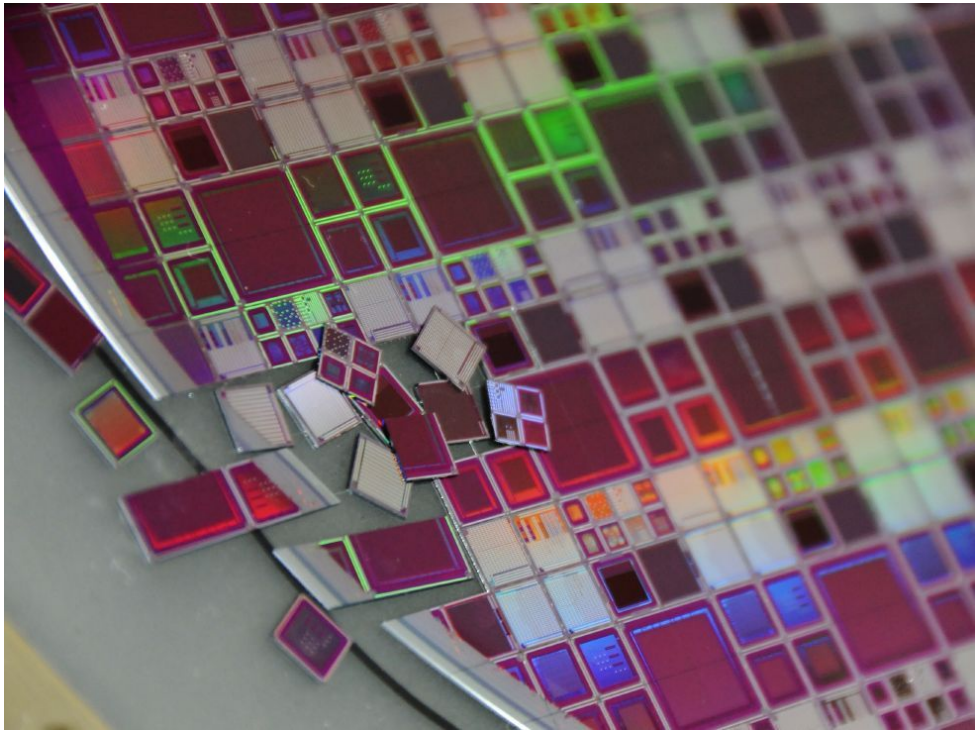
Performance Tests of SOI Pixel Detectors



三好　敏喜
MIYOSHI, Toshinobu
(KEK,
高エネルギー加速器研究機構
高能加速器研究機構
)

2013.2.1 @ IHEP

Outline

- Development history
- Performance test results of

1. DIPIX
2. INTPIX3e
3. FPIX
4. INTPIX5
5. INTPIX4
6. Double SOI sensors

- Summary

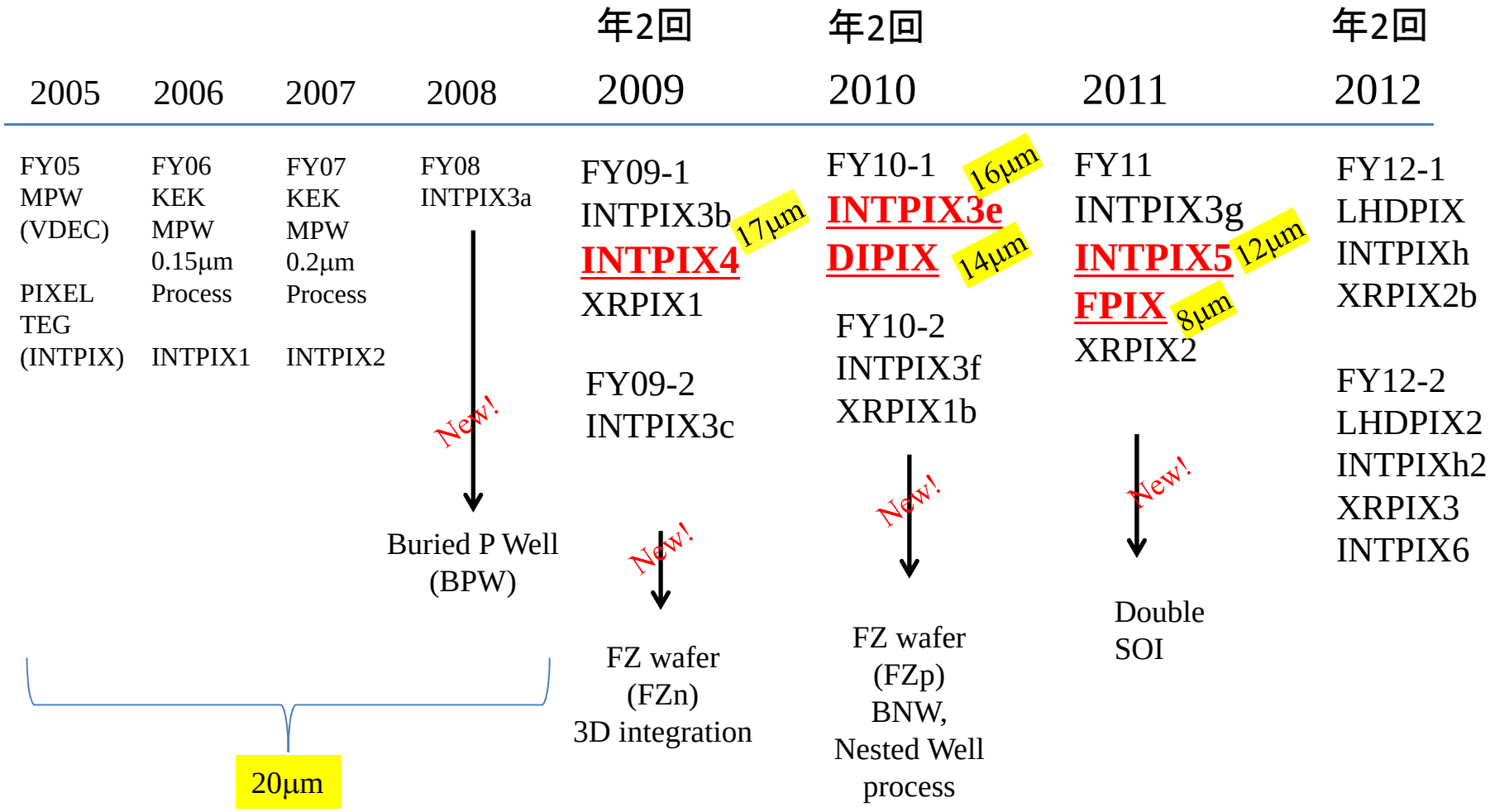
Topics

Spatial resolution
Gain
Noise/Energy resolution
Quantum efficiency
Readout method – static/movie
Front/back illumination
Partial/full depletion
High energy beam test
Visible light, IR, X-ray test

開発歴史

Development history: SOI Integration type pixel detector

KEK is working on integration-type and counting-type / digital (binary) pixel detectors



* Only integration-type detectors are shown

Pixel size

Wafers

Process	Chip name	Wafer			
		HR1(CZn) 700 Ω cm	FZn > 2 kΩ cm		FZp 25 kΩ cm
	Bulk thickness	260um	260um	500um	500um
MX1350	INTPIX4	O	O	O	-
MX1413	INTPIX3e	O	-	O	-
	DIPIX1&2	O	-	O	O (DIPIX2)
MX1501	INTPIX5	O	-	O	-
	INTPIX3g	O	-	O	O
	XRPIX2	O	-	O	-
	FPIX1&1P	O	-	O	O (FPIX1P)
		低抵抗		高抵抗	

O available

- Not fabricated or can not be used

Double SOI MX1501(MPW FY11), MX1542(MPW FY12-1), & MX1594(FY12-2)

2重SOI基板

Summary of INTPIX specification

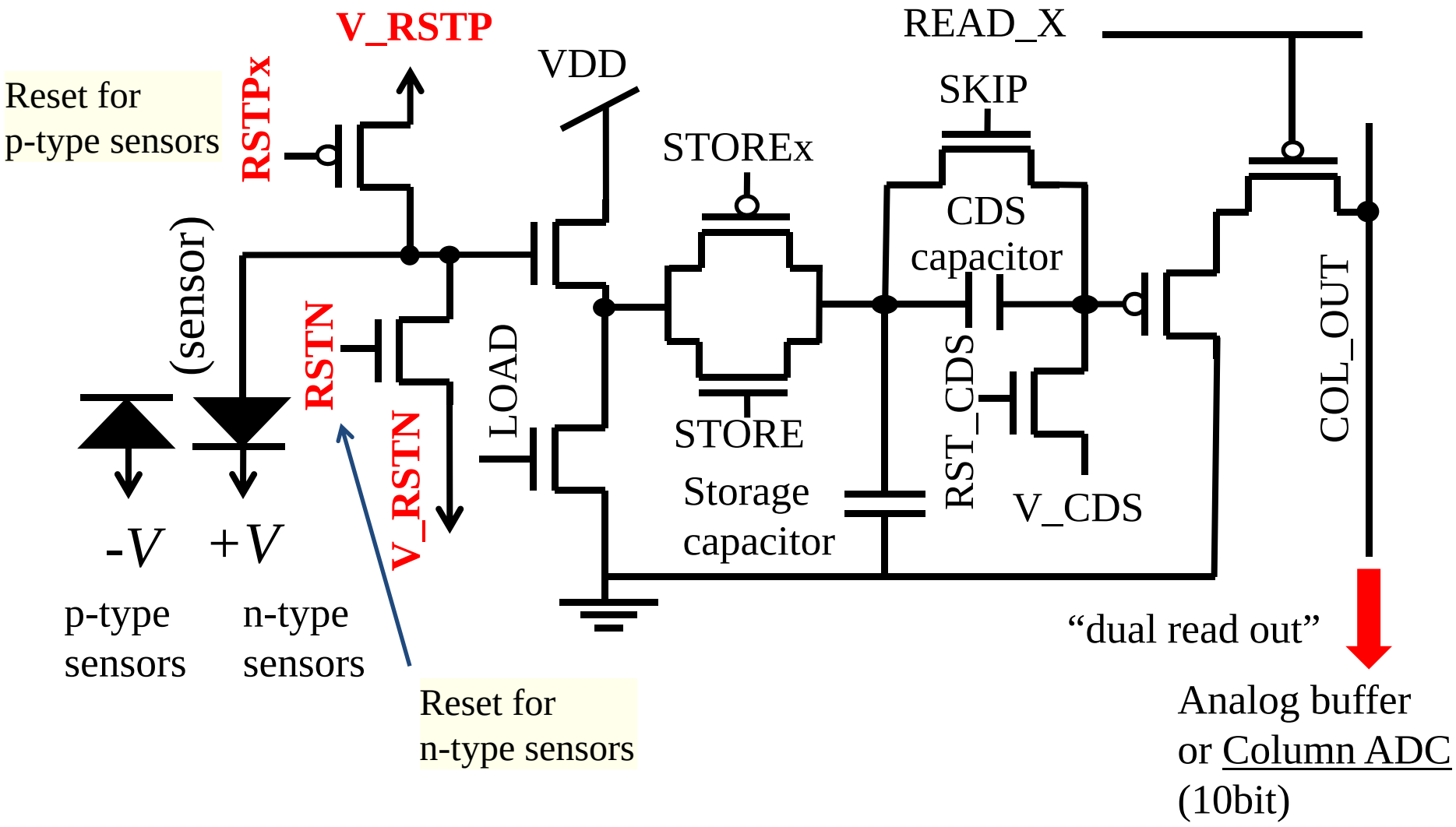
	pixel size [μm]	# of pixels	Effective Area [mm]	Chip area [mm]	Readout Mode	On-chip ADC output
INTPIX4	17 x 17	832 x 512	14.144 x 8.704	15.3 x 10.2	1serial / **13 parallel output**	No
INTPIX3e	16 x 16	192 x 192	3.072 x 3.072	5 x 5	1 serial output	No
DIPIX1&2	14 x 14	256 x 256	3.584 x 3.584	5 x 5	1 serial output	**Yes (10bit)**
FPIX1&1P	8 x 8	512 x 512	4.096 x 4.096	6 x 6	1serial/8 parallel, or rolling shutter mode	No
INTPIX5	**12x12**	**1408 x 896**	**16.896 x 10.752**	**18.3 x 12.2**	1 serial / 11 parallel output	No
INTPIX3g	18x18	256 x 256	4.608 x 4.608	6 x 9	1 serial or 4 parallel with storage cap. or semi rolling shutter mode	No

Performance test results of SOI detectors

1. **DIPIX**
2. INTPIX3e
3. FPIX
4. INTPIX5
5. INTPIX4
6. Double SOI

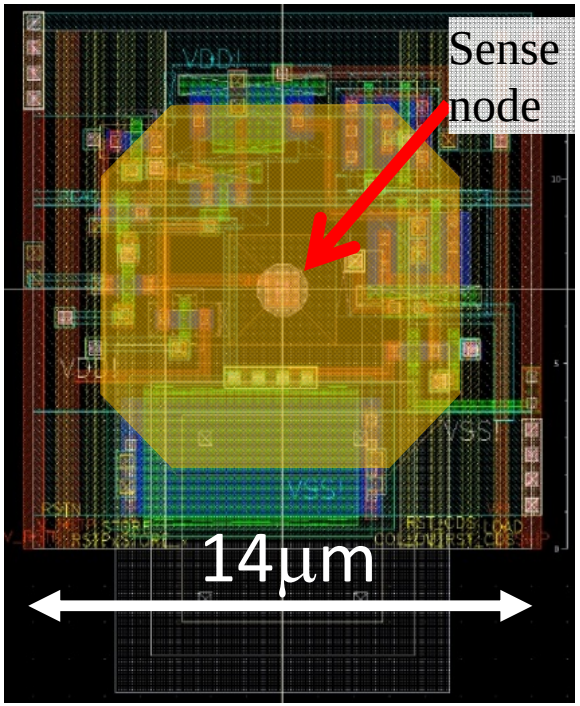
DIPIX1&2(dual-mode integration type pixel)

Pixel circuit 画素回路



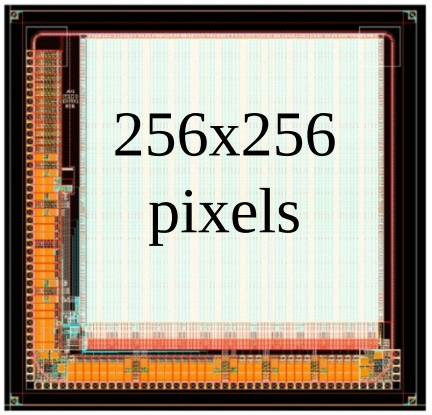
DIPIX pixel layout

Pixel layout

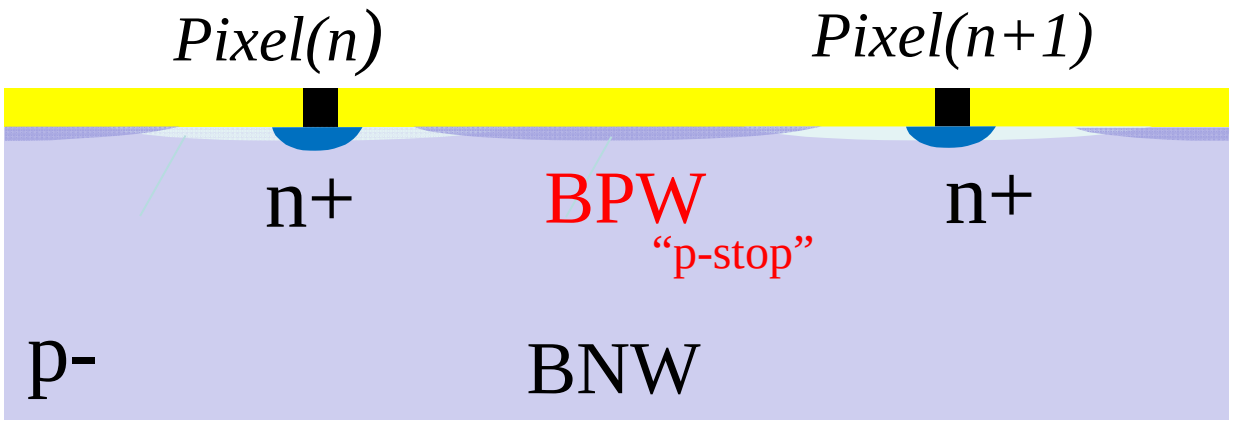


* N-type wafer
* P-type wafer
→ PN diodes receive electrons
→requires “p-stop”

Chip layout



断面図
Side view of DIPIX2b (n-in-p)



How to process: p-n implant are reversed each other :

DIPIX1 n-type: “deep” BPW [BPW+BP2]
←→p-type: “deep” BNW [BNW+BN2]

DIPIX2 n-type: BPW only and BPW & BNW[(256x128) x 2]
←→p-type: BNW only and BNW & BPW

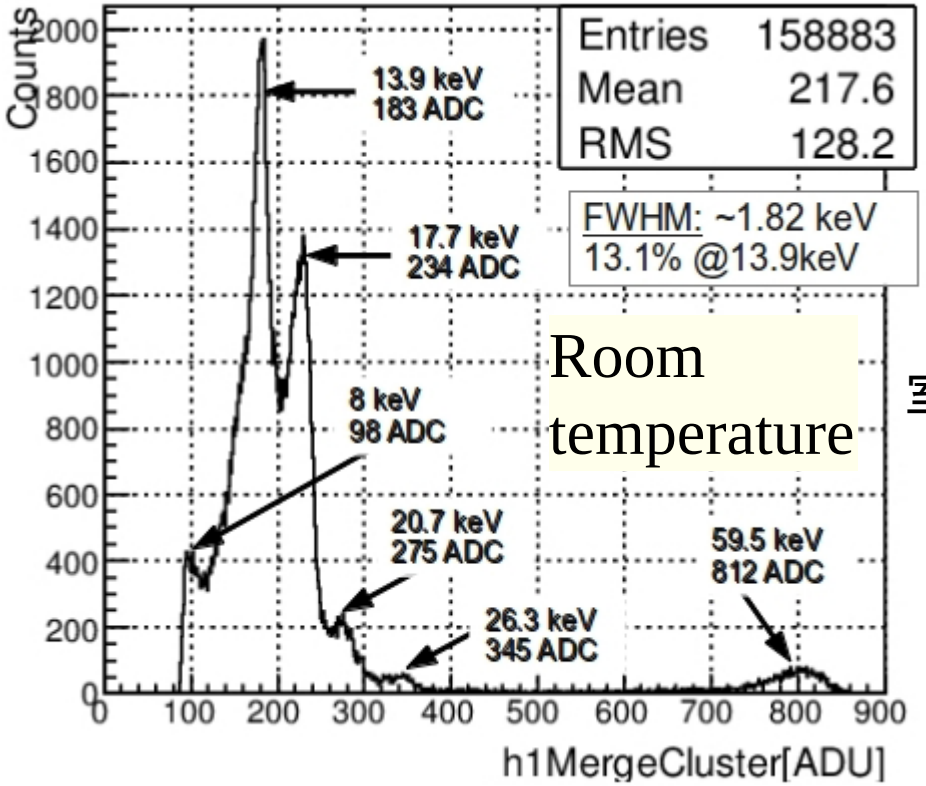
Analog output test

Am-241 source test @ Krakow

M. I. AHMED (Krakow)

Am-241 10 mCi (=370 MBq)
Radiation data

Type	Energy [keV]
Am-241 X-ray	59.5
Am-241 X-ray	26.3
Am-241 X-ray	13.9
Cu L X-ray	8.01
Np L X-ray	17.7
Np L X-ray	20.7



X-ray spectrum (Single pixel cluster only)

Condition
Integration time 100us
back-bias 80 V
Pedestal run 500 +5000 frames

Results
Noise ENC 85 e-
FWHM ~ 1.82keV : 13.1%@13.9keV
Gain 12 uV/e-

Digital output test

P. Kapusta (Krakow)

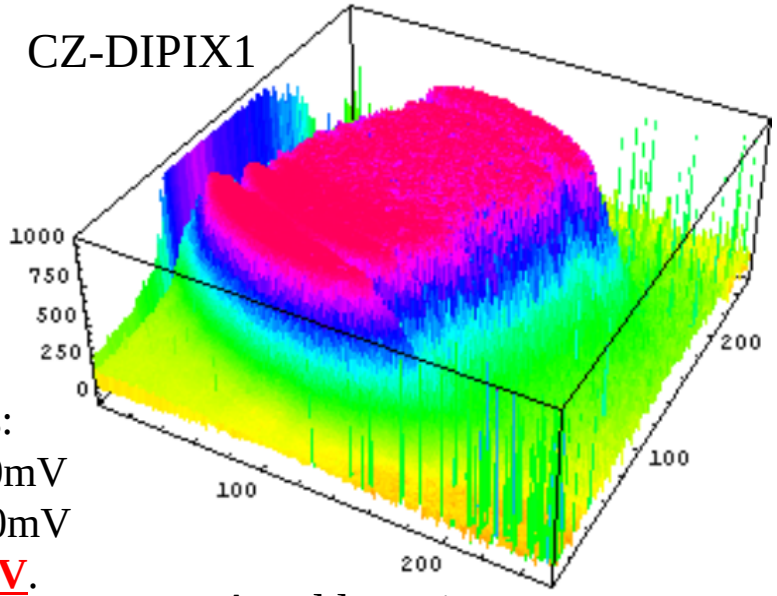
Column ADC

CZ-DIPIX1

Operational condition

I_{RG}=0.67uA, I_{RGSF}=5.2uA, ADC_CLK=50MHz

Conversion time 30 us for 50MHz clock
@1.8V limit (core supply),
Ramping capacitance 9.9 pF, and
Ramping current 0.67uA



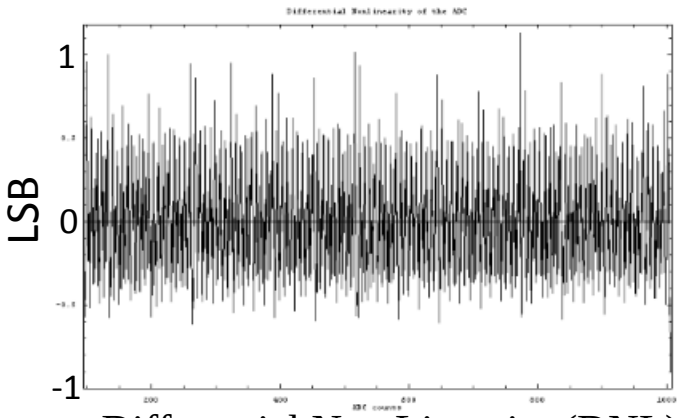
A red laser image

Parameters:
V_{RSTN}=750mV
V_{IPIX}=1800mV
VDET=50V.

Linearity

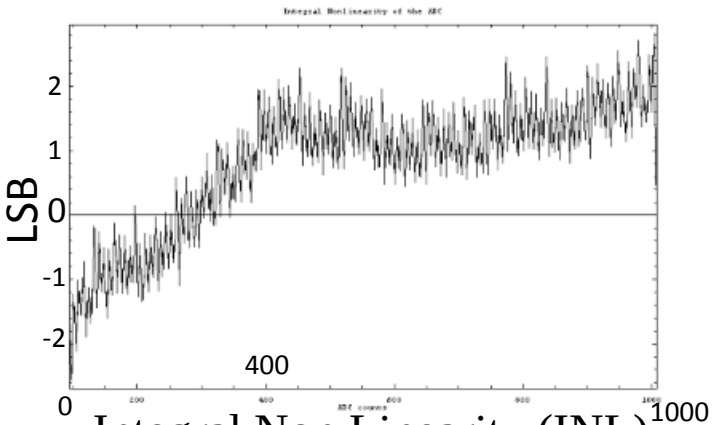
Input signal 720-1780mV(~1V) : ADC 94-1008(10bit).

DNL: -0.95 LSB to 1.13 LSB



Differential Non Linearity (DNL)

INL: -2.6 LSB to 2.8 LSB



Integral Non Linearity (INL)

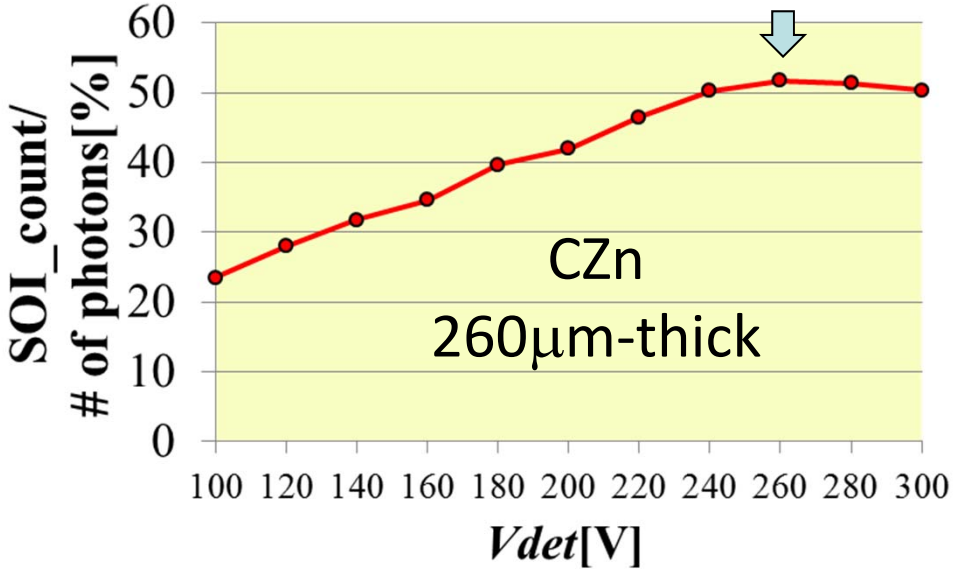
Full depletion study (CZn)

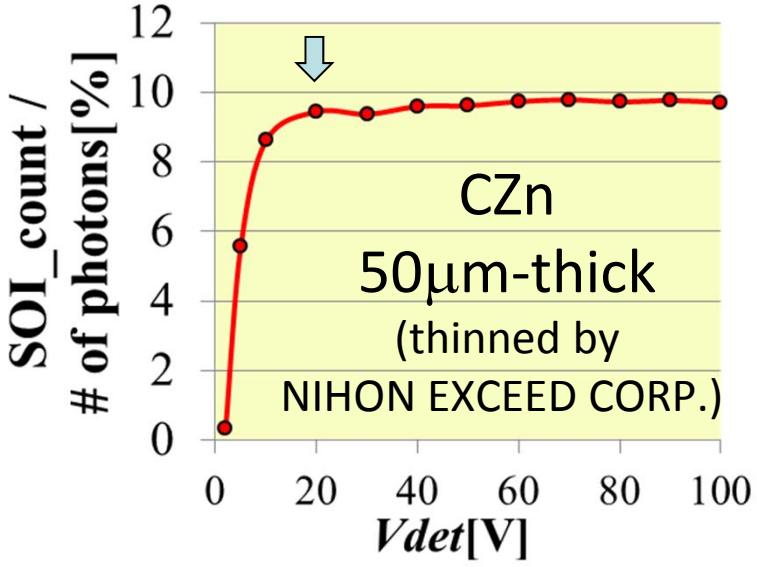
@KEK-PF BL-14A, 17.48keV X-ray

Back illumination

裏面照射

DIPIX2 p-in-n sensors





Full depletion voltage ~260V @ 260um sensor

全空乏化電圧 **~20V @ 50um sensor**

Performance test results of SOI detectors

1. DIPIX
2. **INTPIX3e**
3. FPIX
4. INTPIX5
5. INTPIX4
6. Double SOI

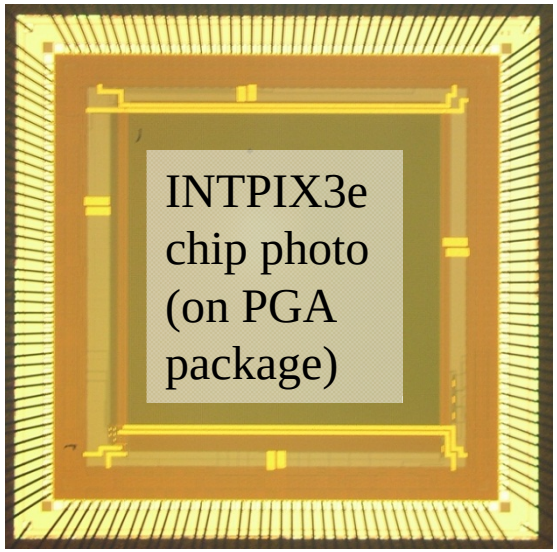
INTPIX3e

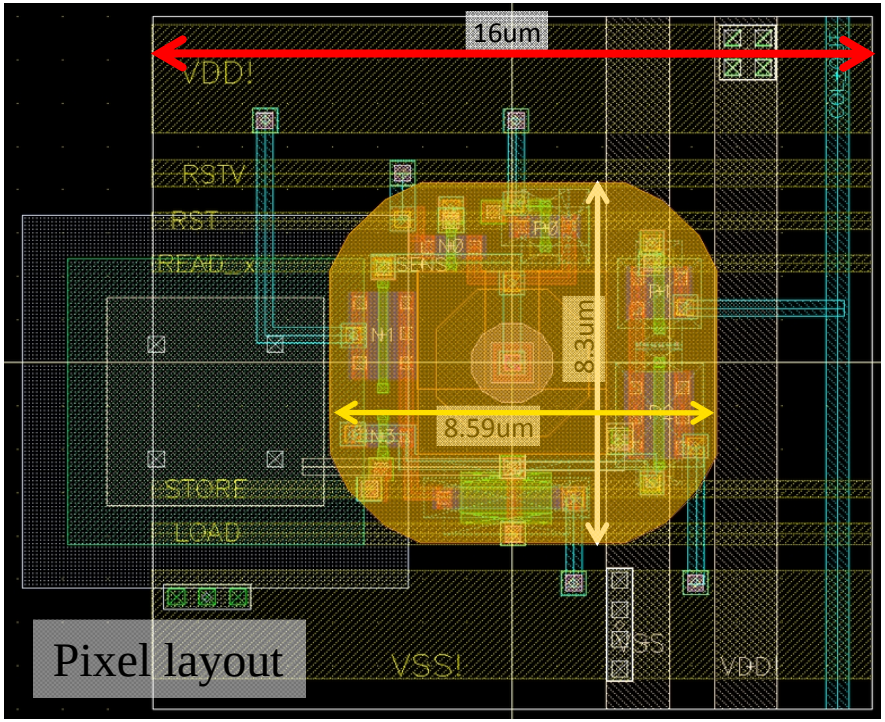
Process MPW FY10-1 MX1413

CZn and FZn wafers

5 x 5 mm square chip
Pixel size 16 x 16 um
Adopt INTPIX3b-pixel No.6
→ higher gain with smaller BPW size
# of pixels 192 x 192= 36864
Effective area 3072 x 3072 um
used for CERN beam test in 2011

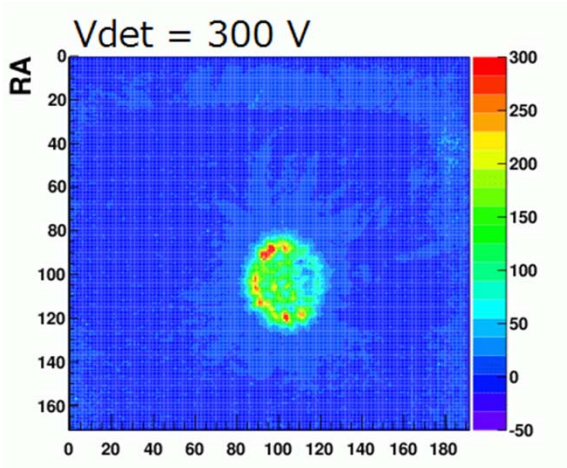
* INTPIX3A/B/C : Pixel size 20 x 20 um,
# of pixels 128 x 128 = 16384,
Effective area 2560 x 2560 um



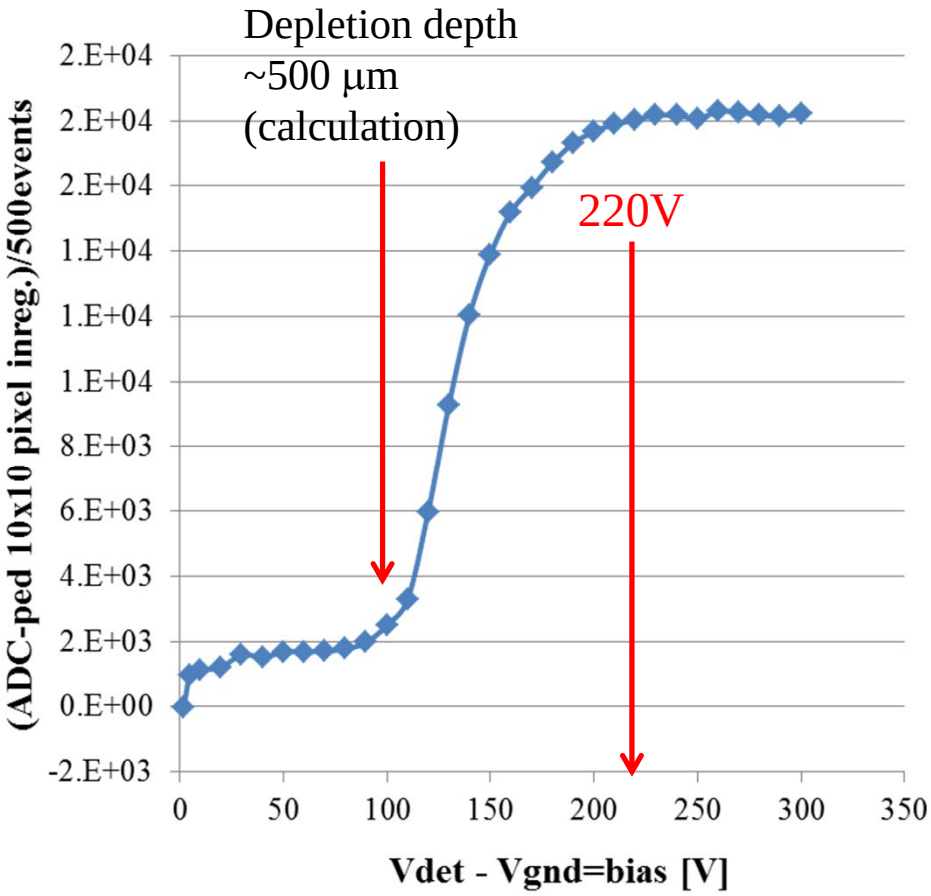


Full depletion study (FZn)

SOI sensor chip : FZn-INTPIX3e
- Resistivity ~8kΩ cm
- Bulk thickness 500 μm
- The back side open (3.1 x 3.1 mm)



Red laser was illuminated
from the back side
Red laser absorption ~ a few μm
1mmϕ Al collimator was used



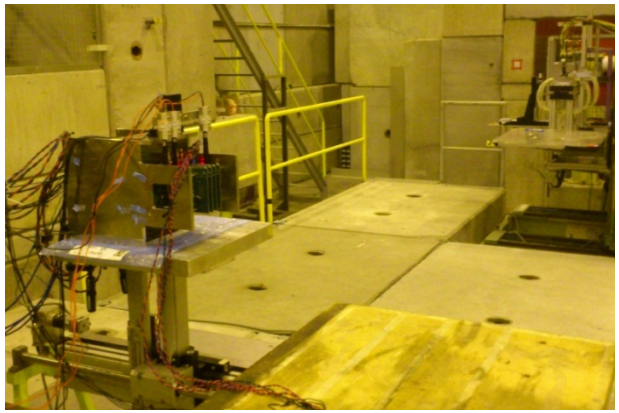
The sensor is fully depleted > 220V

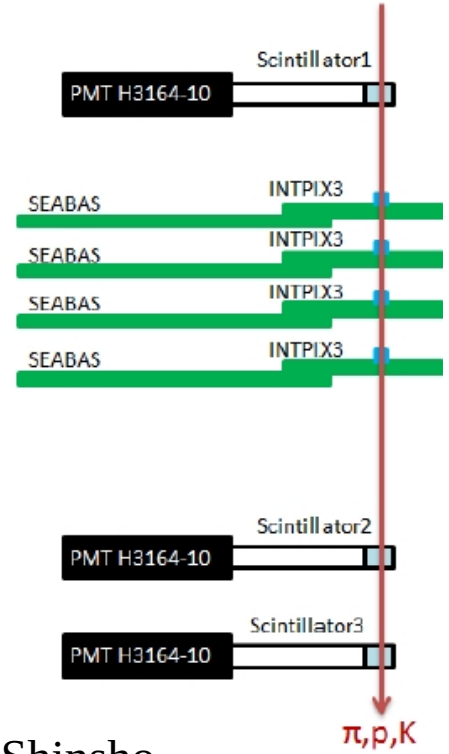
Front (表面) --- circuit
Back (裏面) --- positive voltages are applied

CERN beam test in 2011

CERN SPS NORTH H4-H6
π+ 55%, p 39%, K 5%

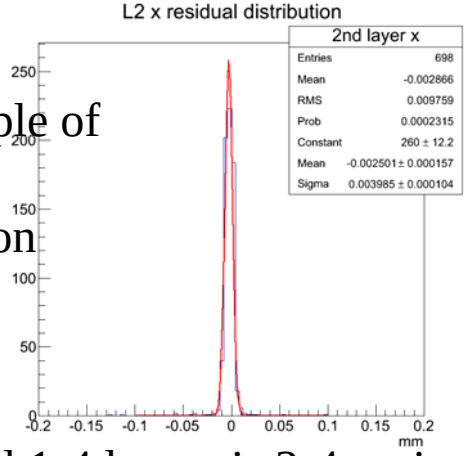
4 layers of INTPIX3e
(pixel size = 16 x 16 um)





From master thesis by Katsurayama
(Tohoku Univ.)
260um-thick CZ INTPIX3e

An example of residual distribution

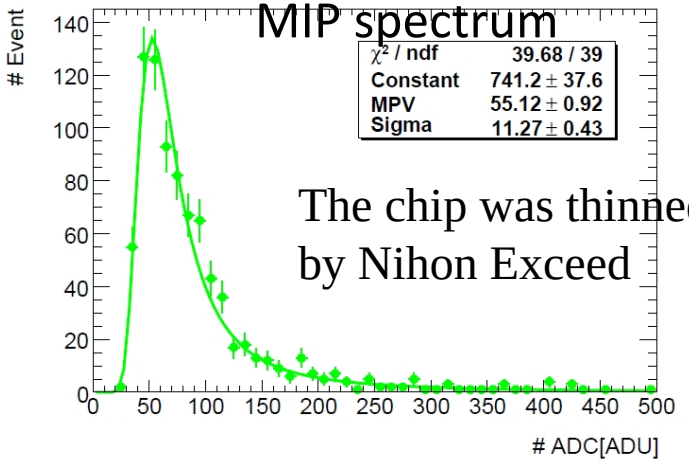


位置分解能

Residual 1-4 layers is 2-4um in σ

From master thesis by Shinsho
(Univ. of Tsukuba)

MIP spectrum



The chip was thinned by Nihon Exceed

CZ-INTPIX3e
50um-thick

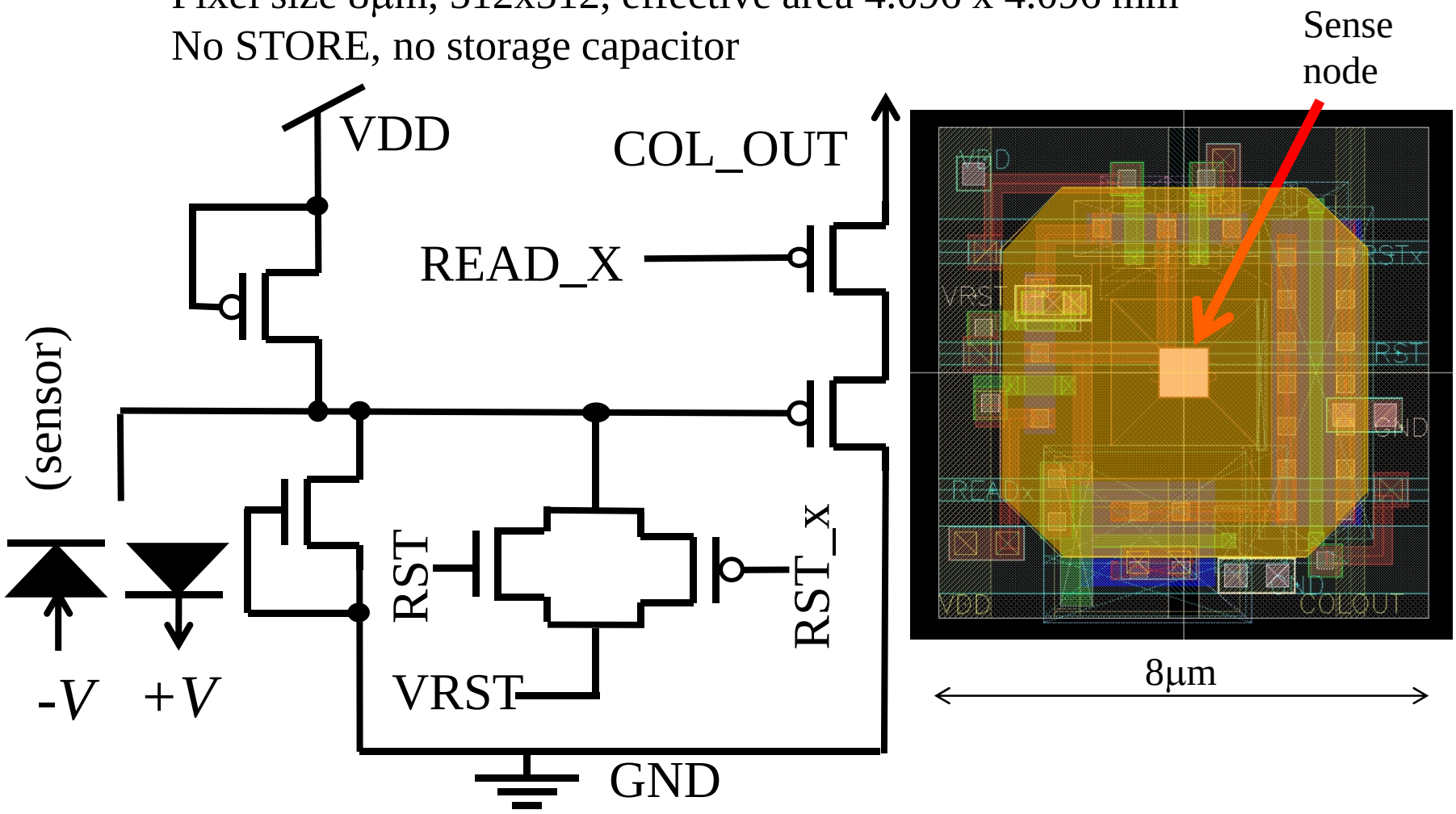
S/N ~ 15

Performance test results of SOI detectors

1. DIPIX
2. INTPIX3e
3. **FPIX**
4. INTPIX5
5. INTPIX4
6. Double SOI

FPIX1&1P

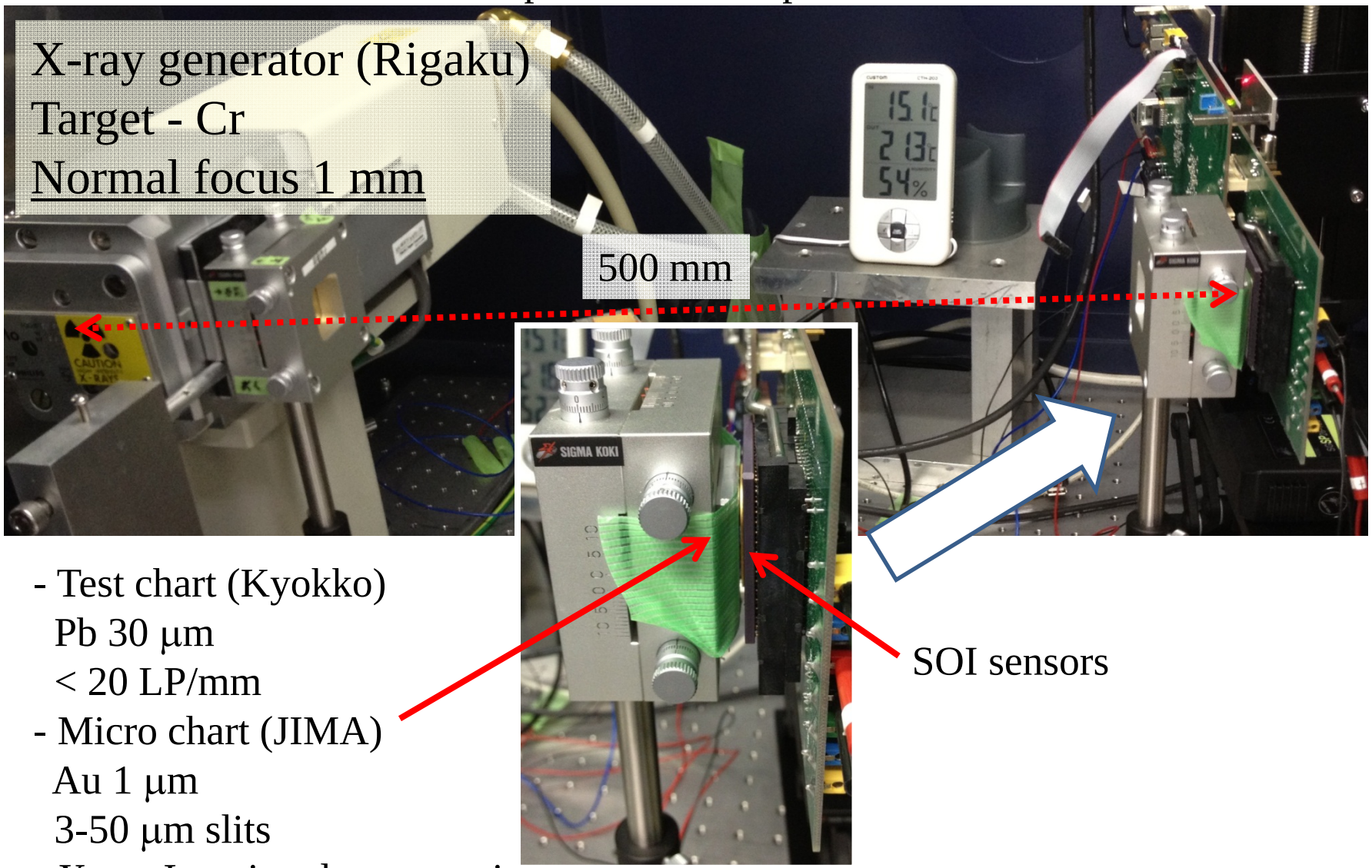
Pixel size 8μm, 512x512, effective area 4.096 x 4.096 mm
No STORE, no storage capacitor



We achieved 8 μm pixel circuit/layout

Spatial resolution study

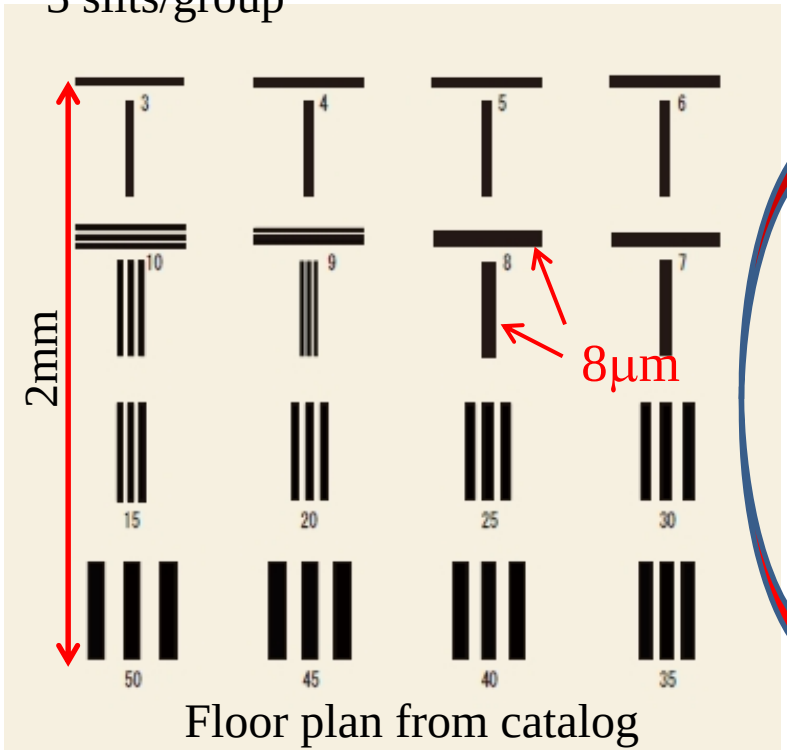
Experimental Setup



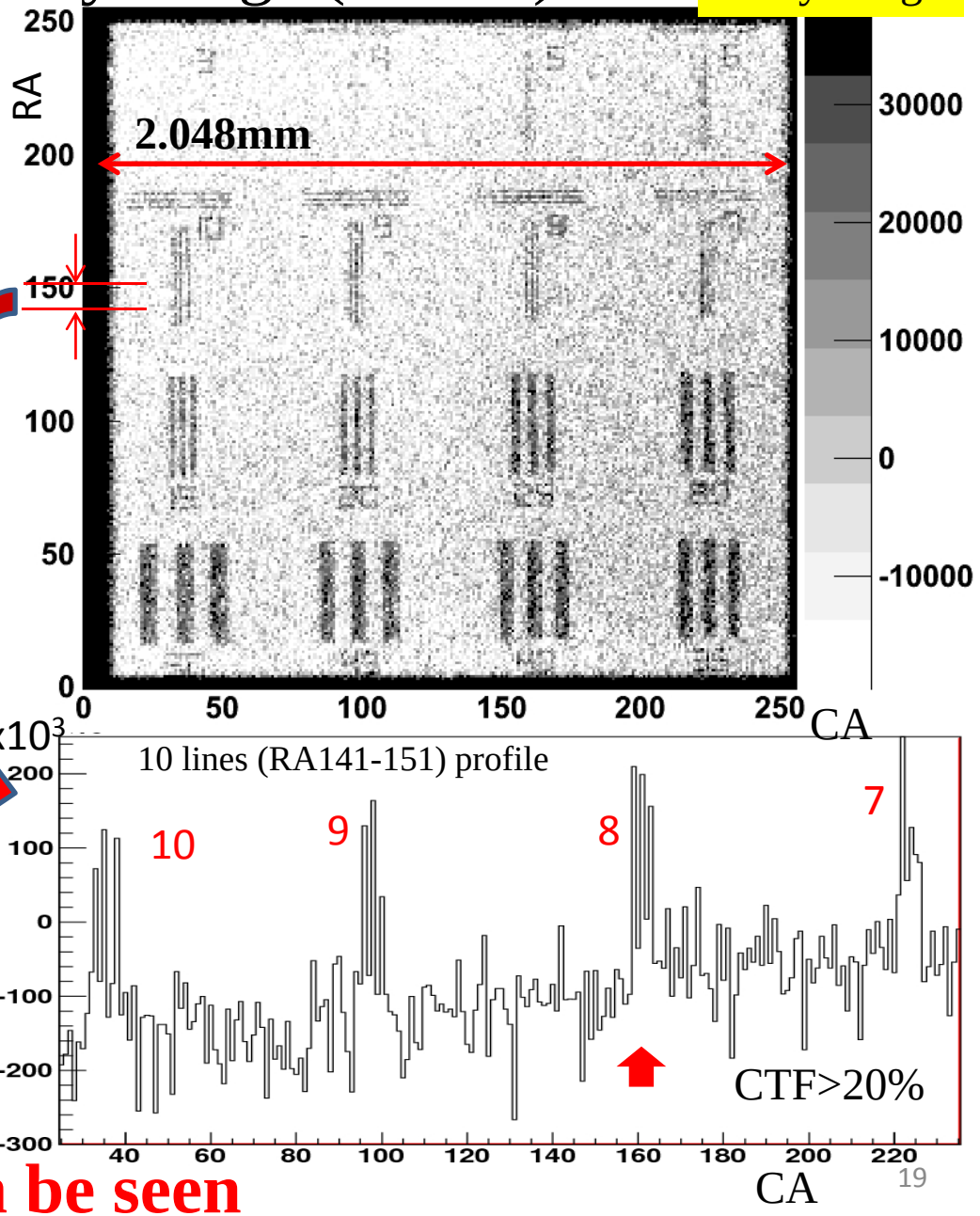
- Test chart (Kyokko)
  Pb 30 μm
  < 20 LP/mm
- Micro chart (JIMA)
  Au 1 μm
  3-50 μm slits
- X-ray Imaging demonstration

Micro chart X-ray image (FPIX1)

JIMA RT RC-05 (1μm-Au absorber)
3 slits/group



Floor plan from catalog



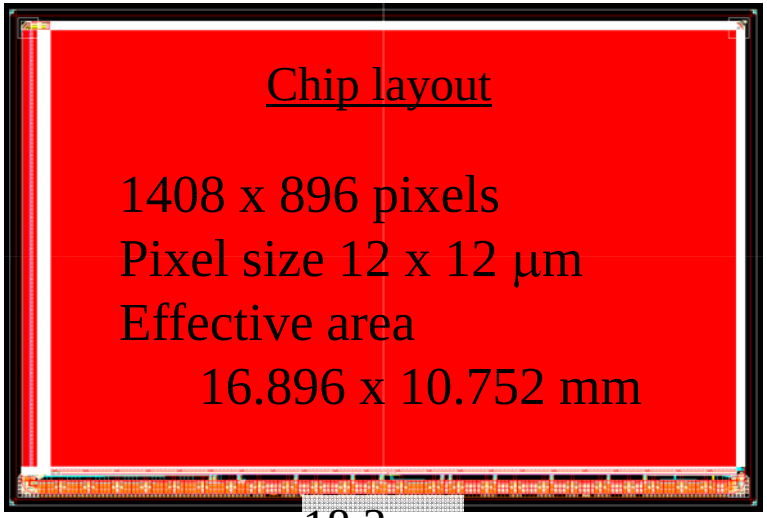
2000 event accumulation
Cr target 30kV-60mA(1.8kW MAX)
FPIX1 (CZn-260um)
Vdet=70V (partially depleted)
Temperature 15deg.

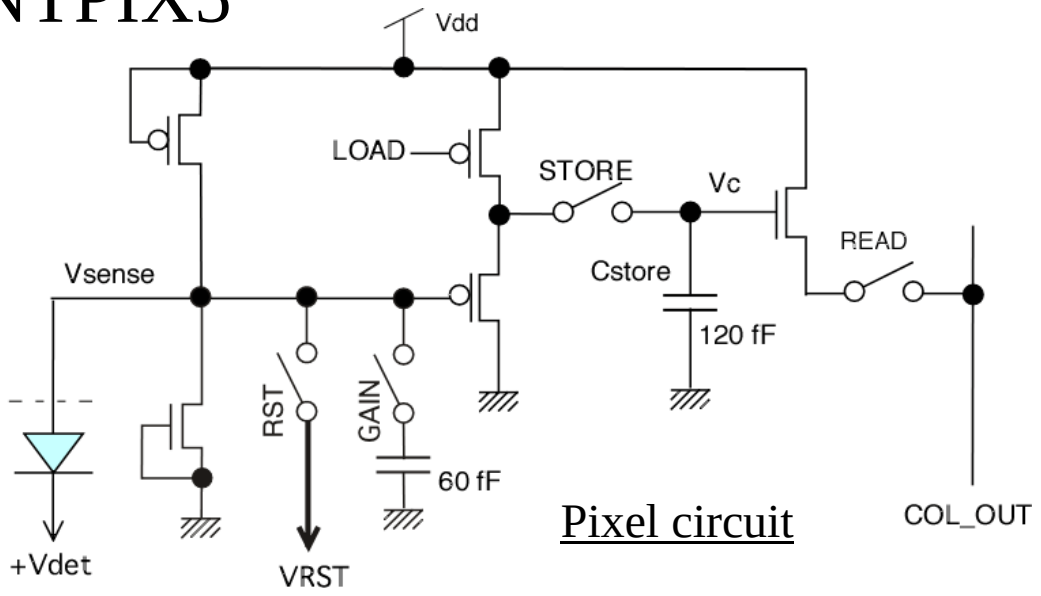
8μm lines can be seen

Performance test results of SOI detectors

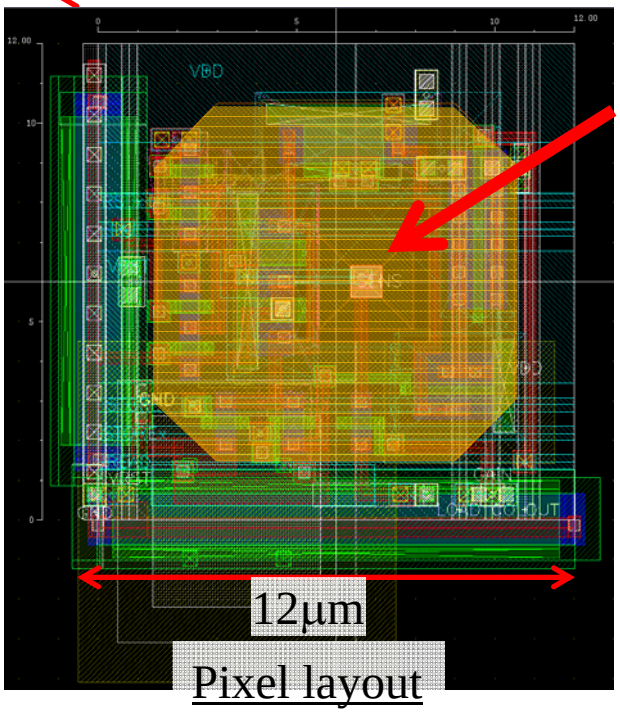
1. DIPIX
2. INTPIX3e
3. FPIX
4. **INTPIX5**
5. INTPIX4
6. Double SOI

INTPIX5



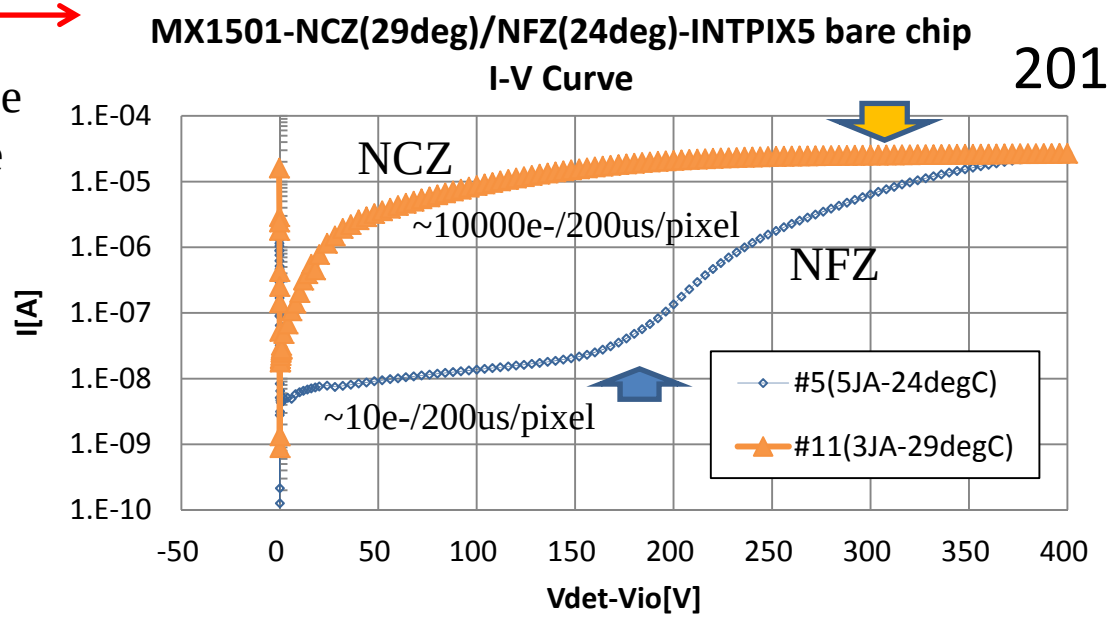


Pixel circuit



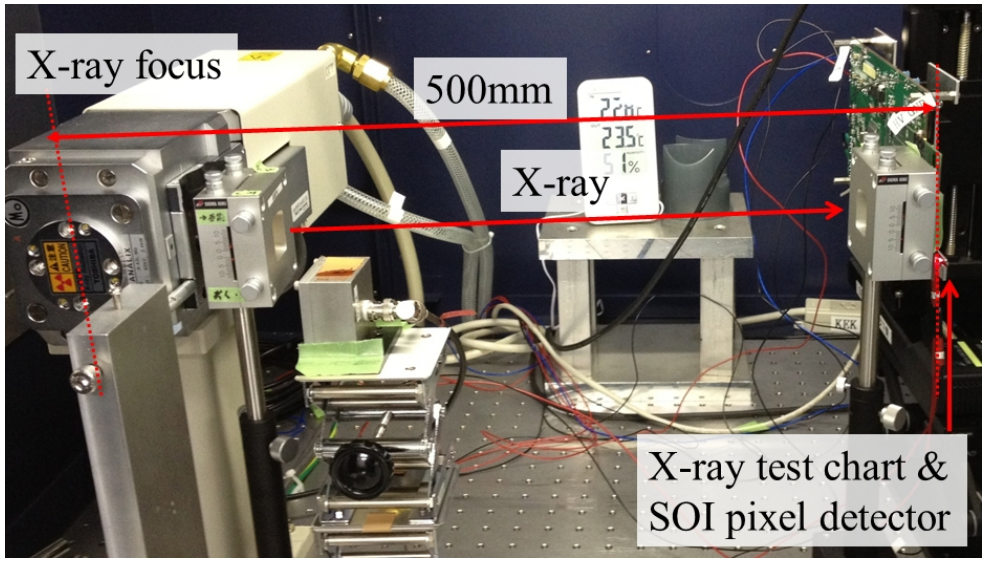
Sense node

Pixel layout



No breakdown up to 400V
Leakage current is higher for CZn-INTPIX5

Spatial resolution study

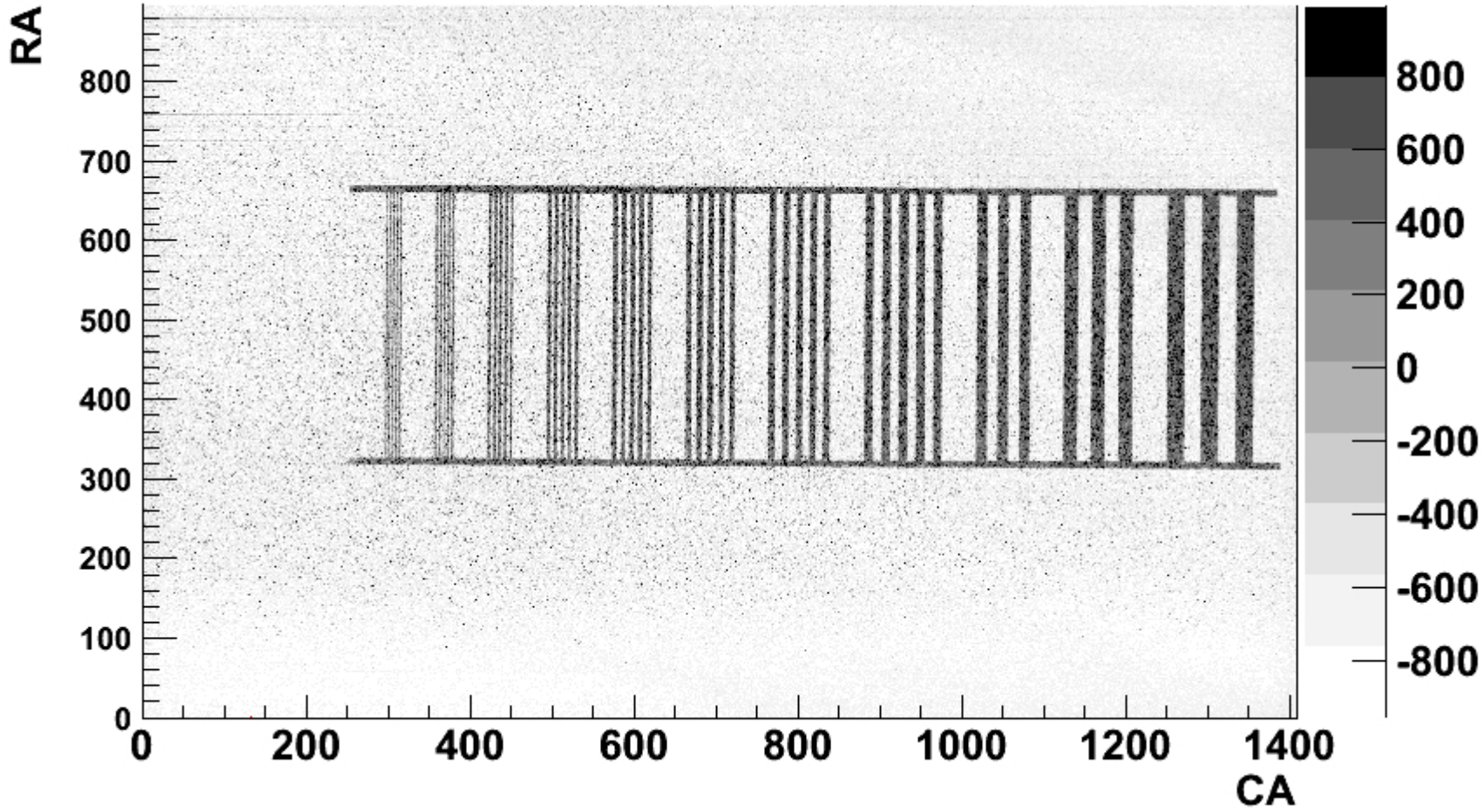


Condition
X-ray generator Cu target
Kα ~ 8 keV
Power 20kV-60mA
SOI back bias (Vdet) 160V
VIO=GND
Integration time 250us
Readout: 256x256 pixel only
# of frame 1000
→net irradiation 250ms
Front illumination

Focus – sensor distance ~500 mm
Sensor – chart distance <3mm

X-ray test chart for mammography
20 lp/mm, 5 lines, Pb 30um
Line & space every 25um
::: 8 keV-X-ray transmission in Pb 30um <1%

X-ray test chart X-ray image (INTPIX5)



Condition

Normal focus (1mm) Cu target X-ray tube

Distance between sensor and target 500 mm

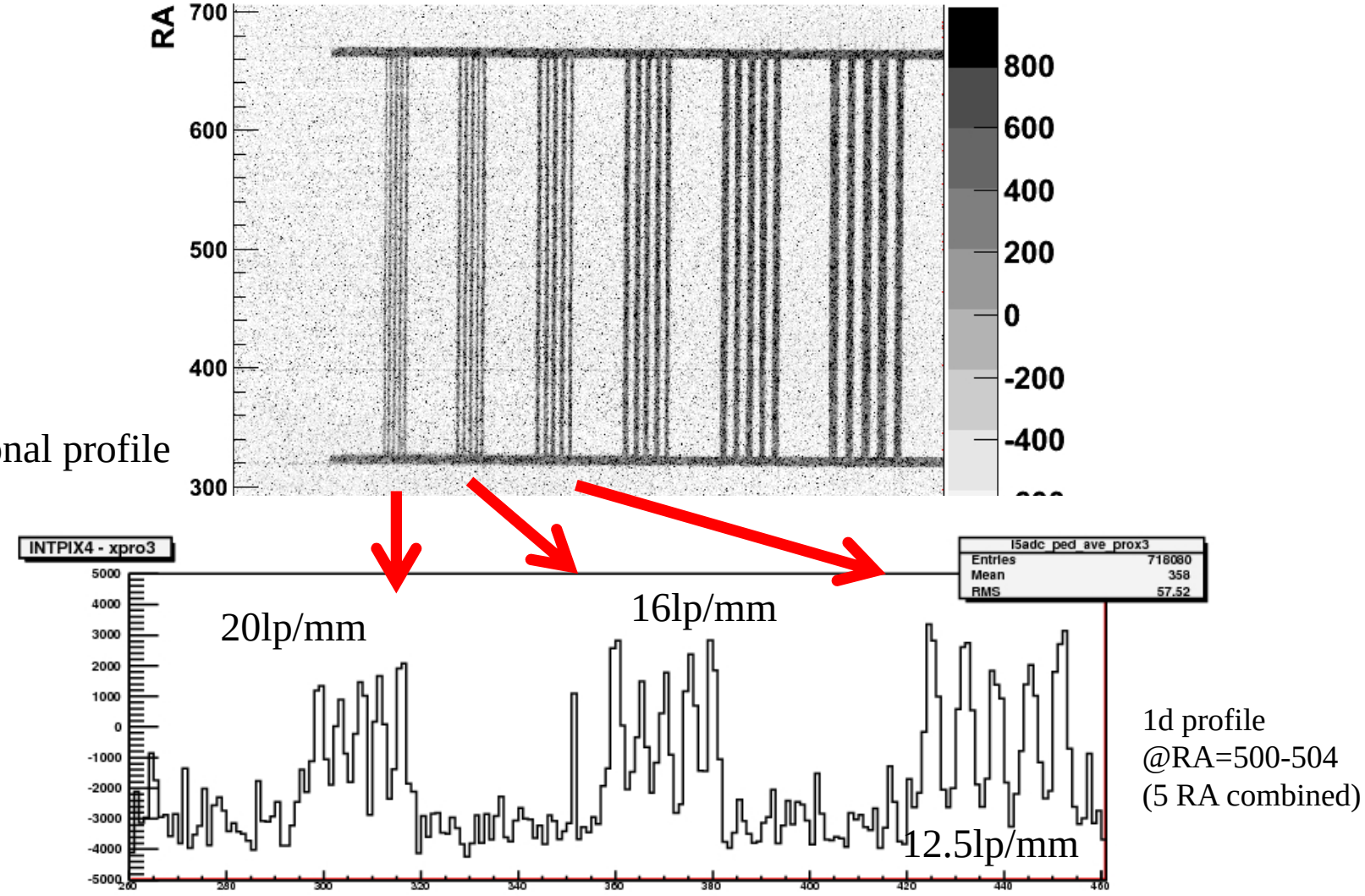
Integration time 200us x 100 shots (net 20 ms exposure)

Sensor voltage (back bias) 150V (partial depletion)

X-ray test chart X-ray image (Zoom-in & profile)

1-dimentional profile

1次元



1d profile
@RA=500-504
(5 RA combined)

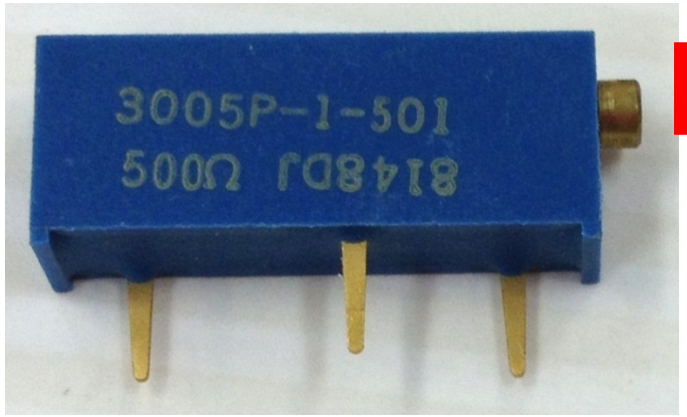
20lp/mm slits are clearly seen

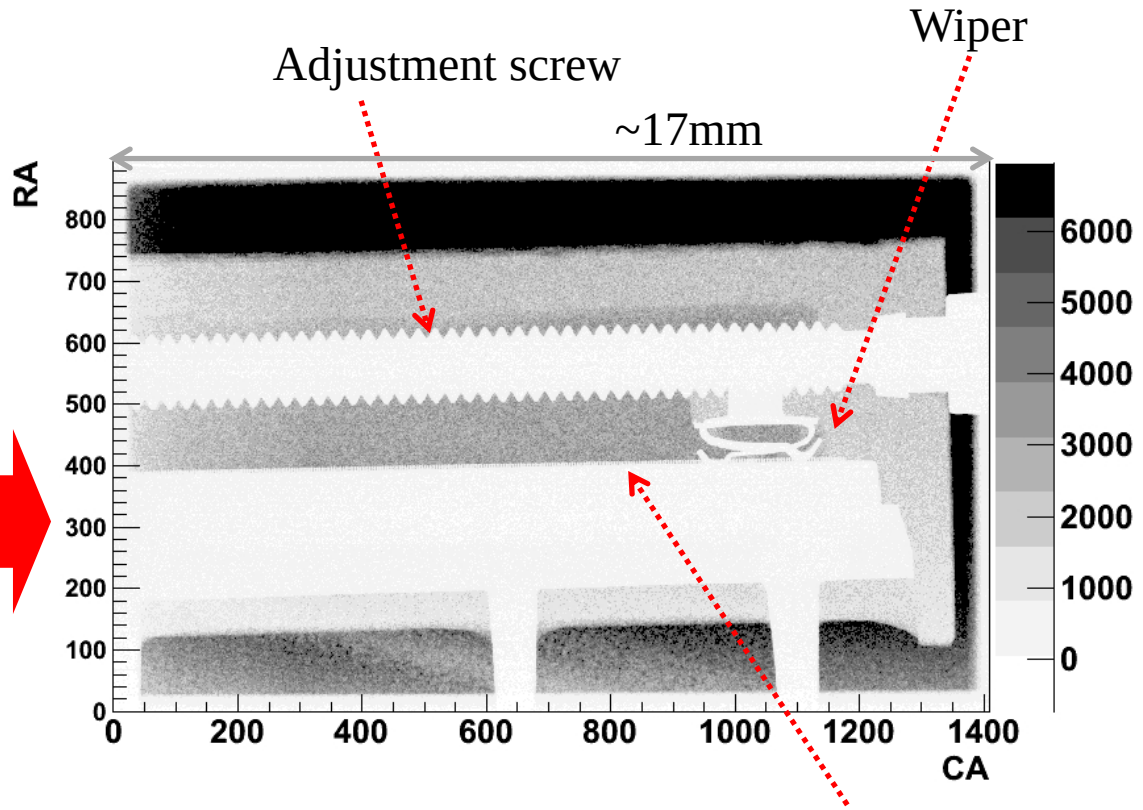
CTF ~ 80%

X-ray imaging demonstration

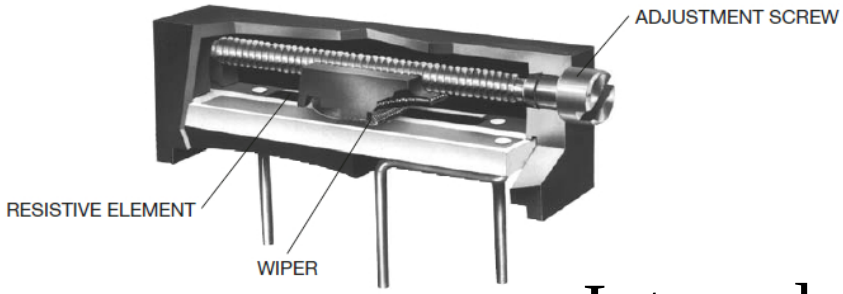
BOURNS 3005
Rectangular Trimpot
Trimming Potentiometer

半固定抵抗





INTPIX5 Back illumination
150V (partially depleted)
W: X-ray 60kV-10mA (L lines+continuous)
normal focus (1mm)
Distance 500mm
Integration time 200us x 100 shots



Schematic diagram
from catalog

Internal structure can be seen clearly

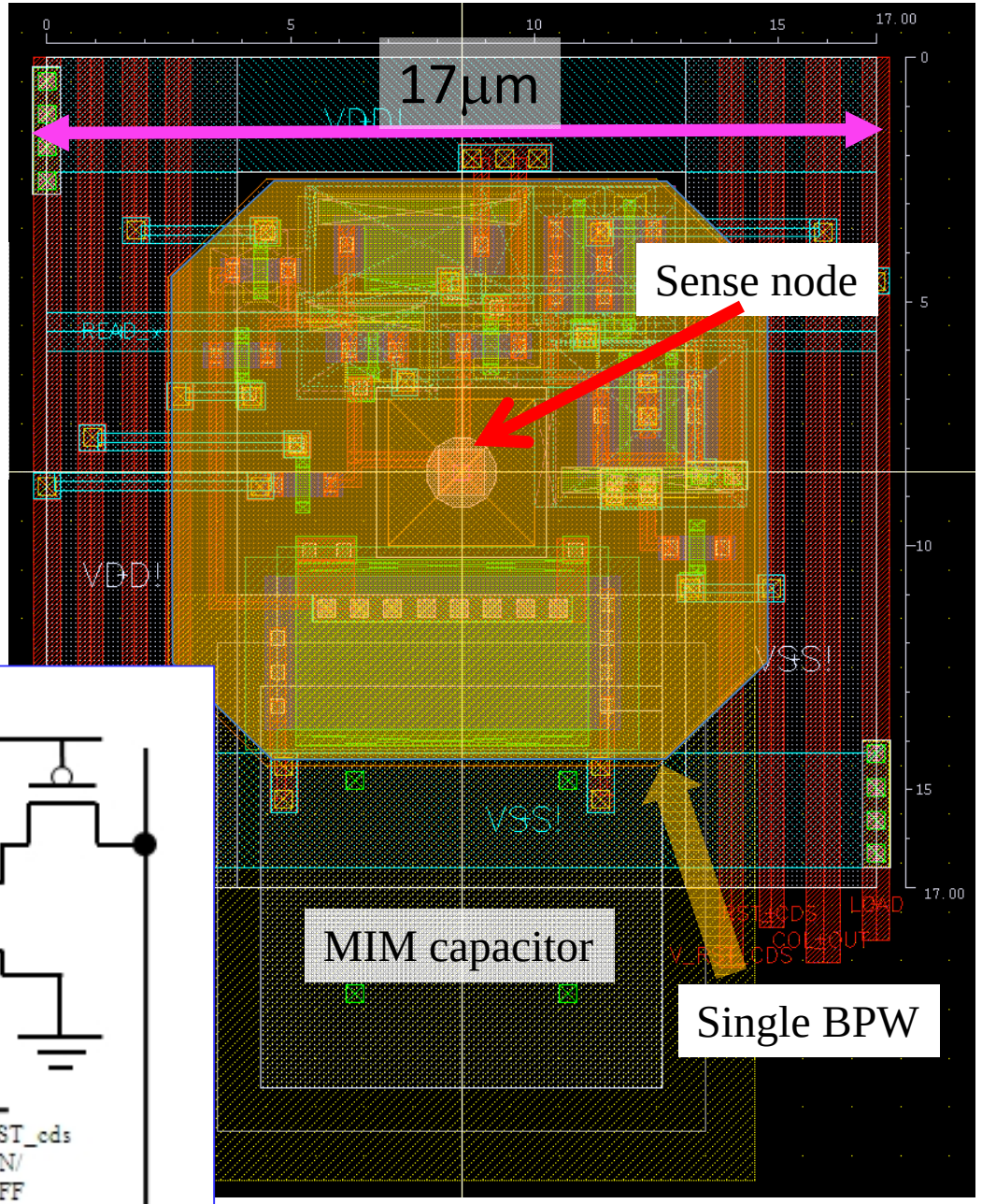
Performance test results of SOI detectors

1. DIPIX
2. INTPIX3e
3. FPIX
4. INTPIX5
5. **INTPIX4**
6. Double SOI

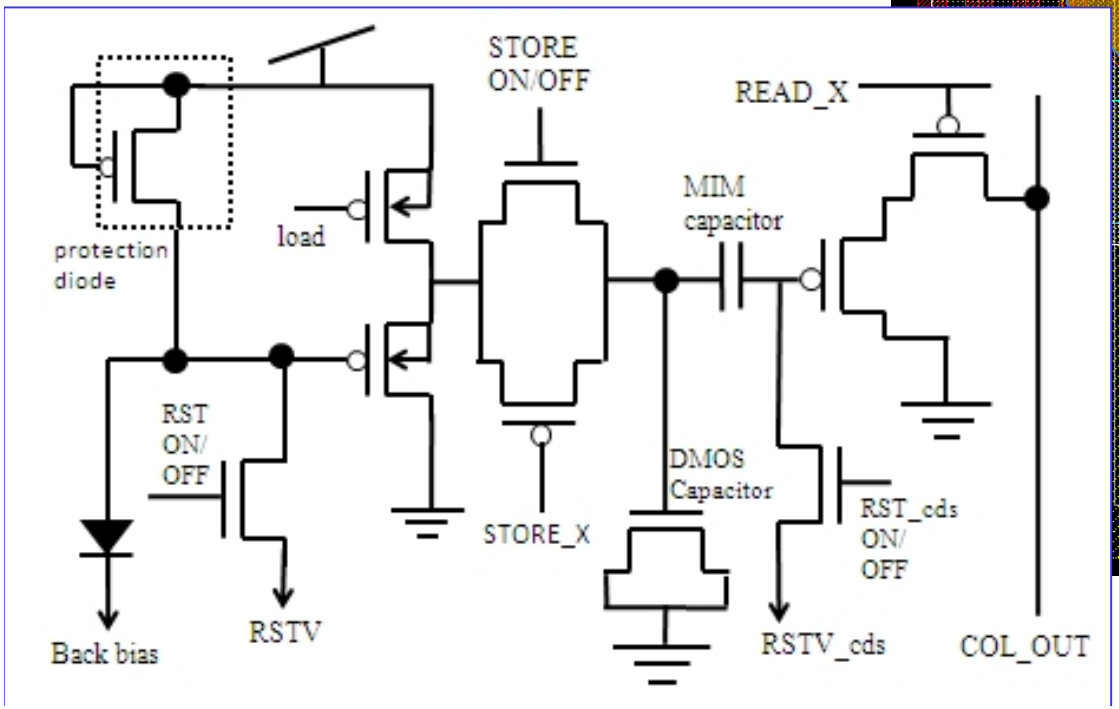
INTPIX4

Pixel Layout

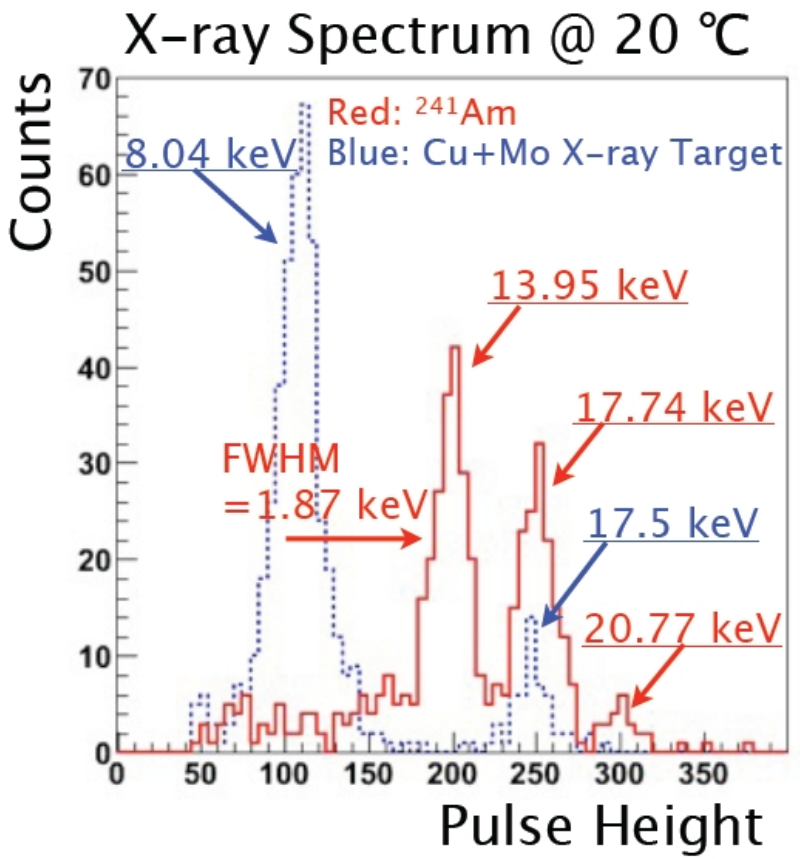
- Pixel size 17 x 17 µm
- Circuit is based on PMOS
- Single BPW inside

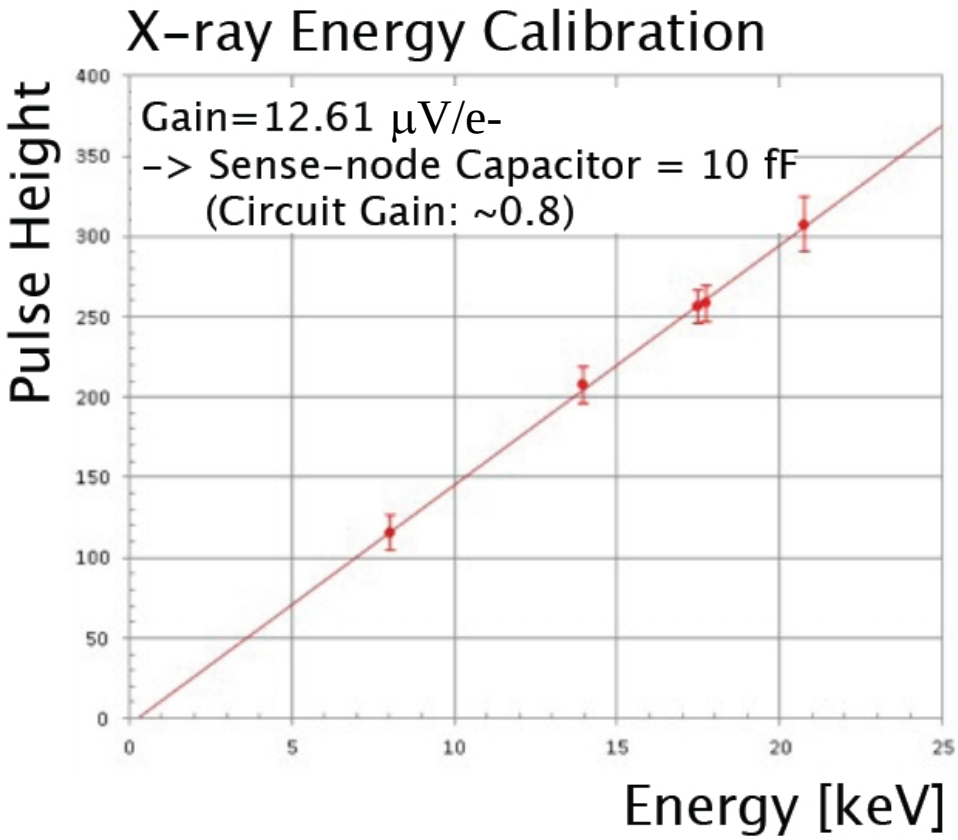


Pixel circuit with CDS



Energy Spectrum @ Room Temperature

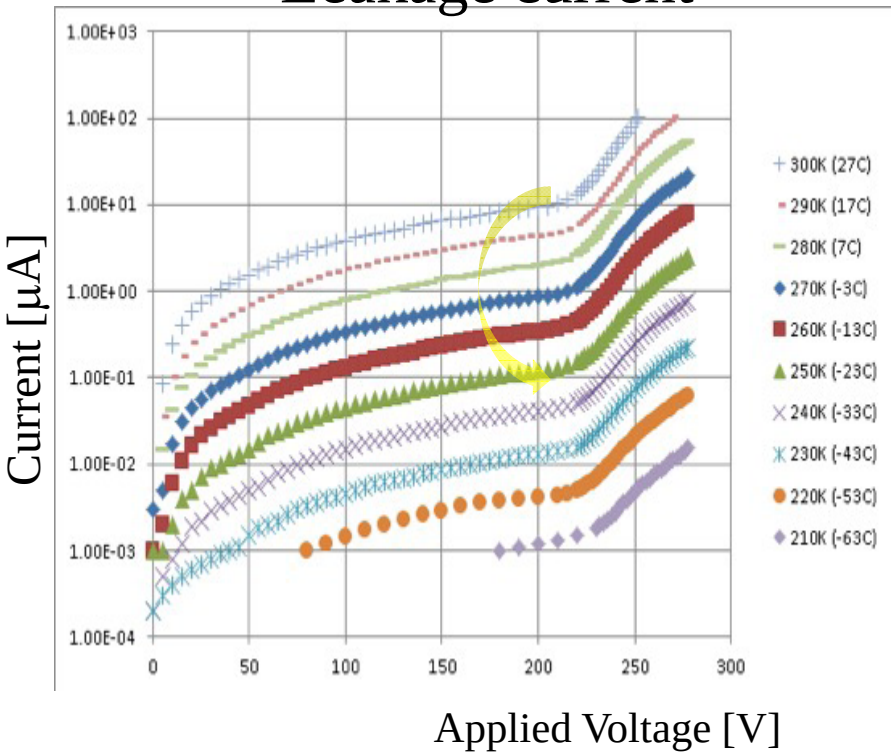




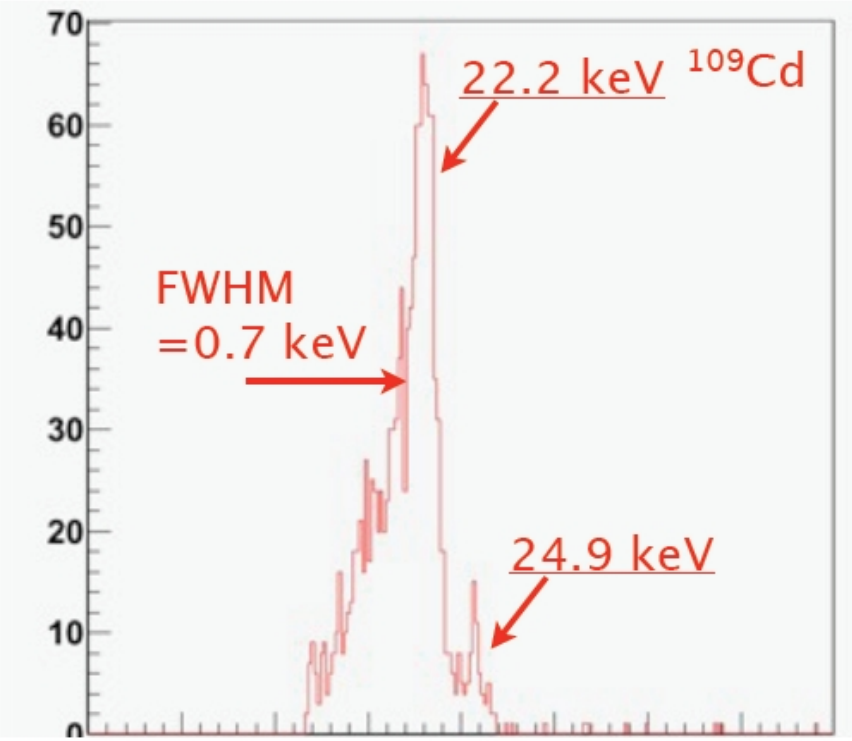
Energy resolution ~ 13% (FWHM) is large for precise X-ray energy measurement
(* For MIP detection, the resolution might be OK)

Energy resolution after cooling

Leakage current



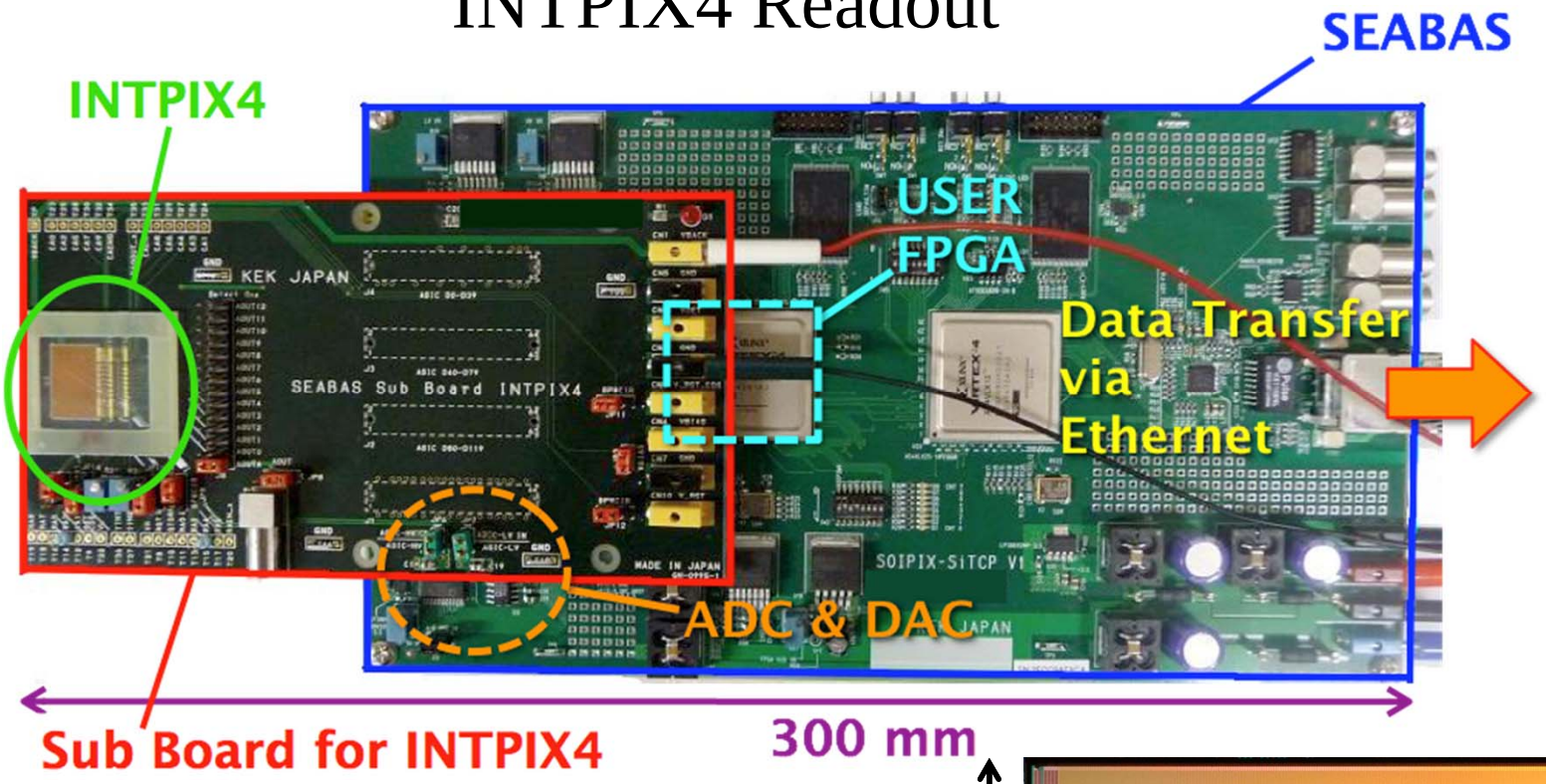
CZ-INTPIX4

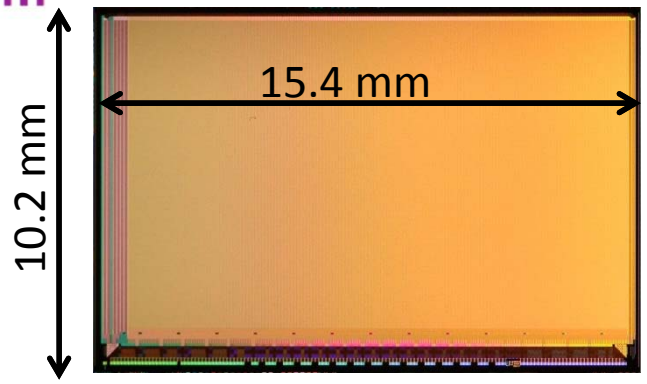


27degC→-23degC
A factor of 10^2

Cooling is required for better energy resolution

INTPIX4 Readout





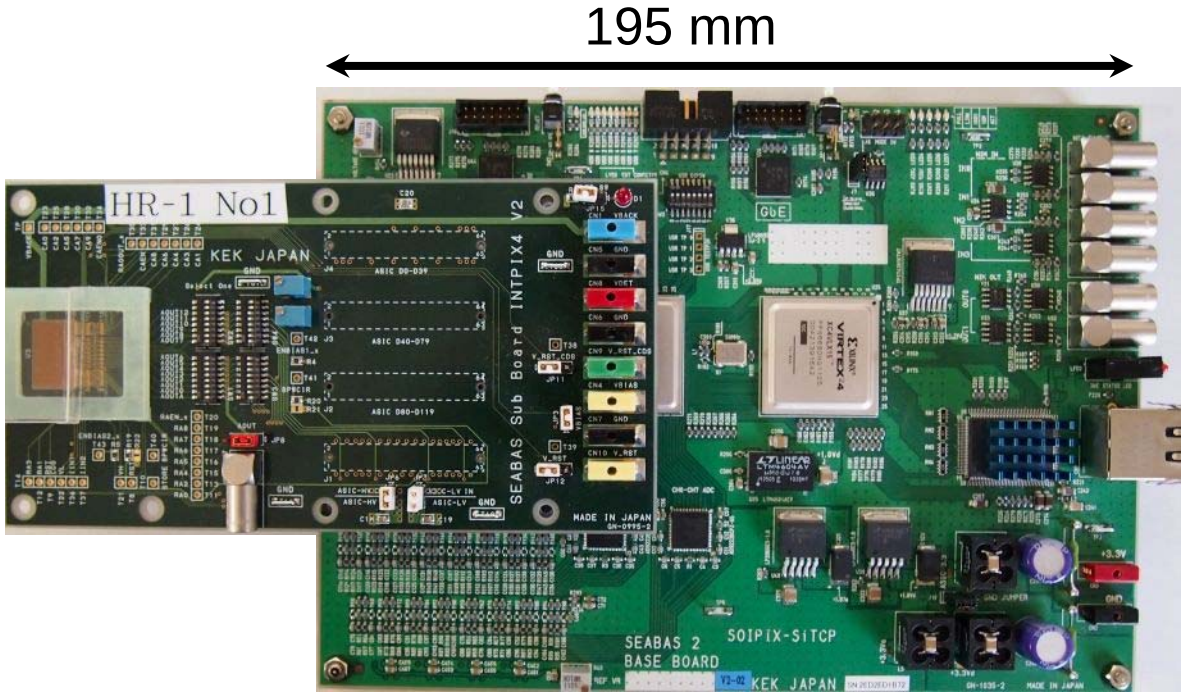
- # of pixels: 512 x 832 pixels
- 13 Analog Out (13x512x64)

However…
- SEABAS1 --- 1 ADC

Pixel scan time 440 ns/pixel x 512 x 832 ~ 200 ms → ~ 5 fps (slow!)

Readout board upgrade : SEABAS2

- Gbit Ethernet
- FPGA Virtex5
- Clock 50 MHz
- ADC 16 ch
- +/- 3.3 V



Pixel scan time 440 ns/pixel x 512 x 64 (x 13 parallel) ~ 14 ms → ~ 70 fps
Can be used for movie measurement

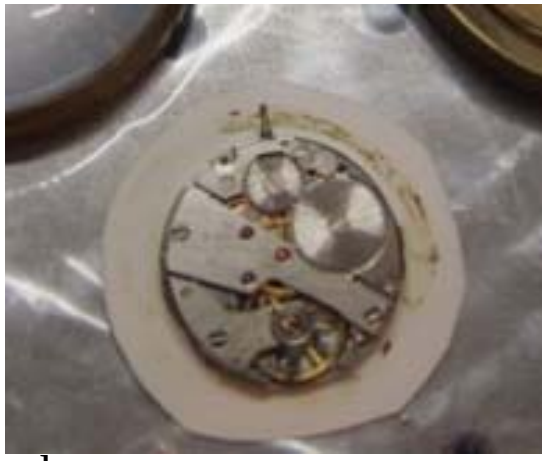
Measurement result:
60 fps for readout only
20 fps with Data save & readout

X-ray movie (Cz-INTPIX4)

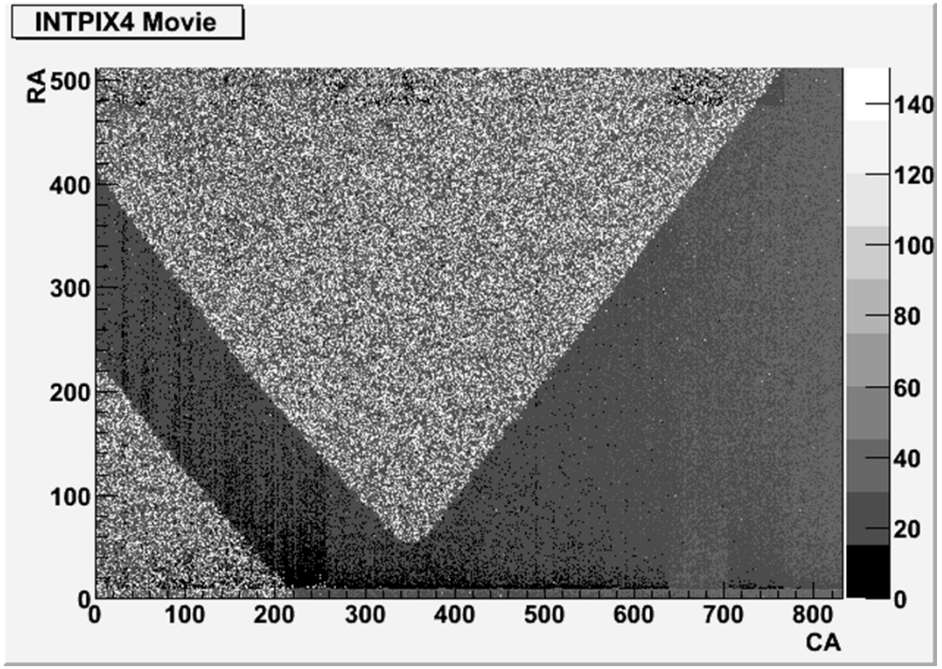
Mo Target 30kV - 40 mA
Integration 200 μs / frame
Back bias 150 V

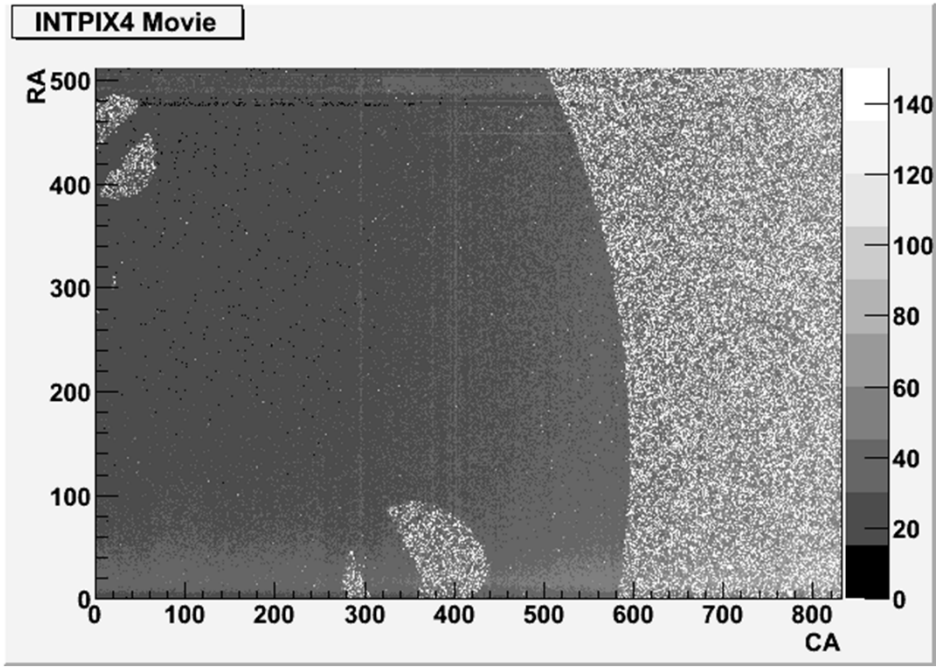
Thickness 260 μm

Optical chopper



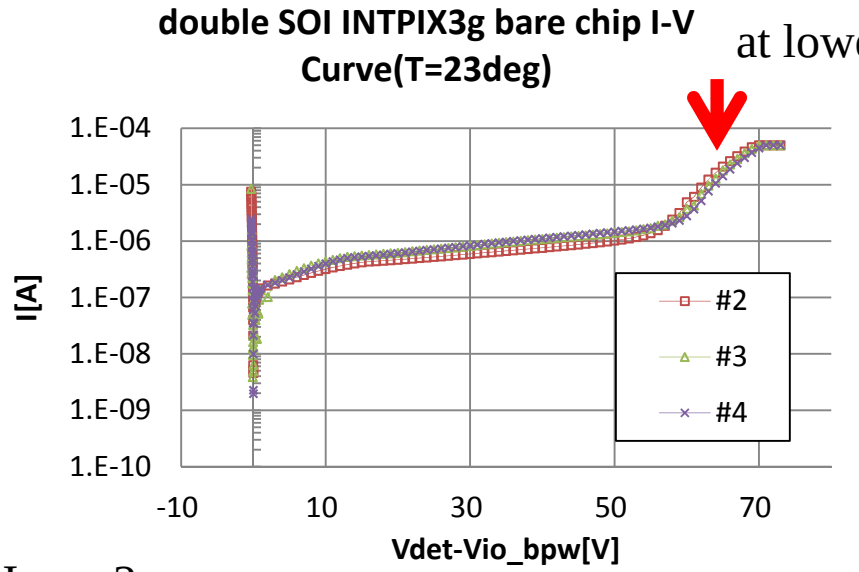
Watch





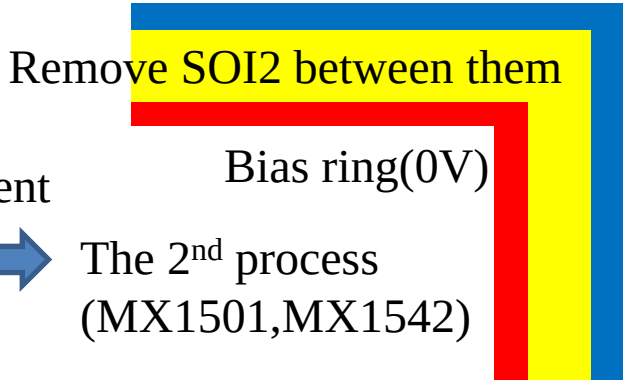
6 Double SOI sensor tests (2012.10 ~)

Issue 1



Breakdown at lower voltage

Improvement

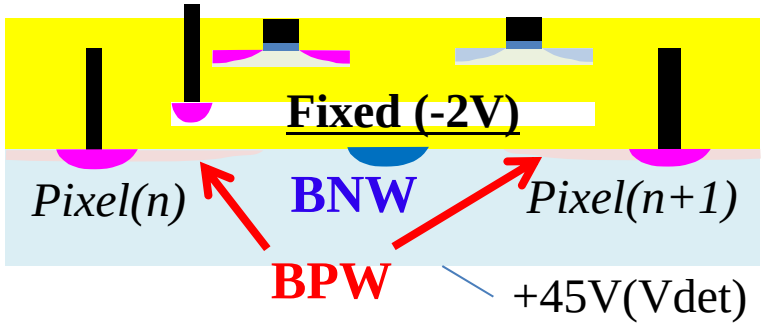


The 2nd process (MX1501,MX1542)

Issue 2

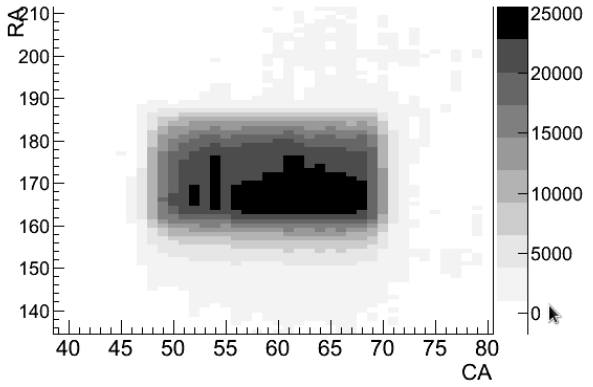
Charge collection efficiency reduction between pixels

→ BNW between pixels (INTPIX3g, PIXOR)



→or, remove DSOI between pixels

X-ray image (0.4x0.4 mm beam spot)
12keV monochromatic X-ray
@KEK-PF BL 14A



DSOI-INTPIX3g

Current issues

課題

* The back-gate effect --- BPW/BNW/Double SOI
* Sensor crosstalk --- double SOI/vertical integration (T-Micro)
  /nested-well structure
* Noise / leak current --- cooling system / electronics development
  /system integration/wafer quality improvement
* Uniformity --- void (noisy points / regions)
* Wafer characteristics --- find the best wafer
* Dynamic range --- Transistor, switchable gain
* Radiation hardness --- double SOI, wafer quality improvement
* Area size --- stitching

Summary

SOI Integration type pixel detectors work very well
We have performed:
- Digital and analog output study (DIPIX1&2…)
- High energy charged particle beam test (INTPIX3a,b, e…)
- Spatial resolution study (FPIX1&1P, INTPIX5…)
- Energy spectrum measurement (DIPIX1&2, INTPIX4, XRPIX(1…)…)
- Full depletion study in Cz- and FZ SOI sensors (INTPIX, DIPIX…)
- Double SOI Study (INTPIX3g, FPIX1P, PIXOR…)

Development of intelligent sensors (including counting-type)
→ add more functions in a pixel (depends on application)

Application　応用
Visible light, IR, X-ray, charged particle detection --- direct detection
Gamma/neutron : SOI with converter　　--- indirect detection

Supplements

補足資料

KEK Photon Factory (PF and PF-AR)