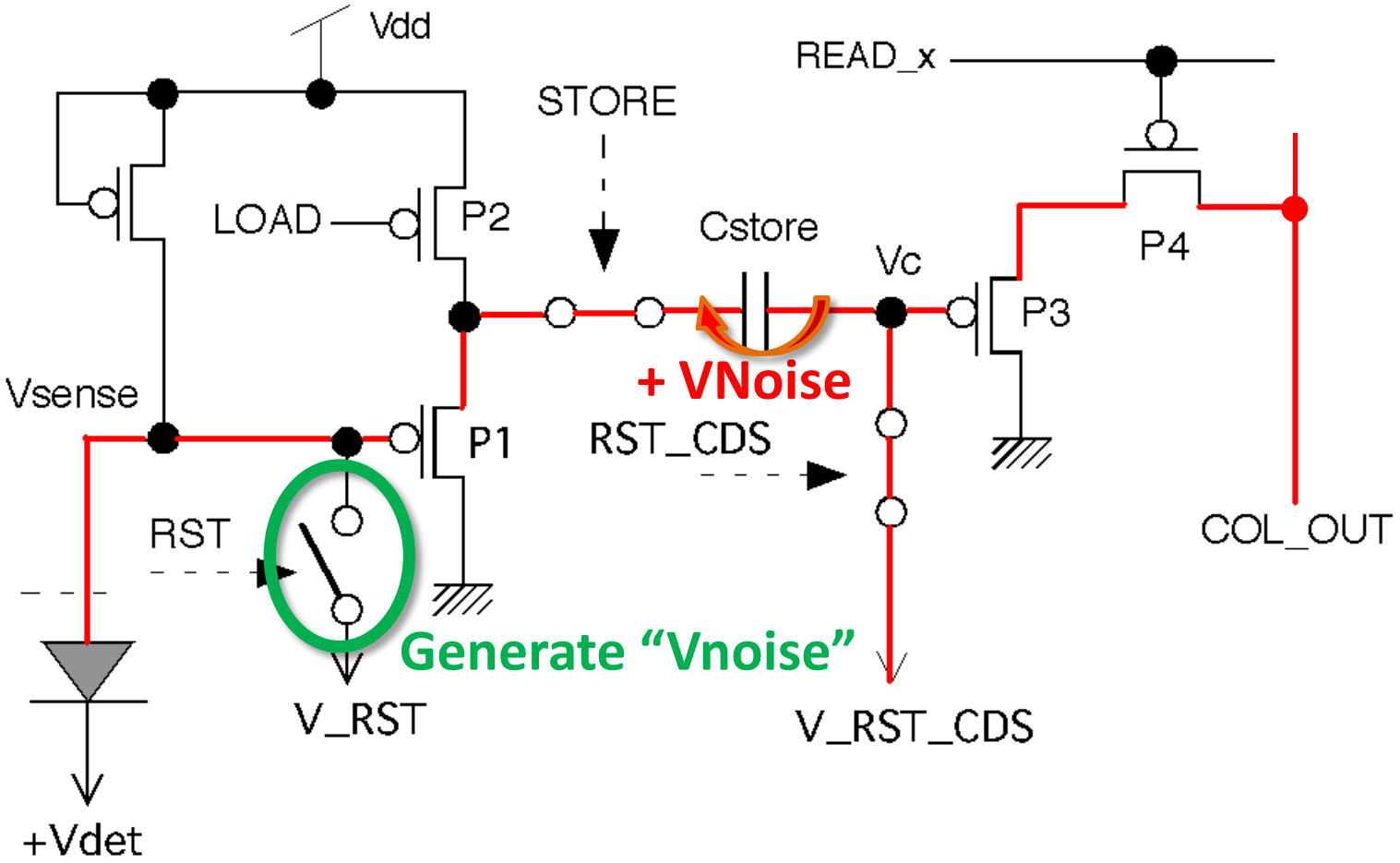
Apply Voltage

Tr_{RST} -> V_RST

Tr_{RST_CDS} -> V_RST_CDS

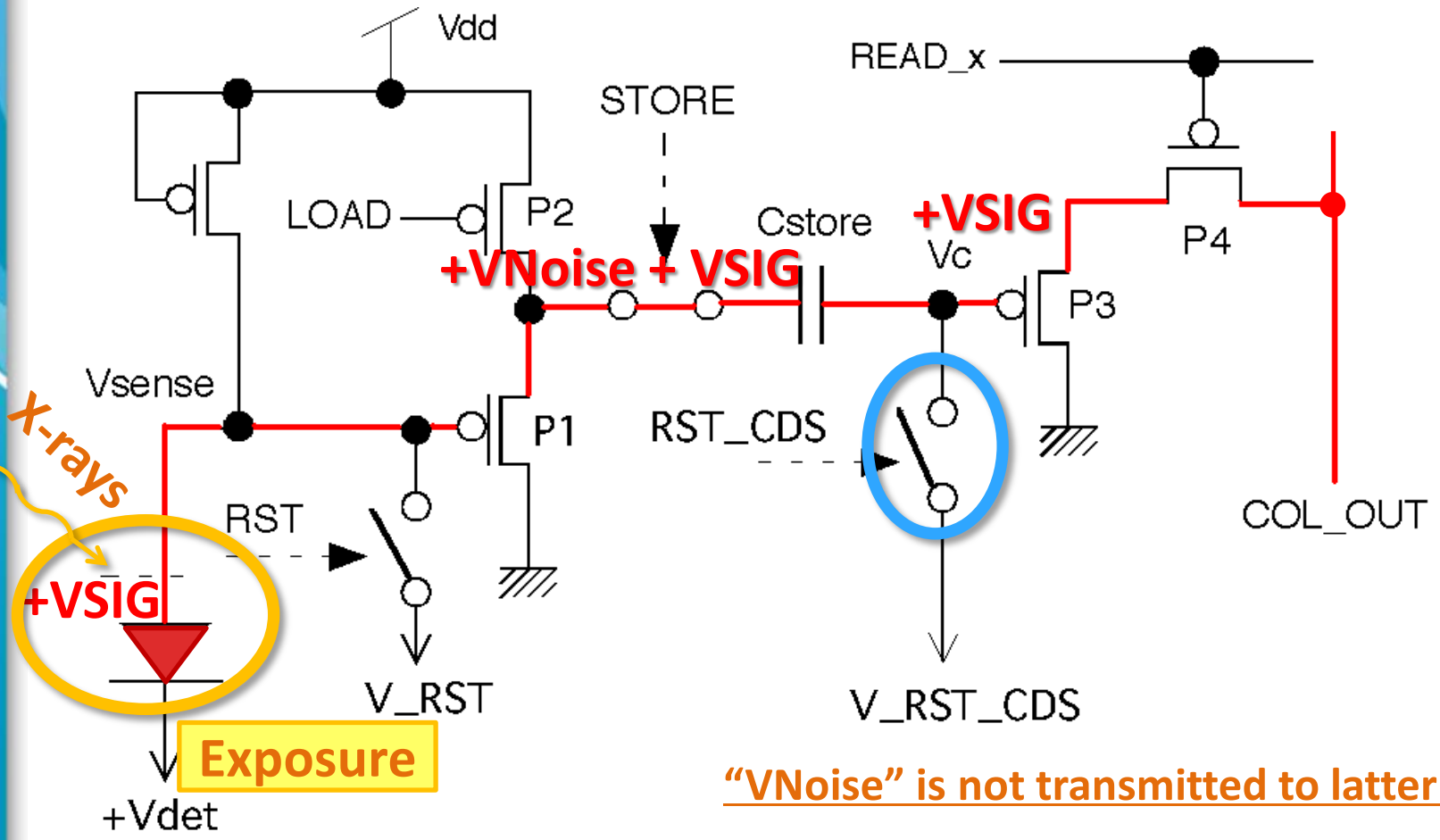
How to Suppress Reset Noise

2. Tr_{RST} is turned off, and noise is generated (VNoise : kTC noise). It is kept the CDS Capacitor (Cstore).



How to Suppress Reset Noise

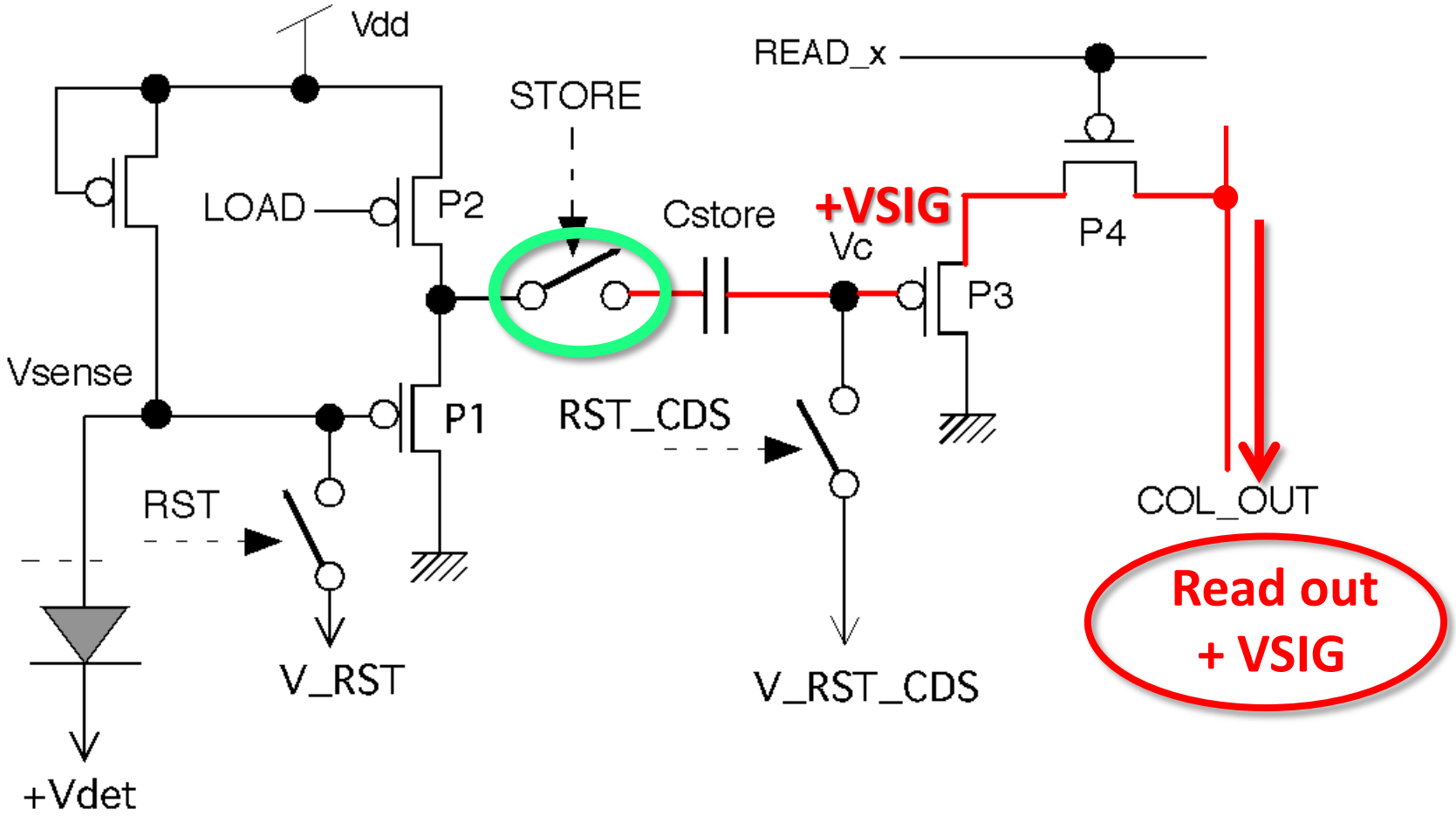
3. Tr_{RST_CDS} is turned off, and exposure of signal (VSIG).
   The signal is added in the circuit.



"VNoise" is not transmitted to latter part.

How to Suppress Reset Noise

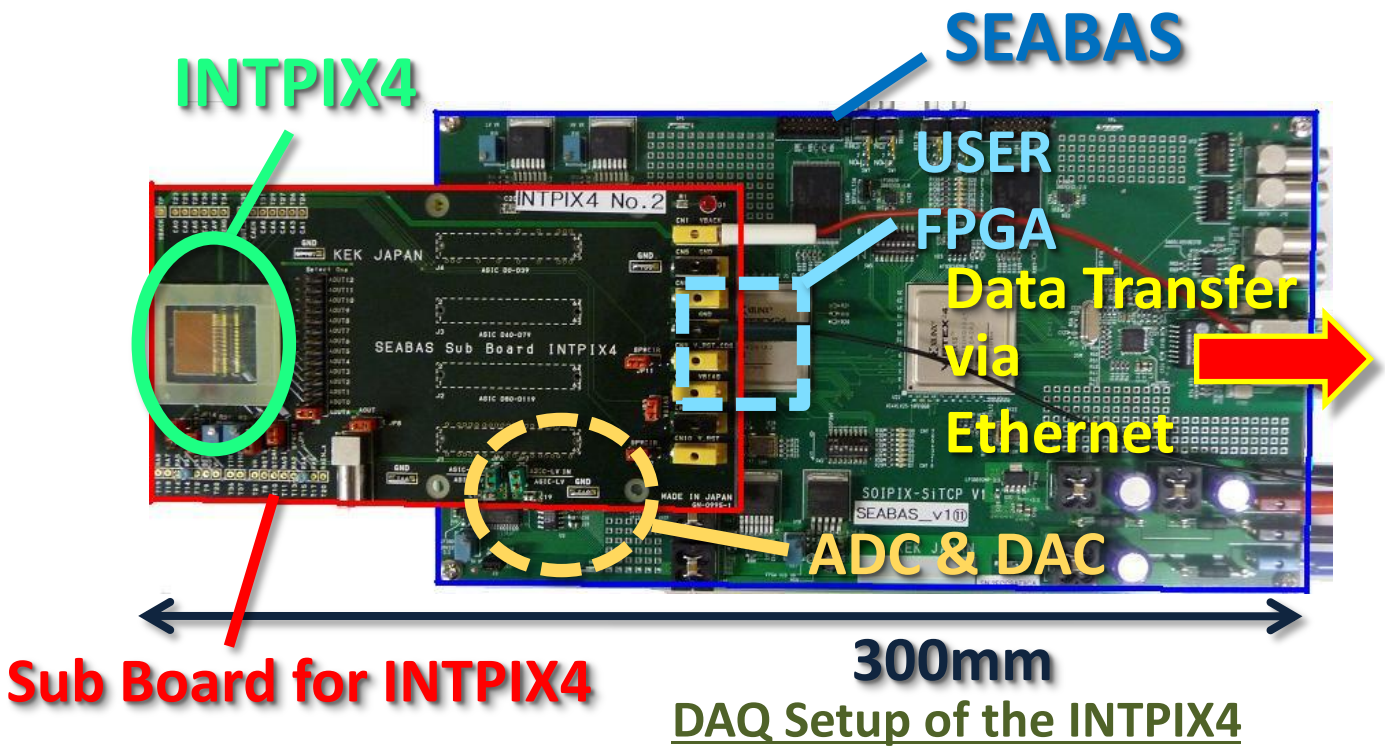
4. After integration time, Tr_{STORE} is turned off. Then the voltage of the Vc node is read out from "COL_OUT". The VNoise will not appear in the read out voltage.



DAQ System

- Soi EvAluation Board with Sitcp (SEABAS)
- General data read out board for SOIPIX.
- A FPGA controls the SOI Pixel chip.
- Directly transferred to Ethernet.

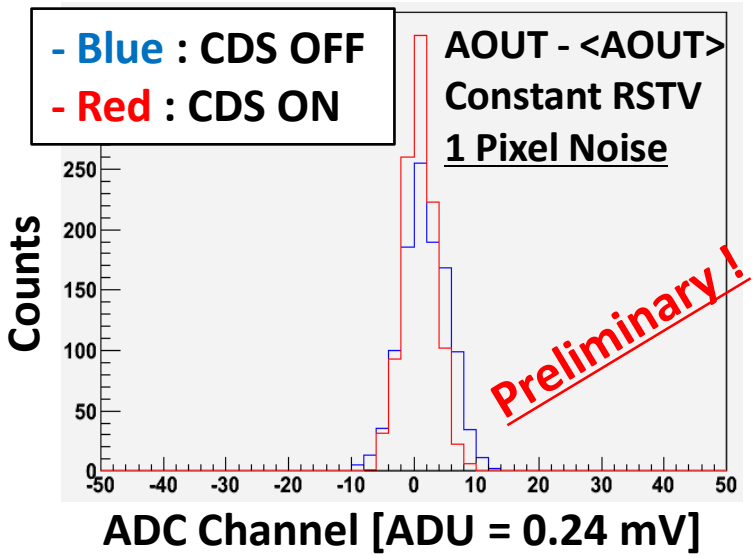
Power Supply : ± 5 V
Clock : 25 MHz
Network : 100 Mbps
ADC, DAC,
NIM IN x2, NIM OUTx 2



DAQ Setup of the INTPIX4

Noise Measurement & Effect of CDS Circuit

- Noise Measurement with 1 pixel @ 7 °C.
- Comparison with measured noise and calculated kTC noise.
- **The CDS circuit is working as expected.**



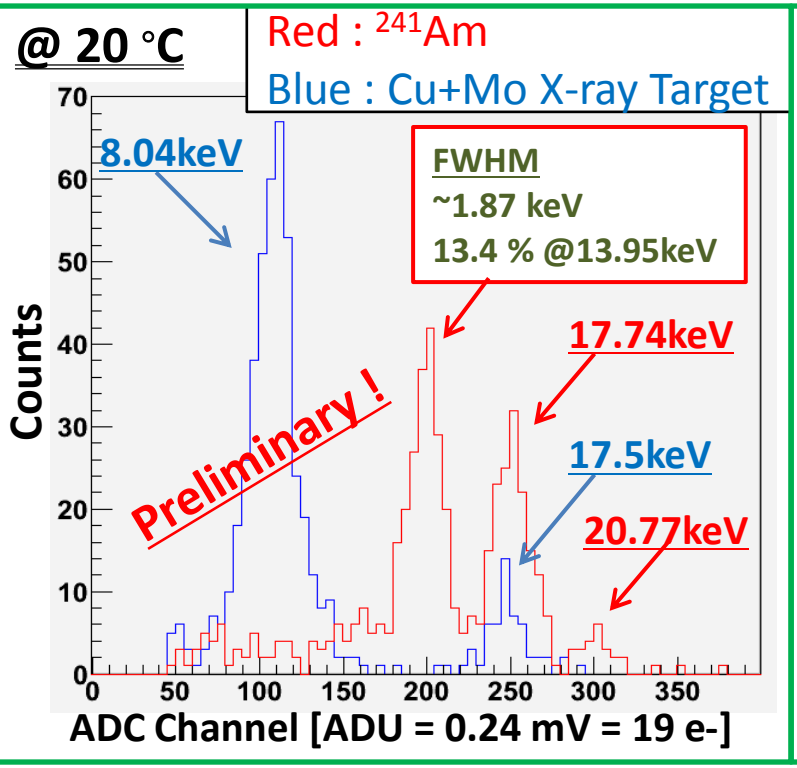
@ 7 °C (280 K)

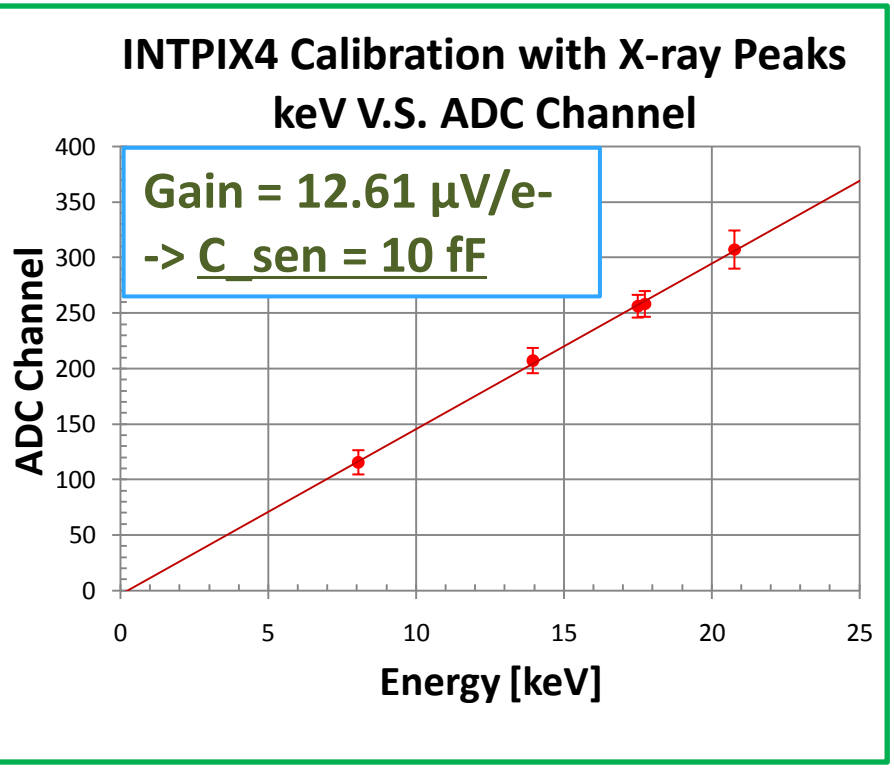
Measured Noise (RMS)		Measured Noise (Δ RMS^2)	Calculated kTC Noise
CDS OFF	CDS ON		
70 e-	49 e-	$(70^2 - 49^2)^{1/2}$ = 50 e-	(kT@280 K / 10 fF) = 49 e-

Energy Resolution

- Energy Spectrum @Room Temp.
  - ^{241}Am and Cu + Mo X-ray Target
- **FWHM : 13.4 % @ 13.95 keV**
- **Sensor Capacitor : 10 fF**

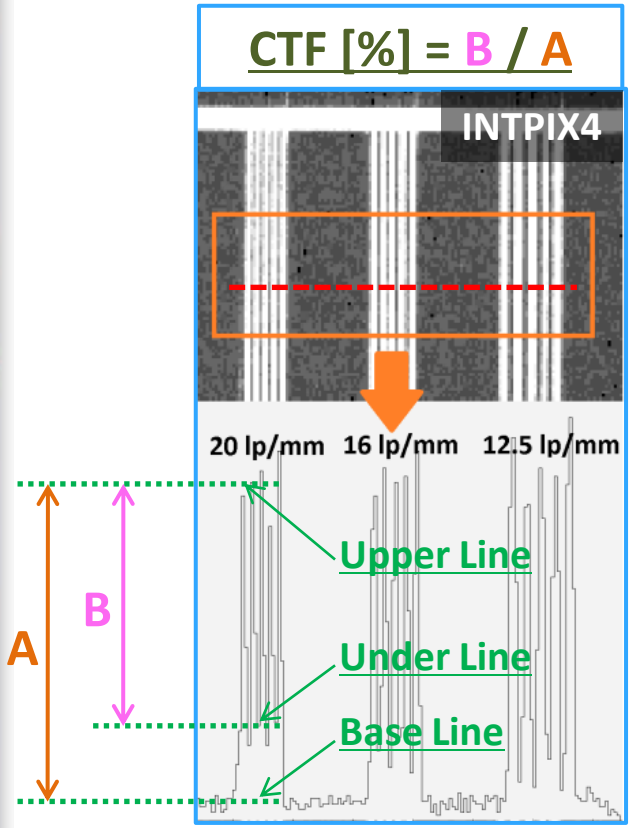
V sensor = 200 V
Integration Time = 250 μs
Back-illumination

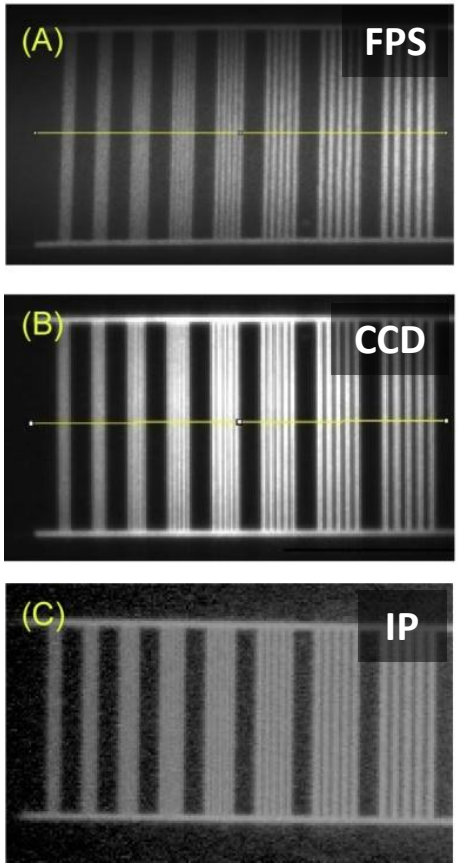


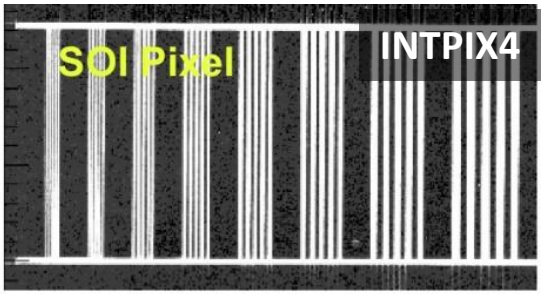


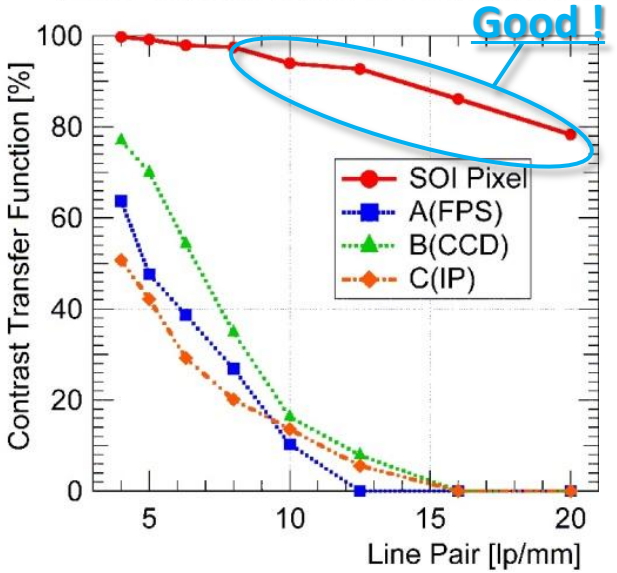
Spatial Resolution

- Comparison of contrasts with commercial X-ray devices.
  - SOI Pixel : INTPIX4, **F**lat **P**anel **S**ensor (FPS), CCD, and **I**maging **P**late (IP)
- **INTPIX4 shows very good sptial resolution !**







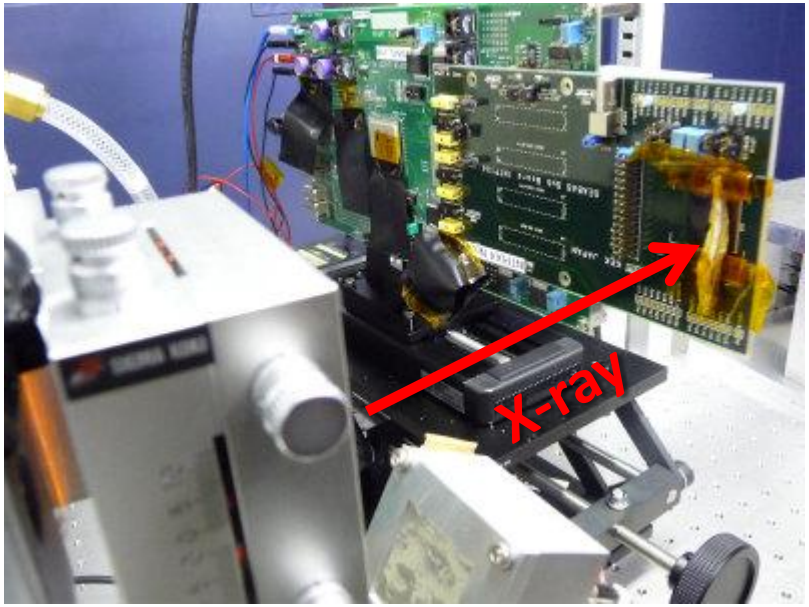


Contrast Transfer Function

INTPIX4 X-ray Imaging

- X-ray Imaging @ Room Temp.
- **Niboshi** (Japanese) : a small dried sardine

V sensor = 200 V
X-ray Tube : Mo, 20 kV, 5 mA

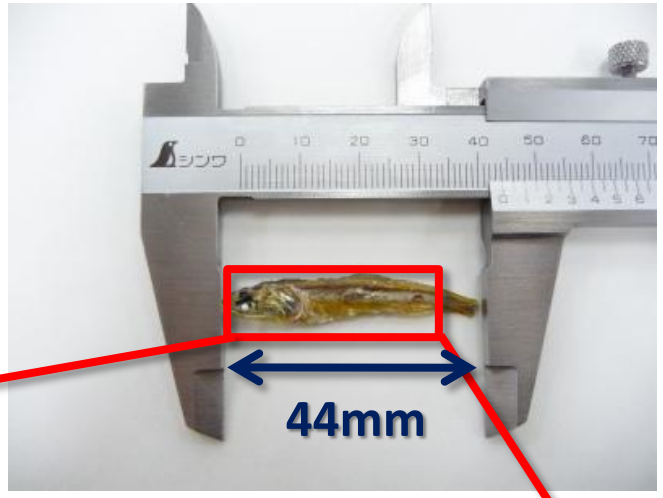


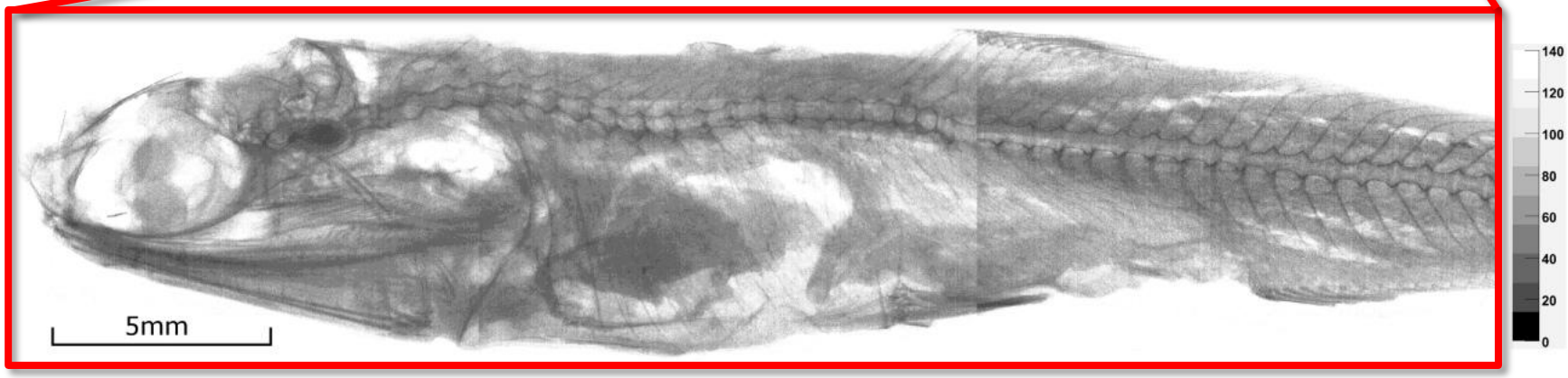
Setup for X-ray imaging taken by an INTPIX4 .

INTPIX4 X-ray Imaging

- **Fine Resolution & High Contrast !**

250 μs Int. x 500 fr
* It is clear even by 100 fr.
** It depends on the number of photons.





X-ray Imaging of a small dried sardine taken by an INTPIX4 (3 images are combined).

Summary

- We have developed a monolithic pixel detector with a 0.2 μm FD - SOI CMOS technology.
- The Integration-type SOIPIX worked successfully.
  - INTPIX4 : 17 μm□, 426 k pixels

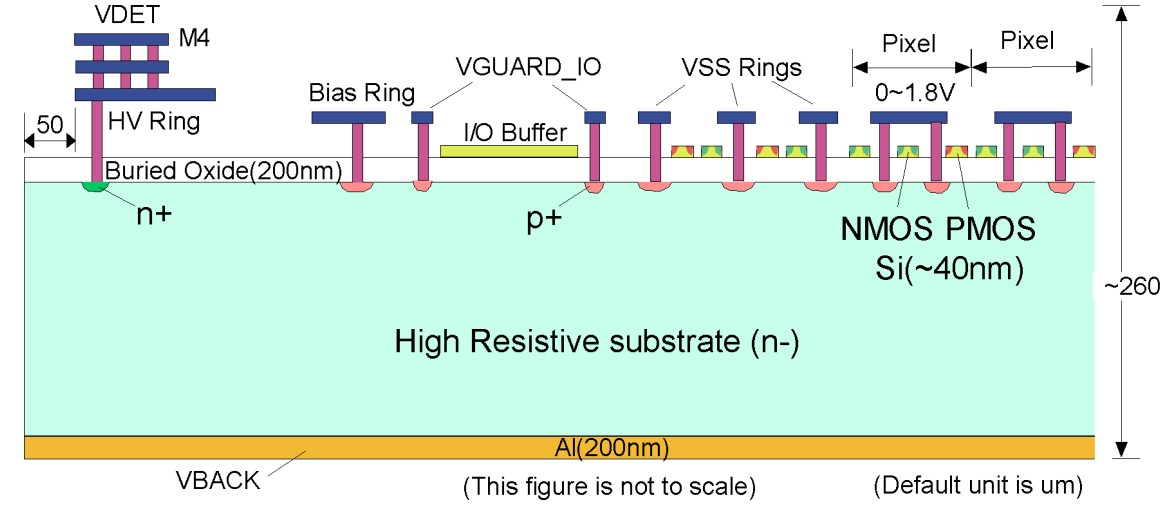
INTPIX4

- Energy Resolution -> FWHM 13.4 % @ 14 keV.
- Sensor capacitor is 10 fF.
- The CDS circuit is operated successfully. (kTC noise suppress)
- INTPIX4 shows very good spatial resolution.
  - CTF : 78 % @ 20 lp/mm.
- We succeeded in acquiring the clear X-ray image @ Room Temp.

BACKUP

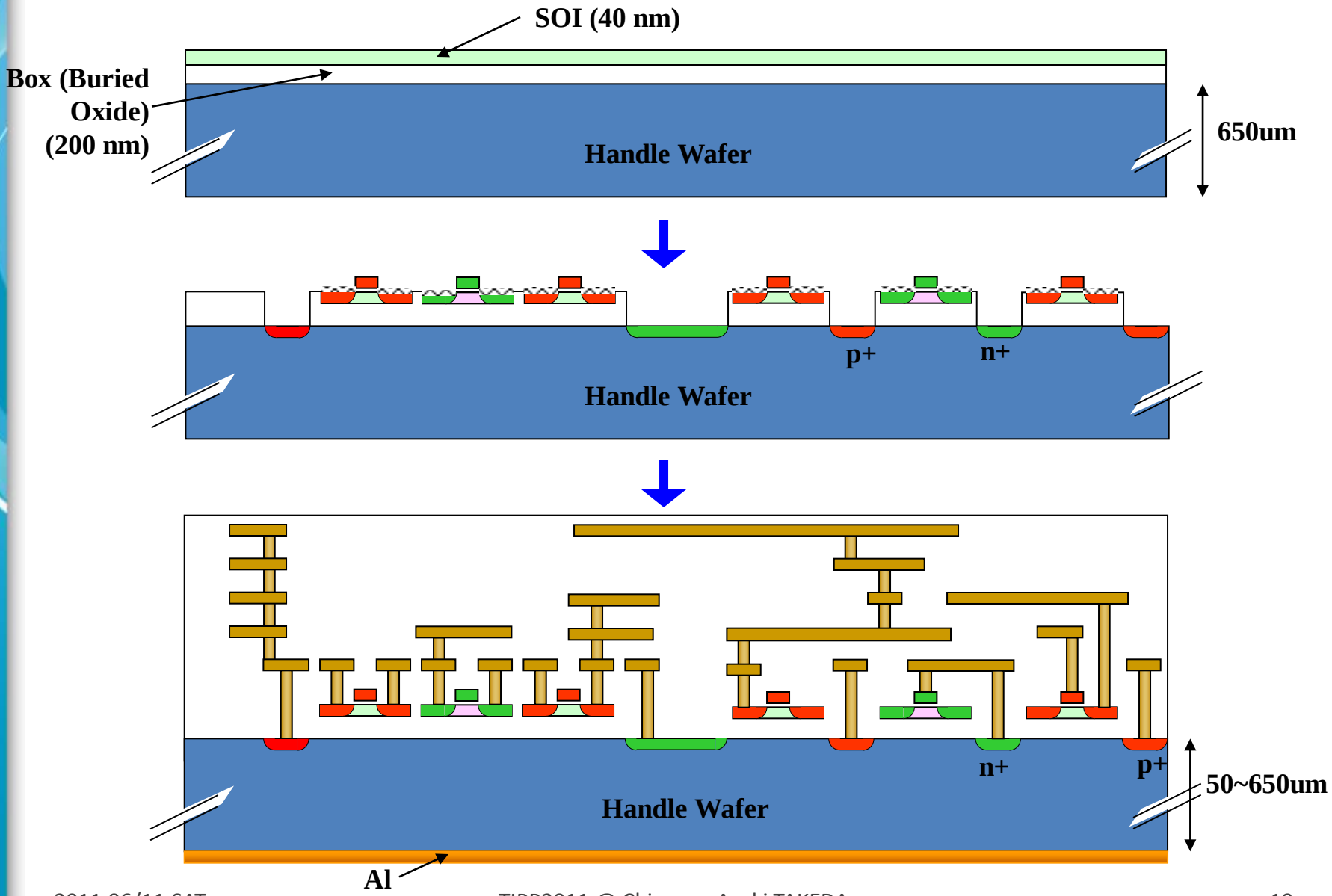
OKI 0.2 μm FD-SOI Pixel Process

Process	0.2μm Low-Leakage Fully-Depleted SOI CMOS (OKI) 1 Poly, 4 (5) Metal layers, MIM Capacitor, DMOS option Core (I/O) Voltage = 1.8 (3.3) V
SOI wafer	Diameter: 200 mmϕ, Top Si : Cz, ~18 Ω-cm, p-type, ~40 nm thick Buried Oxide: 200 nm thick Handle wafer: Cz ~700 Ω-cm (*n-type*), 650 μm thick
Backside	Thinned to 260 μm and sputtered with Al (200 nm).



An example of a SOI Pixel cross section

SOI Pixel Process Flow



Comparison of Spatial Resolution

- INTPIX4 was compared with commercial X-ray devices :

X-ray Flat Panel Sensor (FPS)
Specification:
CMOS APS
Scintillator : CsI
Effective area : 52.8 x 52.8 mm^2
# of pixels : 1032 x 1032
Pixel size : 50 μm□
RMS noise : 80 e-
Minimum exposure time : ~ 0.4 sec
Full well : 450000 e- / pixel
Effective Dynamic Range : ~ 14 bit
Frame rate : 3 fps
14 bit digital output
Application : X-ray diffraction

Fiber-coupling X-ray CCD
Specification:
Fiber-coupling CCD 3.57 : 1
Scintillator : Gadox
# of pixels : 1392 x 1040
Effective Pixel size : ~ 24 μm□
RMS noise : 3.5 ADU
Minimum exposure time : ~ 30 msec
Full well : 225000 e- / pixel
Effective Dynamic Range : ~ 14 bit
16 bit full image with fusion made @ 20 MHz
Application : Phase-contrast imaging, etc ...

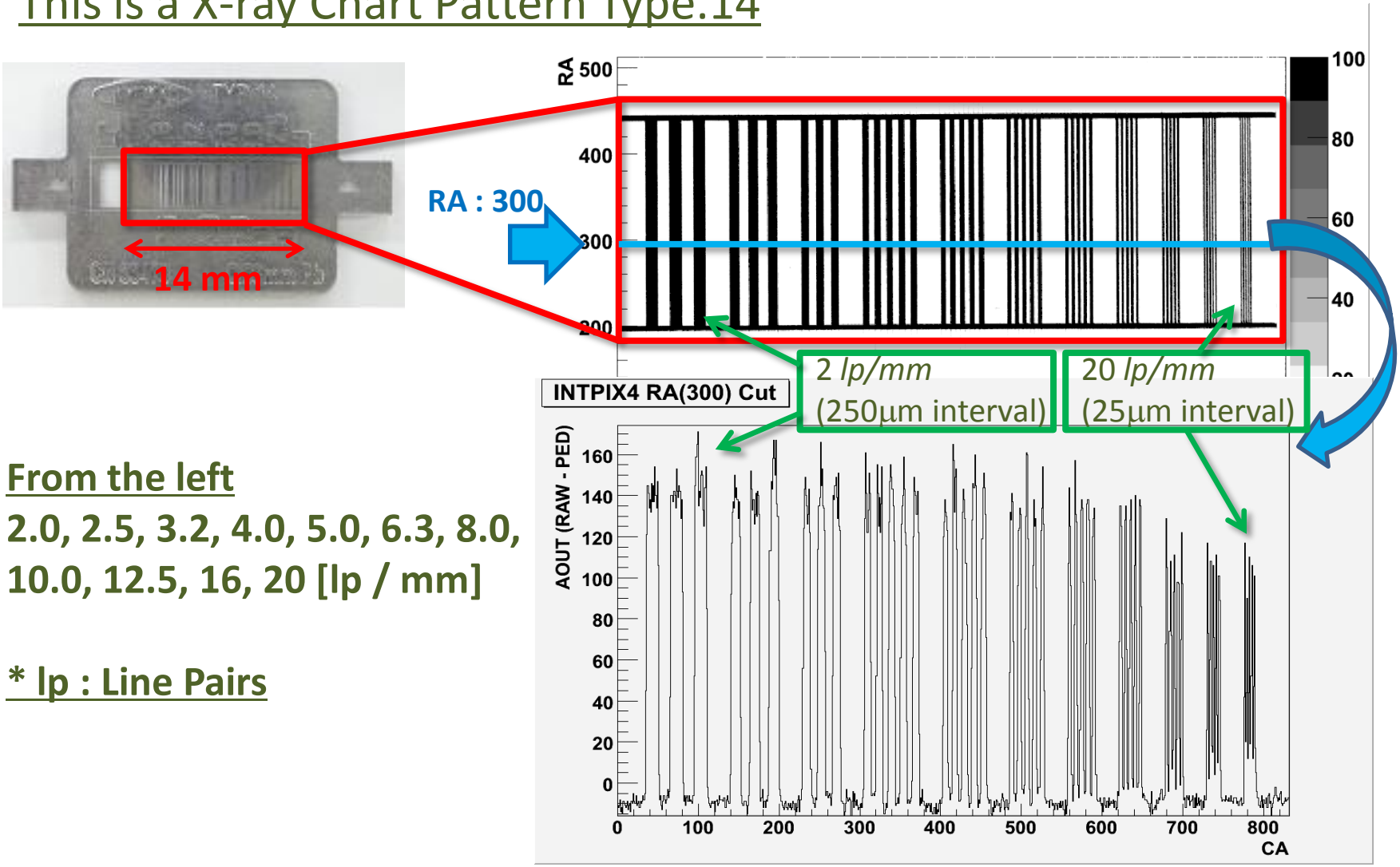
Comparison of Spatial Resolution

- INTPIX4 was compared with commercial X-ray devices :

Imaging Plae (IP)
Specification:
Photostimulatble phosphor (PHP) Plate
Effective area : 20 x 25 cm^2 (Reusable)
Pixel size : 50 μm□ / 100 μm□ / 200 μm□
RMS noise : 65,536 / 256
Effective Dynamic Range : 4 digit / 5 digit
Sensitivity : S = 1,000 / 4,000 / 10,000 / 30,000
Readout time : ~5min.

X-ray Chart Pattern

This is a X-ray Chart Pattern Type.14



From the left

2.0, 2.5, 3.2, 4.0, 5.0, 6.3, 8.0, 10.0, 12.5, 16, 20 [lp / mm]

*** lp : Line Pairs**