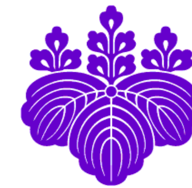


Monolithic pixel detectors fabricated with single and double SOI wafers

T. Miyoshi, Y. Arai, Y. Fujita, Y. Ikemoto, K. Hara[1], S. Honda[1], Y. Ikegami, S. Mitsui, A. Takeda[2], K. Tauchi, T. Tsuboyama, Y. Unno

High Energy Accelerator Research Organization (KEK)
[1]Univ. of Tsukuba
[2]Kyoto University

Thursday
I.b Semiconductors
11:00 - 12:40
Berlagezaal
@Beurs van Berlage

v.5

Outlines

Introduction

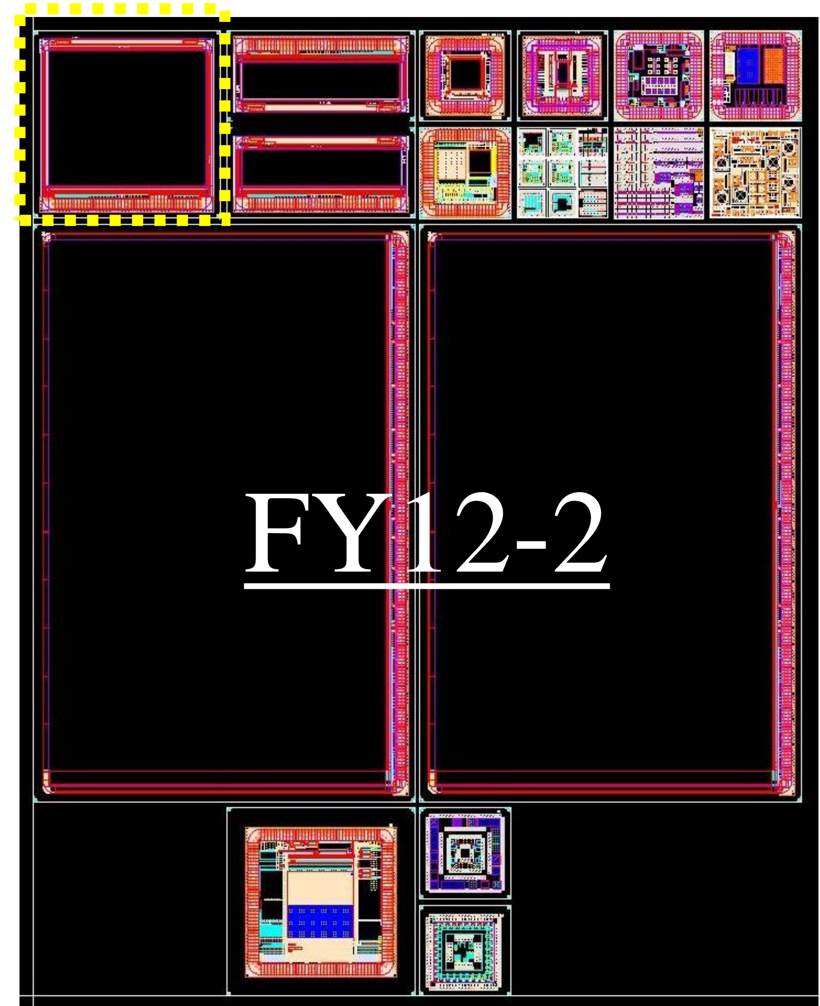
Test results of “INTPIXh2” SOI sensors (Integration-type pixel sensor)

Future plan and summary

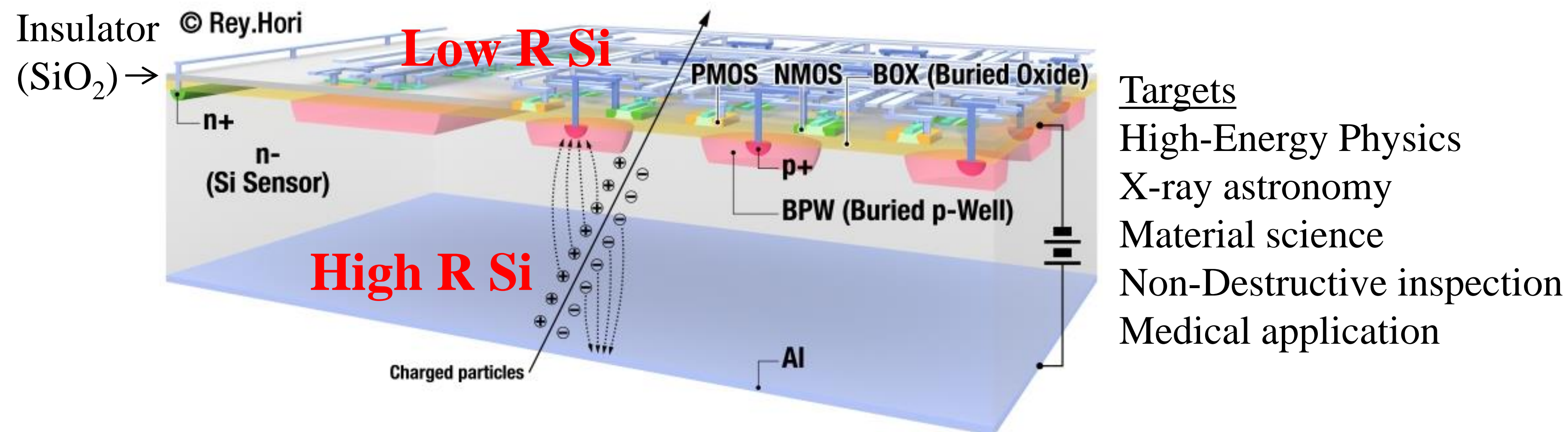
Related slides:
II.b Astro & Space
11:20 Development and Evaluation of Event-Driven SOI Pixel Detector for X-ray Astronomy
11:40 Development of X-ray SOI Pixel Sensors: Investigation of Charge-Collection Efficiency

→XRPIX (Integration type pixel sensor)

INTPIXh2
MX1594
6mm-sq.



SOI Monolithic pixel detector



The features of SOI monolithic pixel detector

- No mechanical bump bonding. Fabricated with semiconductor process only
  →high reliability and low cost
- Fully depleted (thick & thin) sensing region
  with low sense node capacitance (~10fF@17μm pixel) → high sensor gain
- Wide temperature range (1-570K)
- Low single event cross section
- Technology based on industry standards

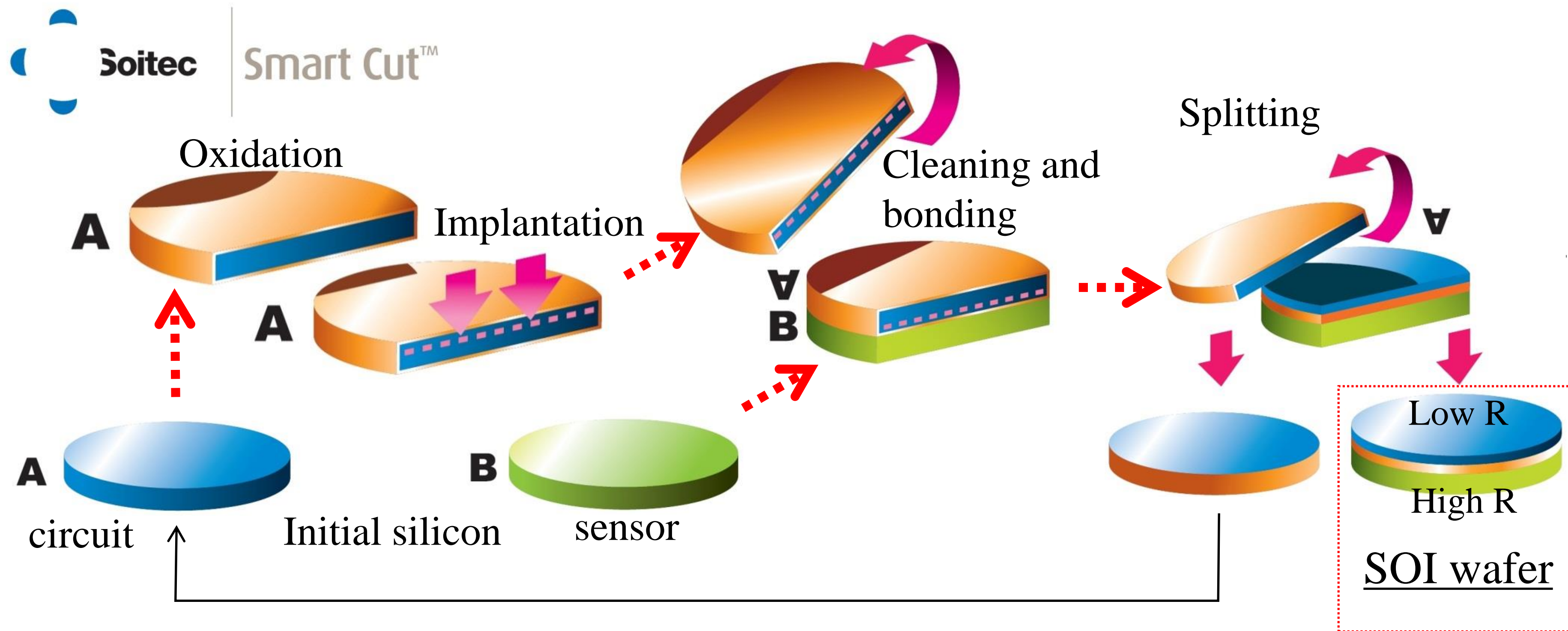
Process Summary

- KEK organizes MPW runs twice a year
- Mask is shared to reduce cost of a design
- Including pixel detector chip and SOI-CMOS circuit chip

Process (Lapis Semiconductor Co. Ltd.)	0.2μm Low-Leakage Fully-Depleted (FD) SOI CMOS 1 Poly, 5 Metal layers (MIM Capacitor and DMOS option) Core (I/O) voltage : 1.8 (3.3) V
SOI wafer (200 mm ϕ =8 inch)	Top Si : Cz, ~18 Ω-cm, p-type, ~40 nm thick Buried Oxide: 200 nm thick Handle wafer thickness: 725μm → thinned up to 300μm (Lapis) or ~50 μm (commercial process) (Handle wafer type: see the following slides)
Backside process (2011~)	Mechanical Grind →Chemical Etching →Back side Implant →Laser Annealing → Al plating

SOI Wafer Production

Smart cut™ by Soitec

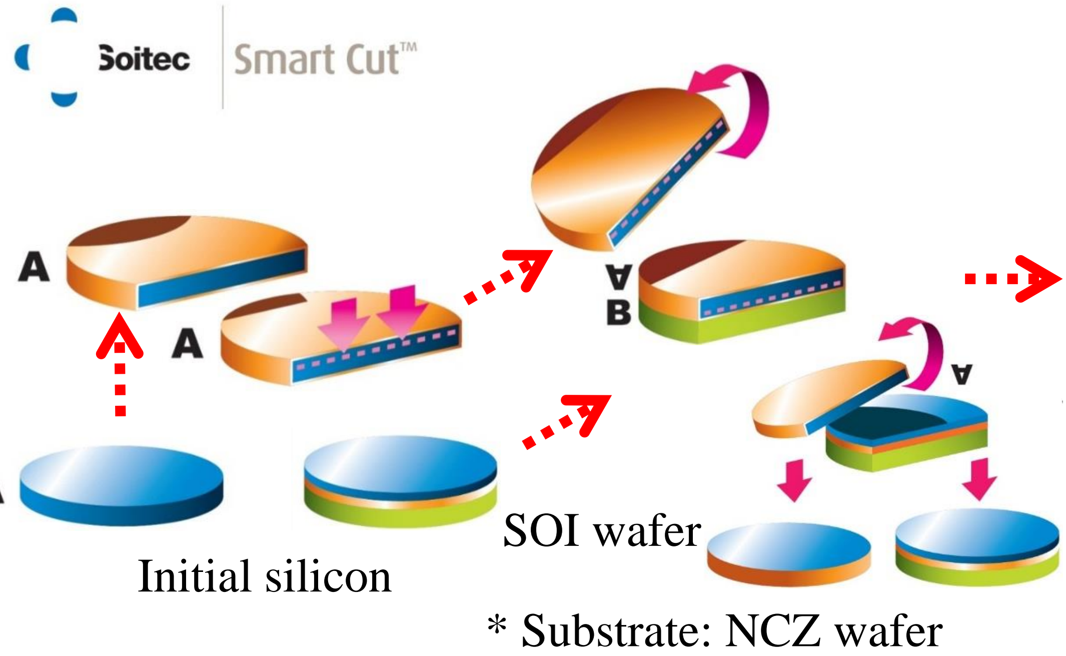


High Resistivity Silicon: Two choices

N-type Czochralski, NCZ, 700 Ohm-cm, 300um-thick

N-type Float Zone, NFZ, 2-7k Ohm-cm, 500um-thick

Double SOI pixel sensor

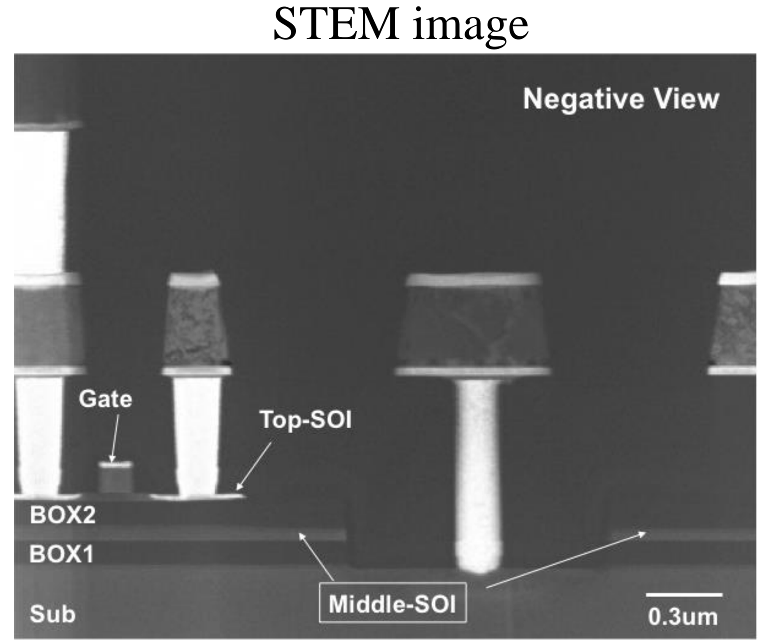


Initial silicon

SOI wafer

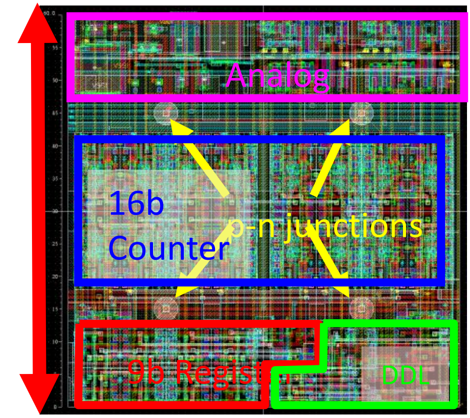
* Substrate: NCZ wafer

STEM image



Additional shield layer

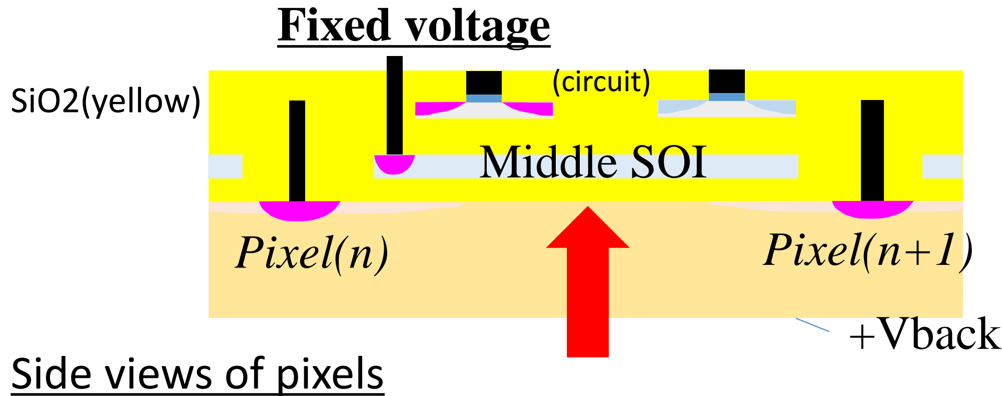
Shield the back gate effect
Compensate effect of box charge
Shield the sensor to circuit crosstalk
→ counting-type pixel (CNTPIX) with double SOI wafer is now being developed.



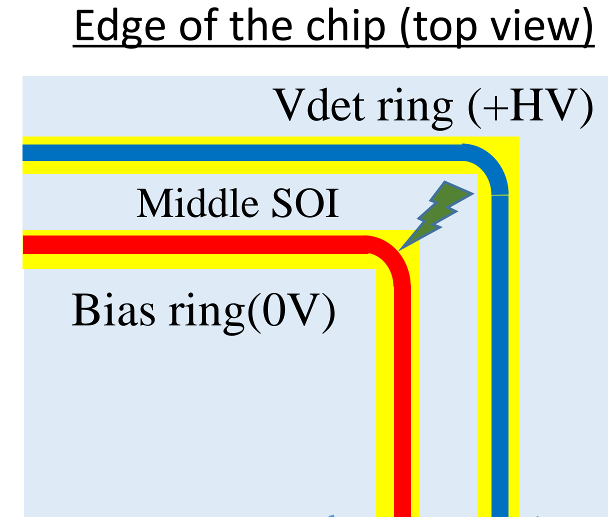
64um-sq. counting-type pixel

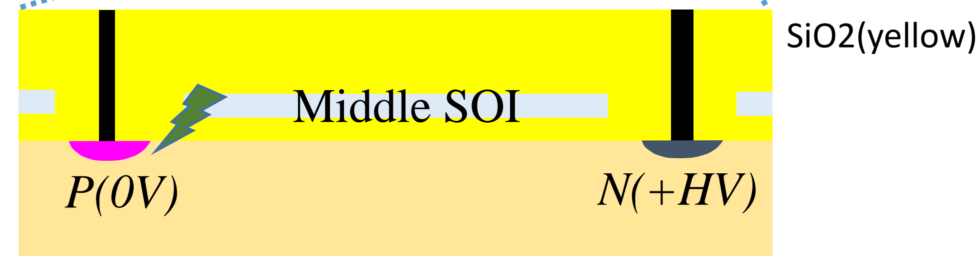
Double SOI sensor development

The 1st trial in MPW FY11 **Mask layout : Draw etching region of the middle SOI**



Side views of pixels





Enge of the chip (side view)

- potential between pixels is flat.

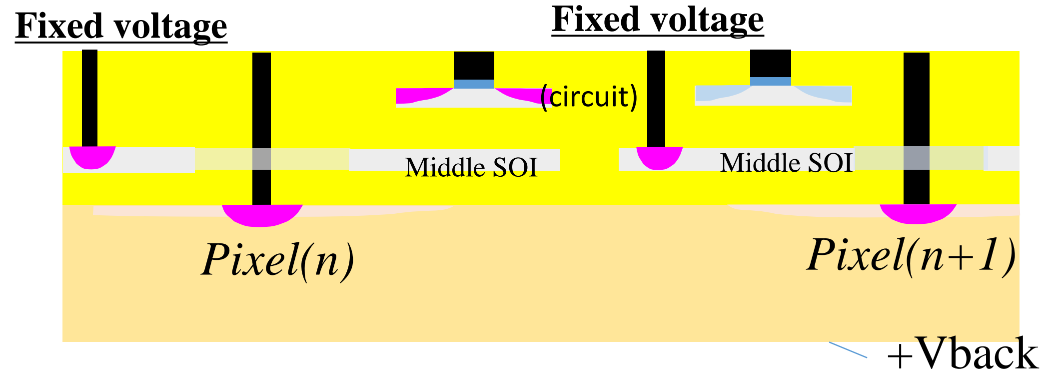
→Affects charge collection efficiency

- micro discharge at the edge of outer guard ring occurred due to potential change by the floating middle SOI

→ Lower breakdown voltage

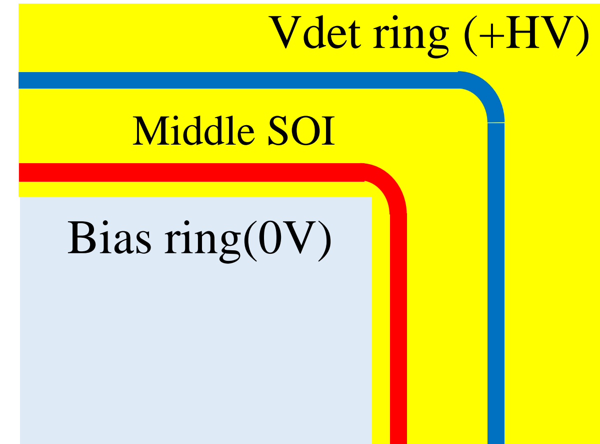
Double SOI sensor development

The 2nd trial in MPW 12-1 & 12-2
Layout rule was changed to draw middle SOI region directly



The side view of pixels

Edge of the chip (top view)



- potential between pixels is not flat

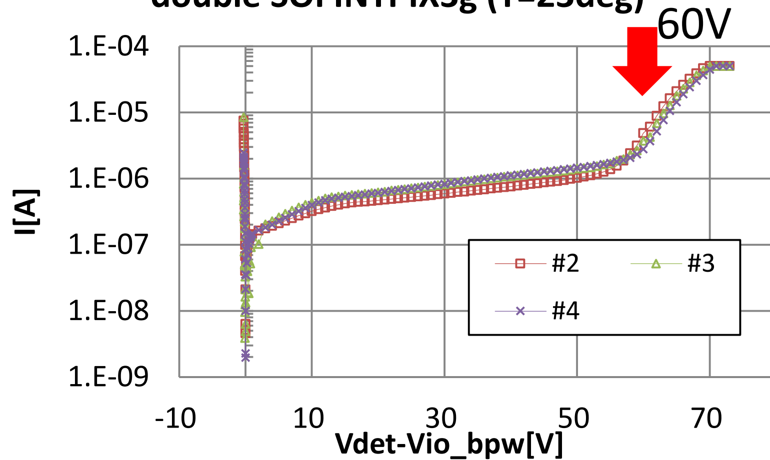
→spatial resolution study

- recover high breakdown voltages

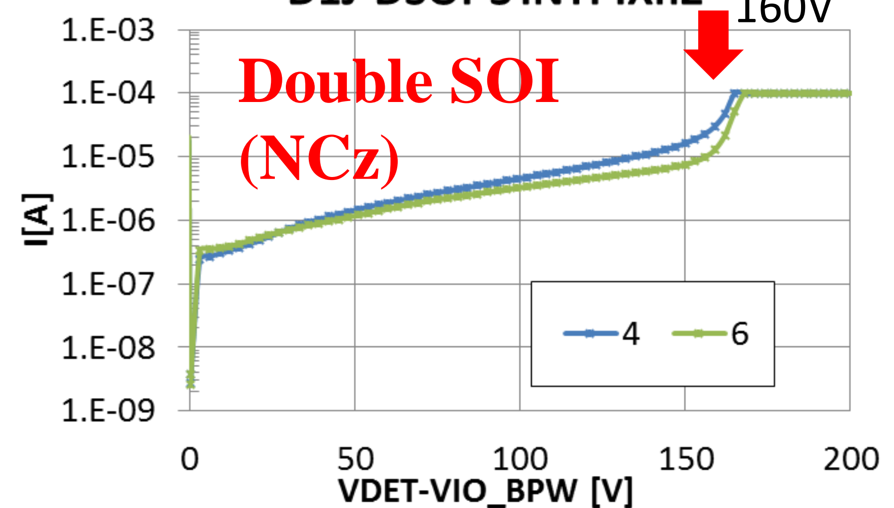
→ I-V measurement

Double SOI sensor I-V measurement

Double SOI 1st trial



Double SOI 2nd trial



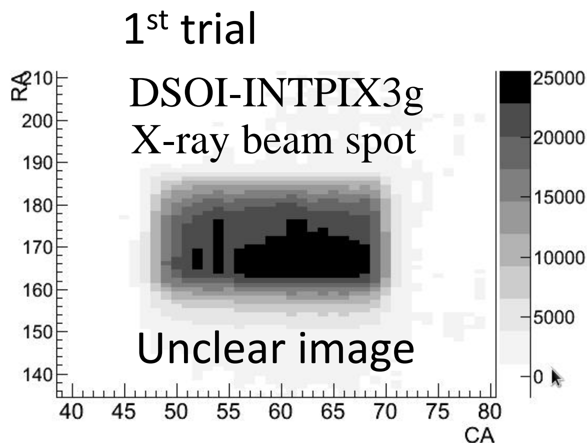
Breakdown voltage is recovered
similar to the single SOI case

Spatial resolution in Double SOI sensor

border of xy slit
16LP/mm(32um slit)
20LP/mm (25um slit)
r2
r3
r1
DSOI-INTPIXh2
SOI2=0V

16LP/mm
20LP/mm
DSOI-INTPIXh2
SOI2=0V

1st trial



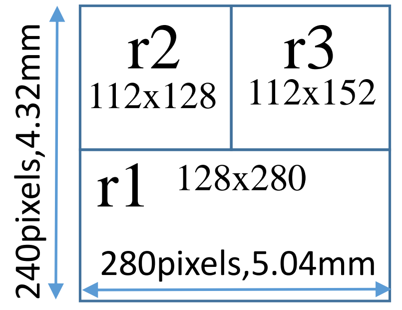
X-ray test chart
Mo Target X-ray (17.5keV)
Vdet +50V
Integration Time 50us/image x 1000 frames

25um slit can be resolved.
Effective to remove double SOI layer between pixels.

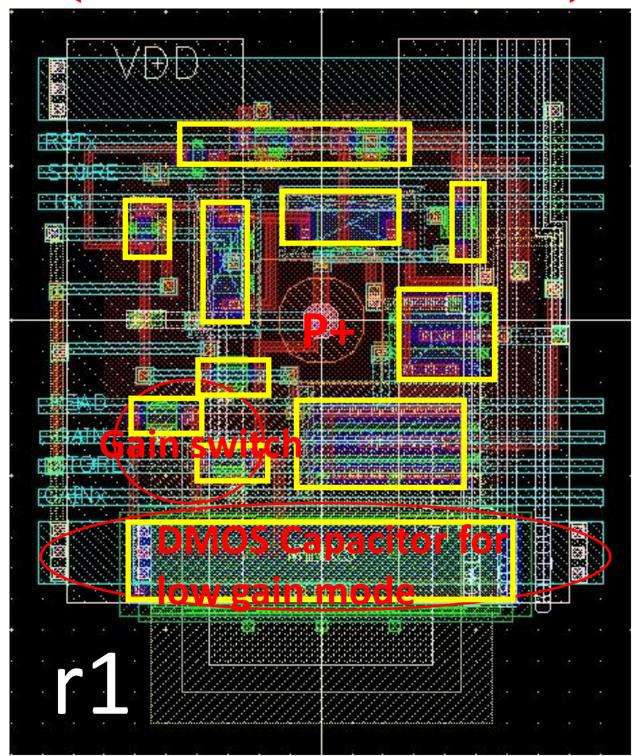
Sensor study

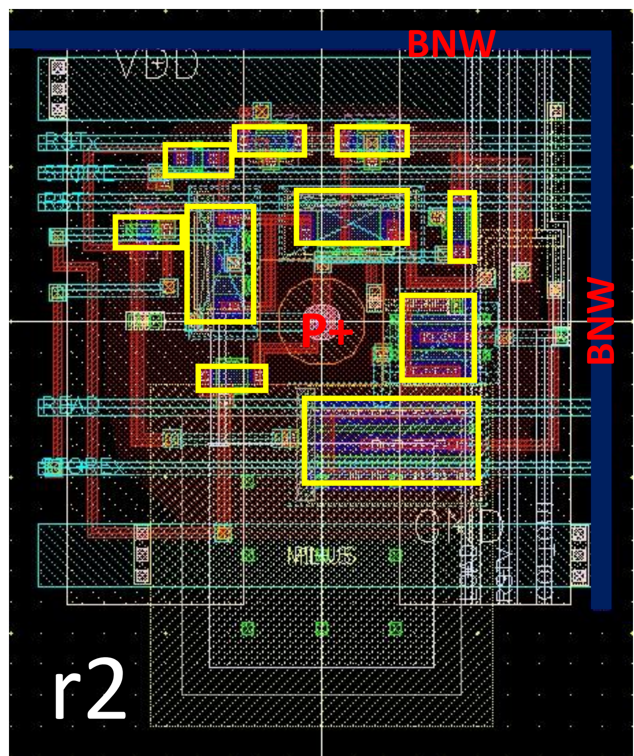
Top View of 3 Pixels

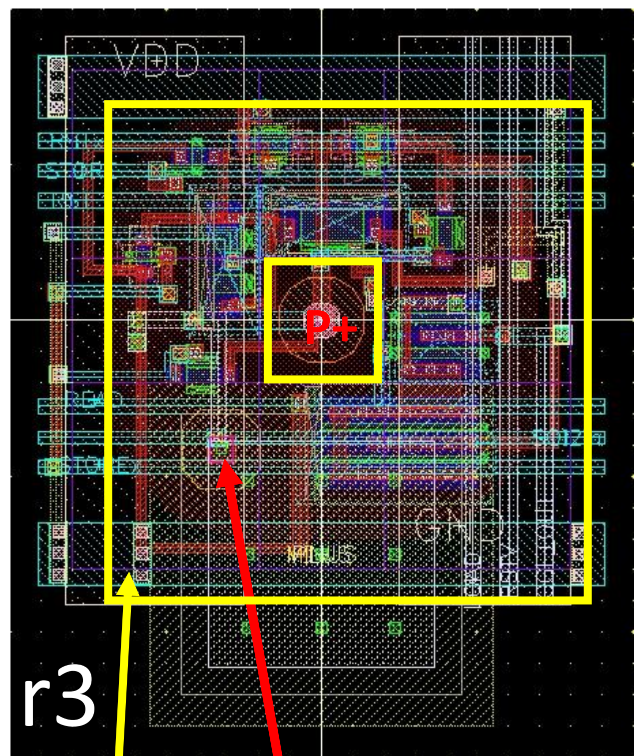
INTPIXh2
MPW12-2 MX1594
6mm-sq chip



Pixel size 18um-sq





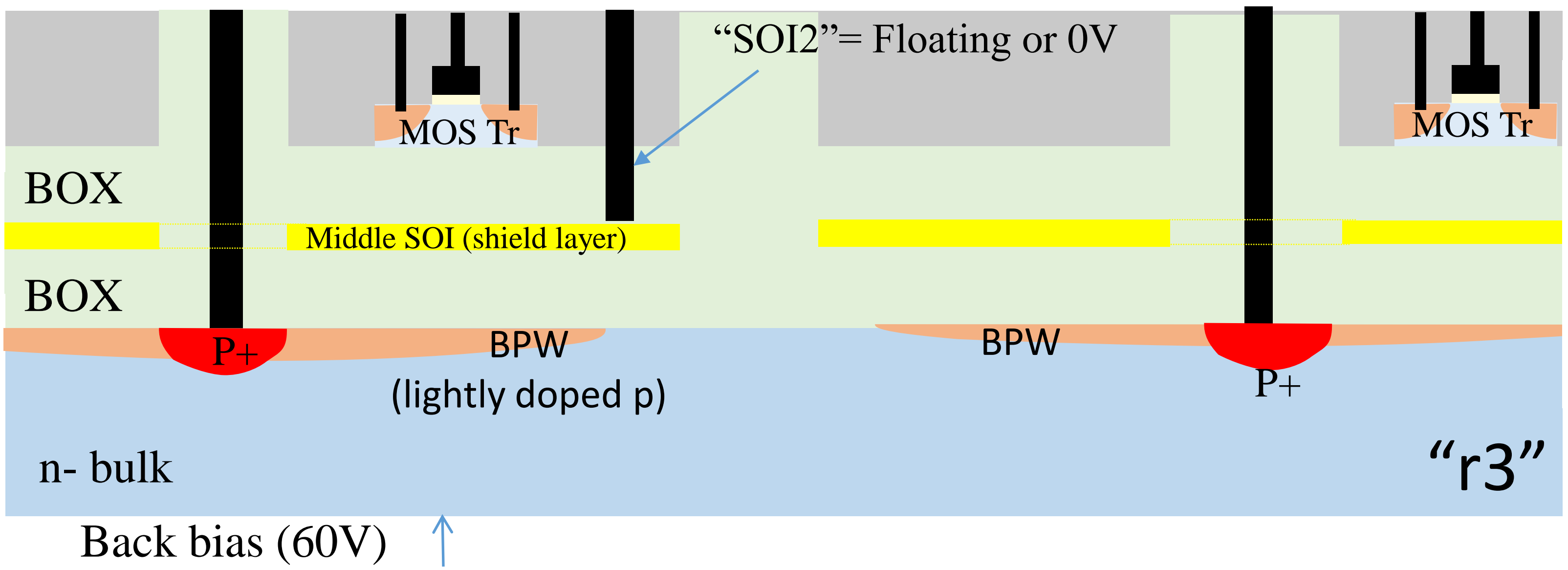


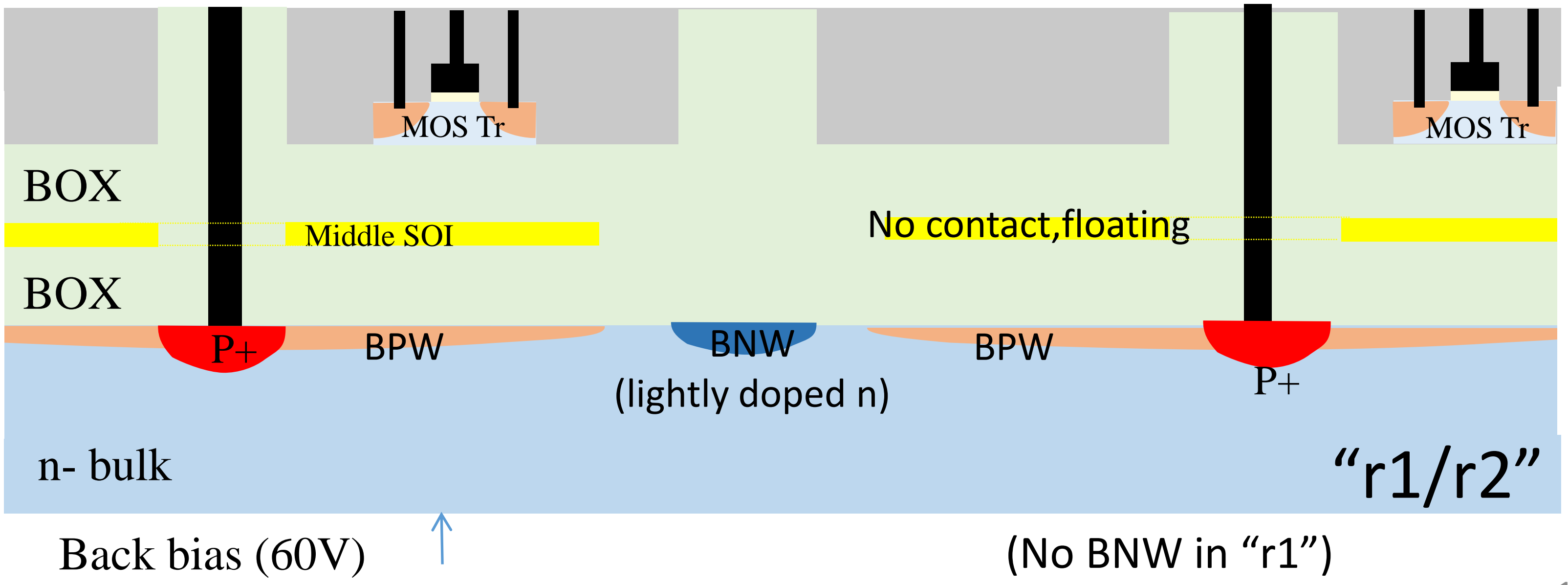
SOI2 layers are kept only
Below the active area

"SOI2" contact

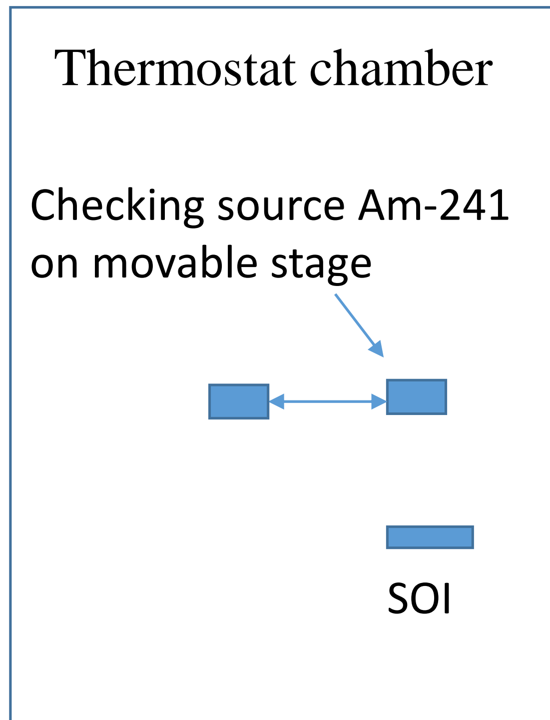
SOI2 (rectangle)
16um x 16um

Side view of Pixels





Low temperature test of noise and energy resolution



Min. -60 degC ~ Room temp.

- Leakage current
- Am-241 X-ray spectrum
- Noise, Gain, Energy resolution

Settings:

1: NCZ
Thickness 300um, 700 Ohm-cm
<u>Depletion ~ 150um (back bias 100V)</u>

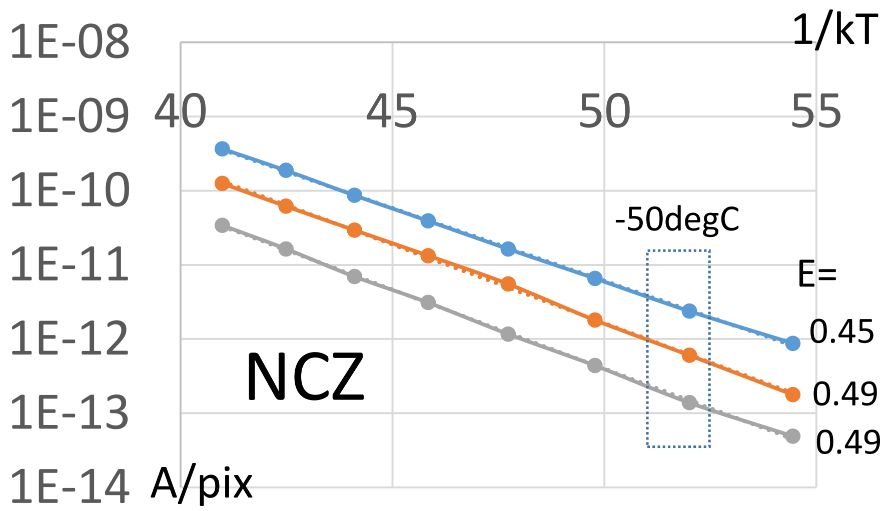
2: NFZ
Thickness 500um, ~ 4 kOhm-cm
<u>Depletion ~ 300um (back bias 100V)</u>

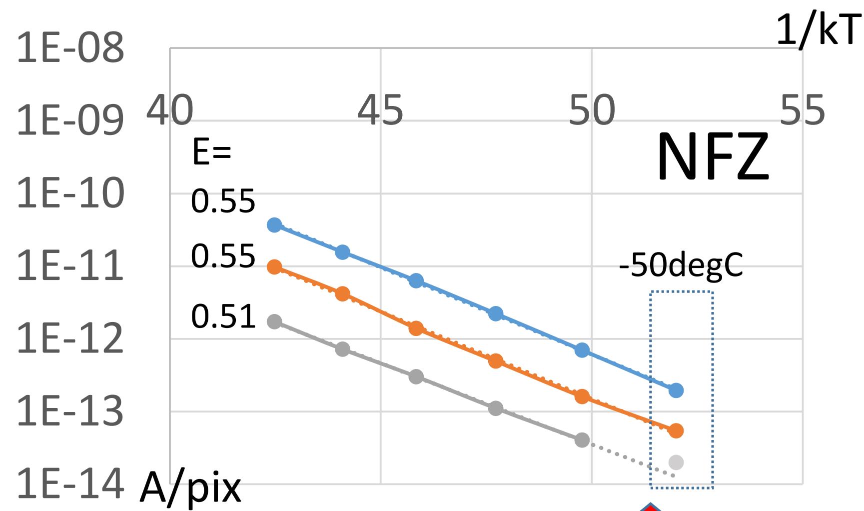
3: DSOI(NCZ)
Thickness 300um, 700 Ohm-cm
<u>Depletion ~ 100um (back bias 60V)</u>
Middle SOI floating

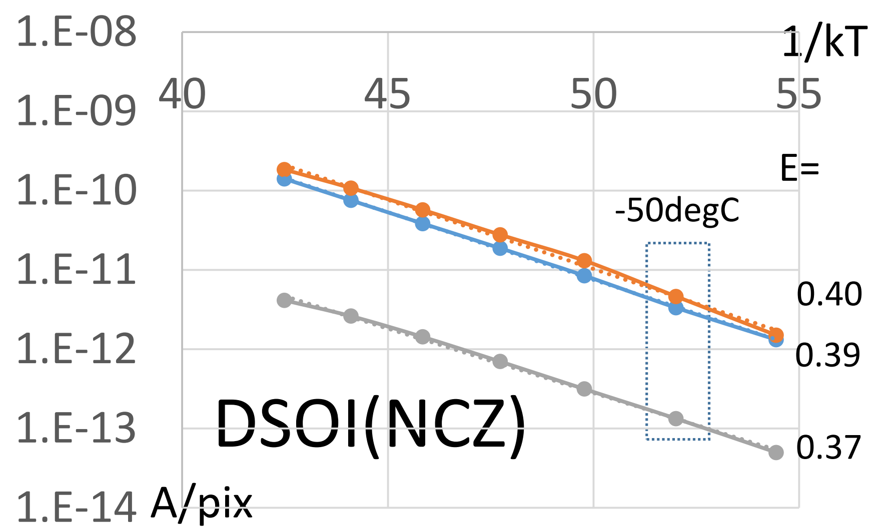
* Middle SOI floating or fixed to 0V → no difference in the sensor gain

Pixel leakage current

r1 --- r2 --- r3 ---







EXP[-E x (I/kT)]

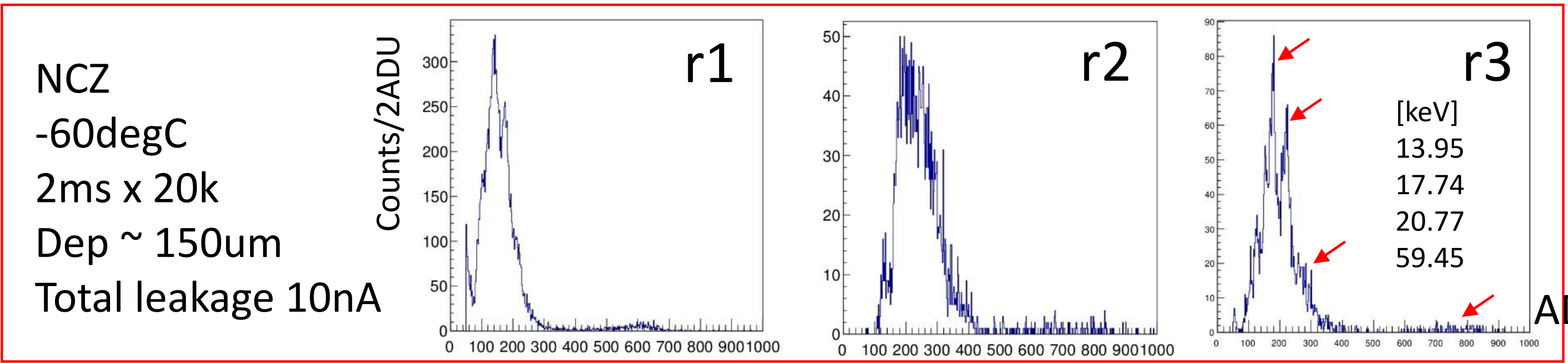
Arrhenius plot
E Activation Energy (Eg (bandgap)/2=0.56(Si))
E~0.56; Generation current

NFZ E~Ea
NCZ,DSOI E<Ea
I[NFZ]/pix ~ 10nA/cm2 @ -50deg.

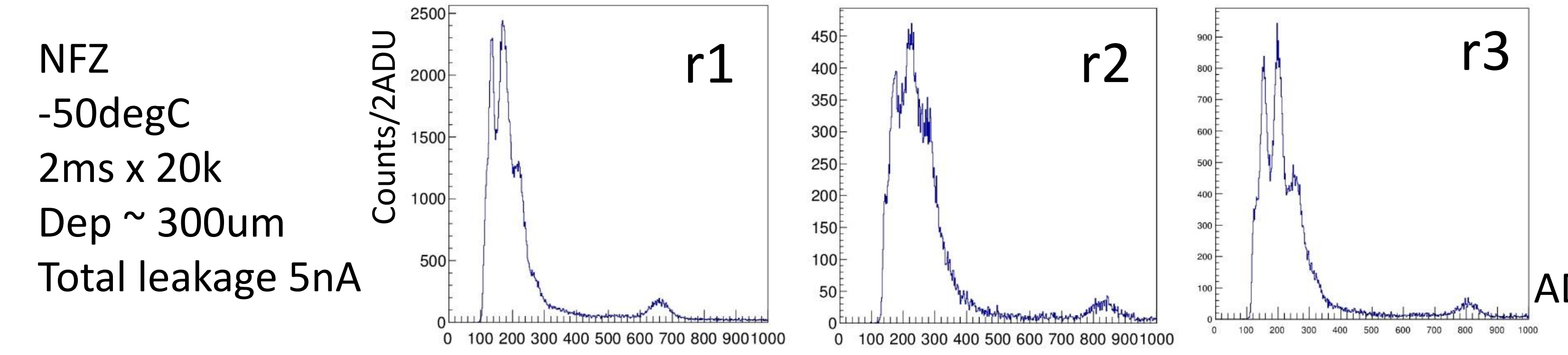
10^-13 A /[pixel=18 um x18 um] x 3x10^5 = 30 nA/cm2

Am-241 spectrum

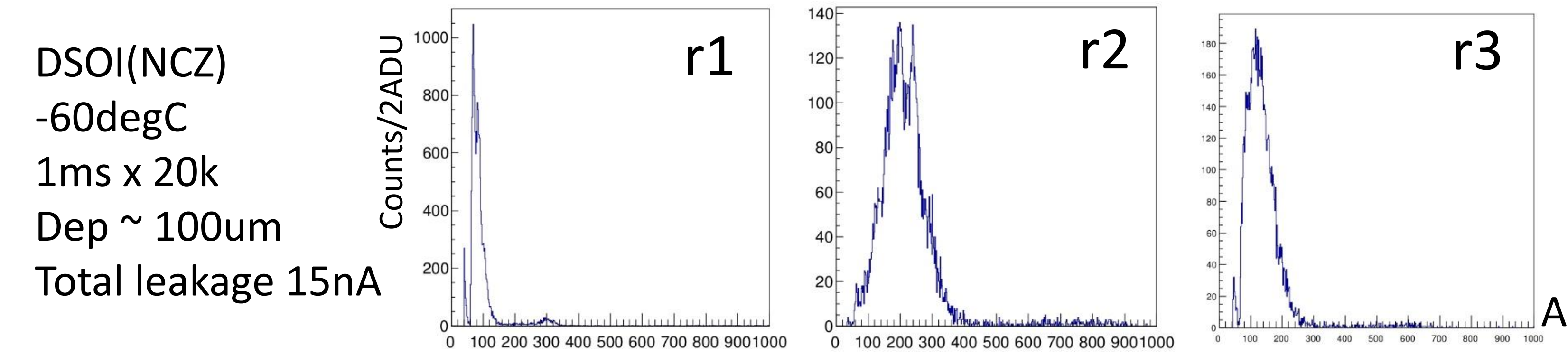
X:ADU, Y:Counts/2ADU



Memo:"a3"
Reset 400mV



Memo:"a2"
Reset 400mV



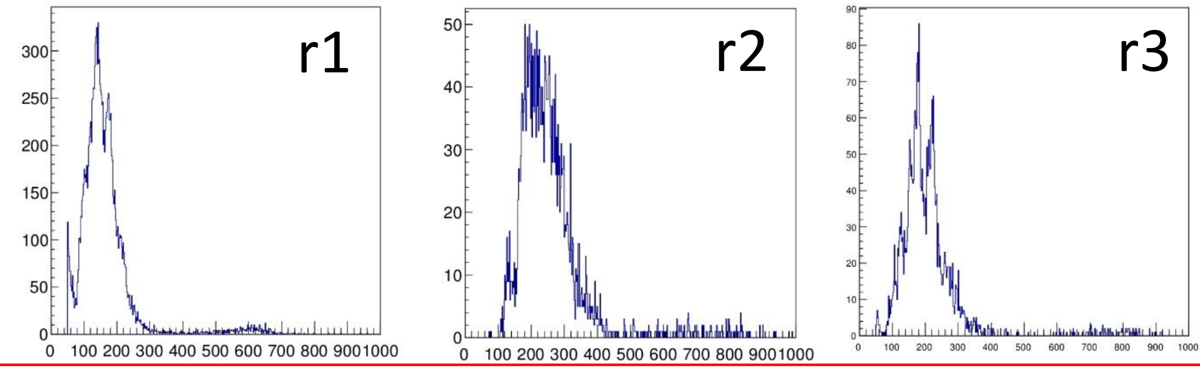
Memo:"a3"
Reset 400mV
BGonly

NCZ: Noisy (High leakage current), low efficiency

Am-241 spectrum

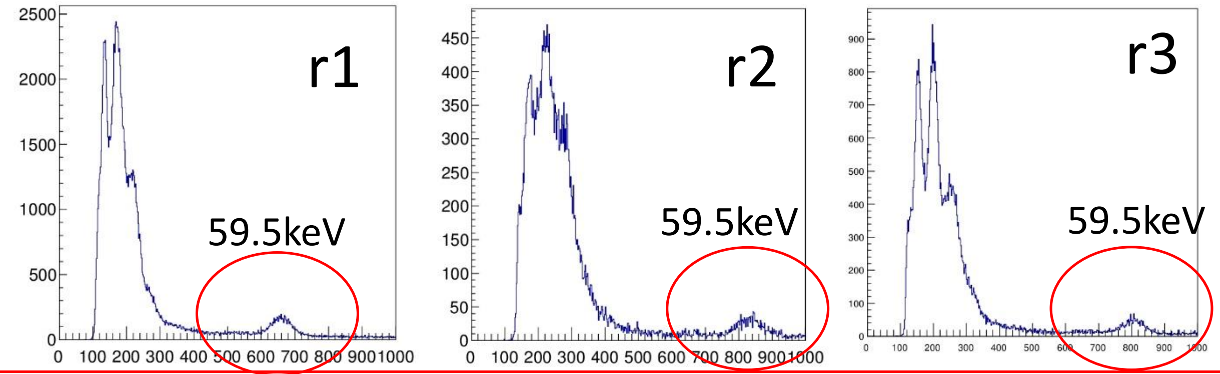
X:ADU, Y:Counts/2ADU

NCZ
-60degC
2ms x 20k
Dep ~ 150um
Total leakage 10nA



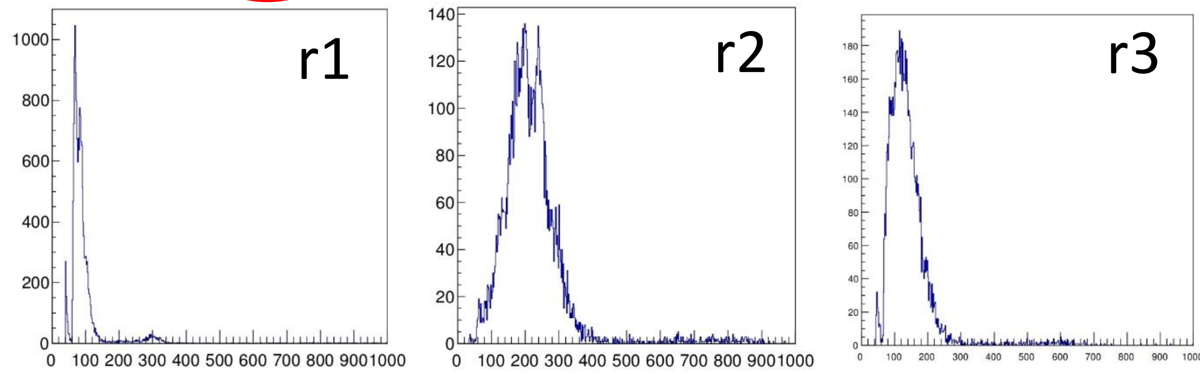
Memo:"a3"
Reset 400mV

NFZ
-50degC
2ms x 20k
Dep ~ 300um
Total leakage 5nA



Memo:"a2"
Reset 400mV

DSOI(NCZ)
-60degC
1ms x 20k
Dep ~ 100um
Total leakage 15nA



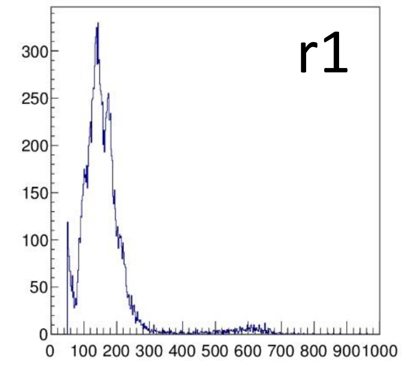
Memo:"a3"
Reset 400mV
BGonly

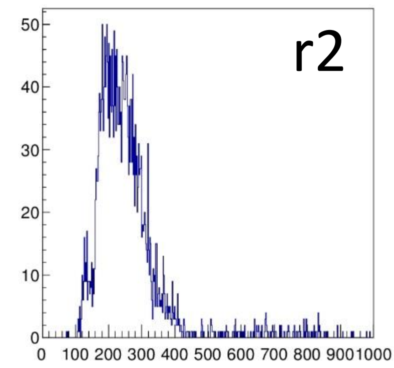
NFZ: Low noise (Low leakage current), High efficiency

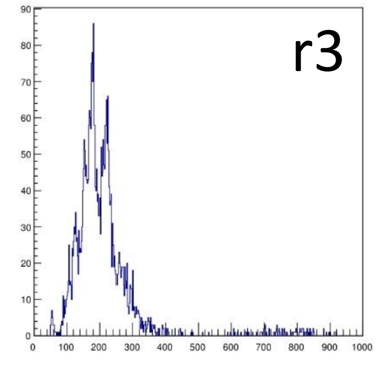
Am-241 spectrum

X:ADU, Y:Counts/2ADU

NCZ
-60degC
2ms x 20k
Dep ~ 150um
Total leakage 10nA

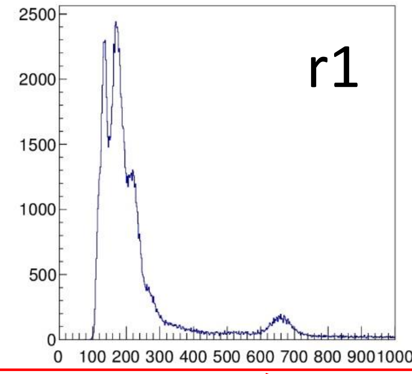


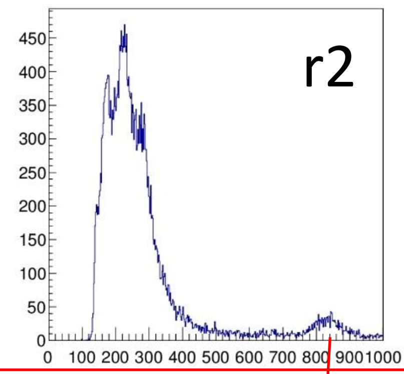


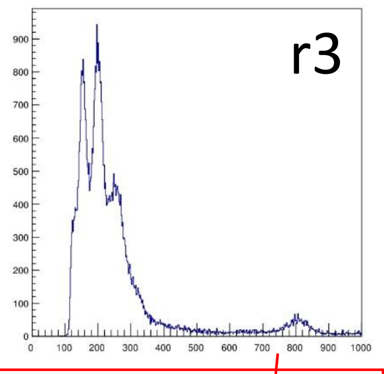


Memo:"a3"
Reset 400mV

NFZ
-50degC
2ms x 20k
Dep ~ 300um
Total leakage 5nA

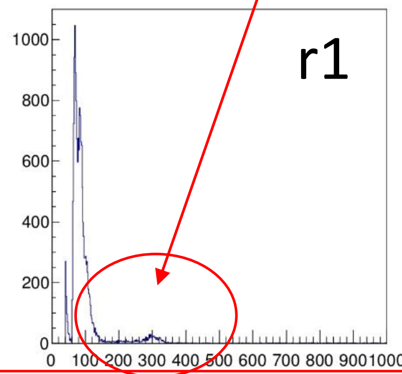


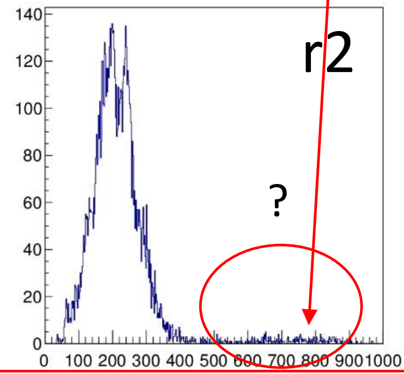


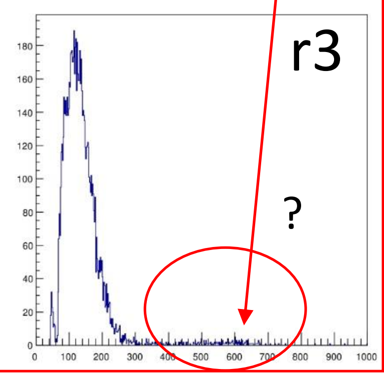


Memo:"a2"
Reset 400mV

DSOI(NCZ)
-60degC
1ms x 20k
Dep ~ 100um
Total leakage 15nA





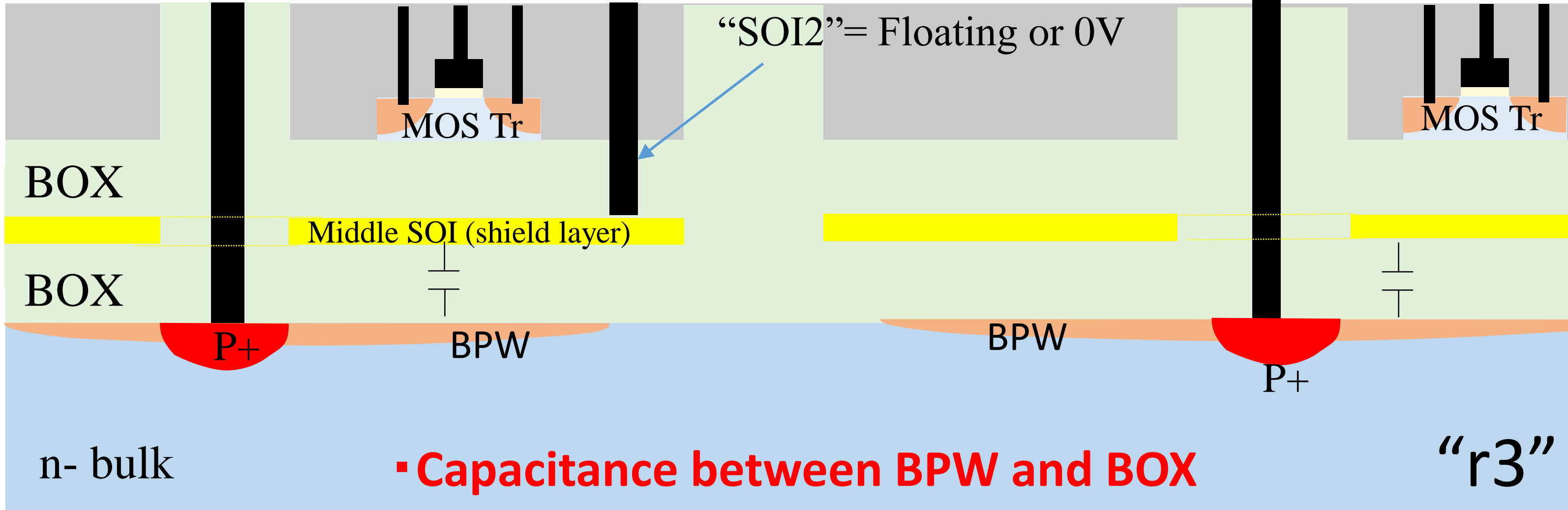


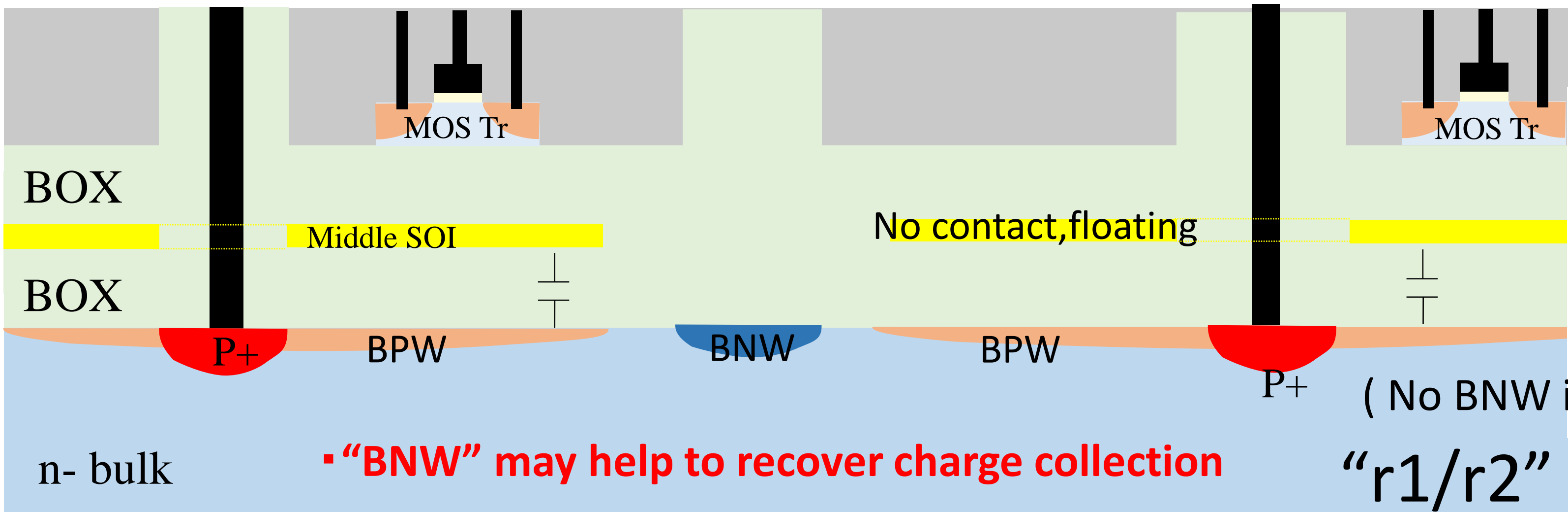
Memo:"a3"
Reset 400mV
BGonly

DSOI(NCZ): Noisy (High leakage current), Low efficiency, Low gain (Except Region 2)

Why the gain is low?

Side view of Pixels



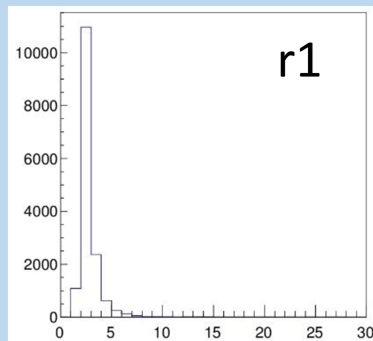


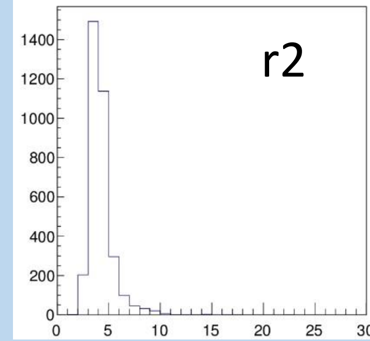
Cluster size distribution

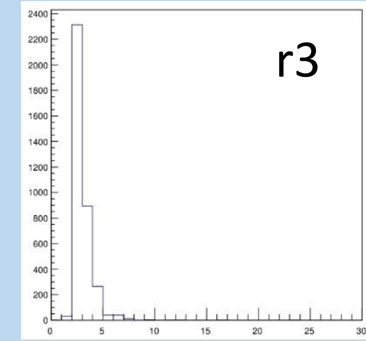
X: cluster size Y:# of cluster

NCZ
(300um)

Depletion depth
~150um

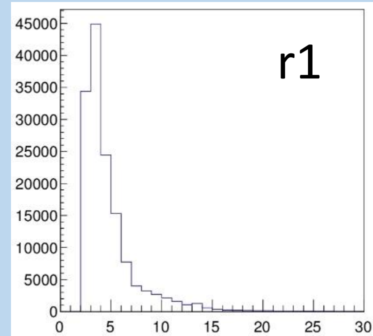


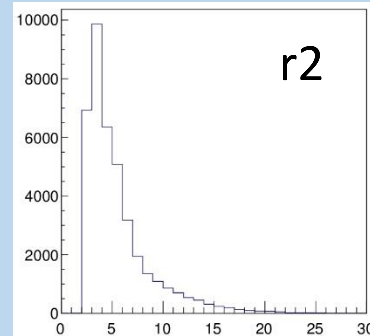


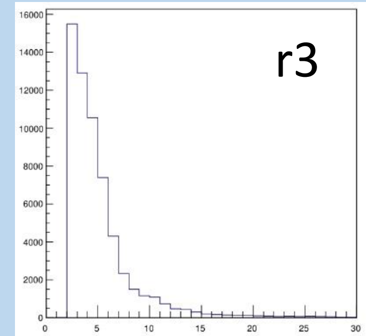


NFZ
(500um)

Depletion depth
~300um

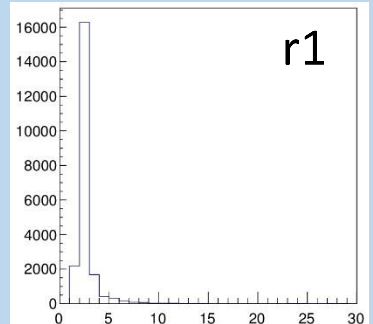


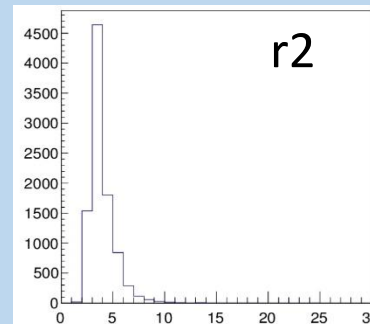


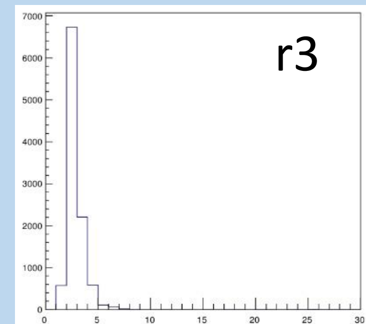


DSOI
(300um)

Depletion depth
~100um

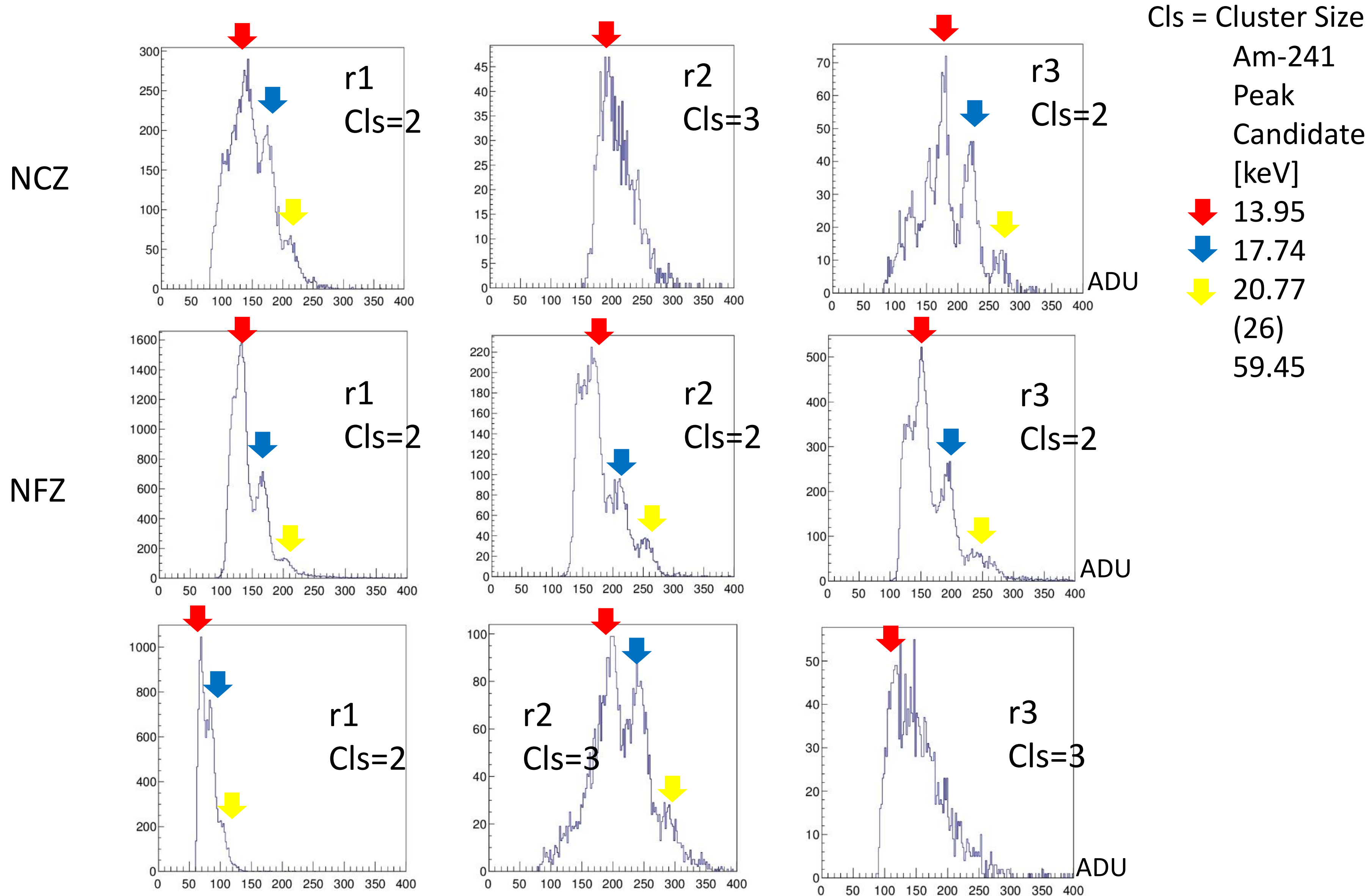






Peak: r1, r3 cluster size = 2
Peak: r2 cluster size = 3 (larger compared with r1&r3)
NFZ larger cluster size compared with NCZ&DSOI(NCZ)

Some X-ray spectra with selected cluster size



Each cluster plot was checked one by one, then the gain was evaluated.

Summary of source test (Am-241)

-50degC,2ms(NFZ)
-60degC,2ms(NCZ)
-60degC,1ms(DSOI)
*Integration time

		r1	r2	r3
Gain NCZ	[uV/e-] or [mV/ke-]	5.35	7.13	6.65
Gain NFZ		5.04	6.73	6.51
Gain DSOI		2.45	7.09	4.70
E.Resolution NCZ	keV[FWHM] @13.95keV	4.07	4.95	1.93
E.Resolution NFZ		2.39	5.23	2.81
E.Resolution DSOI		4.03	7.80	14.5
Dark Noise NCZ	keV [FWHM]	1.39	2.29	0.62
Dark Noise NFZ		0.71	0.72	0.72
Dark Noise DSOI		1.29	0.84	1.21

E.Resolution=Energy Resolution

Sensor gain
- low for Double SOI sensor except region 2

require BNW between pixels (or remove BPW? → to be studied)

Energy resolution
- NFZ r1&r3, NCZ r3 : good

Dark noise
- NFZ, NCZ r3, DSOI r2 : good

* Gain is not corrected in pixel by pixel

Summary

Double SOI sensor has successfully been fabricated
Breakdown voltage & Spatial resolution
seems to be the same as the case of single SOI with proper design
Difference in wafers;
- NCZ low R, low eff. with lower back bias V., high leakage current
- NFZ high R, high eff. with lower back bias V., low leakage current
DSOI(NCZ) low R, low eff. with lower back bias V., high leakage current, partally low gain

DSOI(NCZ):
Charge collection issue
- Find better pixel structure

The 3rd trial: optimize pixel design with p-type DSOI sensors (2014 July)

Total Ionization Damage Compensations in Double Silicon-on-Insulator Pixel Sensors
S. Honda et al., **6/6/2014 14:00 - 14:20**

Tomorrow!

SPRiT (SOI Portable Radiation imaging Terminal)

Thank you!

http://rd.kek.jp/project/soi/

Supplement

Future Plan

INTPIXh2 measurement
- NFZ-INTPIXh2 Am-241 spectrum @ -60degC
- Cd-109 spectrum @ -60degC
- DSOI-INTPIXh2 Am-241 spectra
:Dependence of the middle SOI potential (-1V~+1V)
- KEK-PF monochromatic X-ray

New design for double SOI p-wafer (p-type sensor)
The 3rd trial will be completed hopefully in July

Optimize pixel structure
- Utilize BPW and/or BNW (nested structure etc…)
- Double SOI pixel without BPW (in-pixel)
- Separate mid.SOI(PMOS) with mid.SOI(NMOS)

Development of counting-type double SOI sensor
- Reduce sensor-circuit crosstalk

Some other plots…

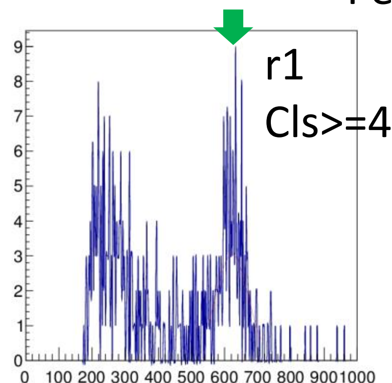
Peak(59.5keV) is very useful

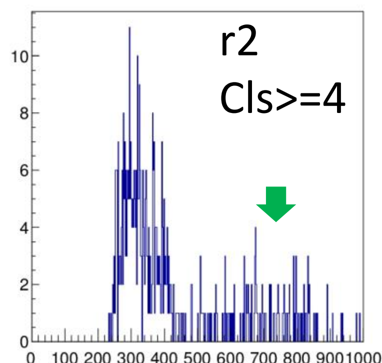
Cls = Cluster Size

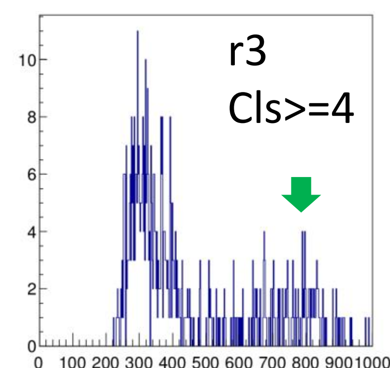
Am-241 Peak Candidate [keV]

- 13.95 (red arrow)
- 17.74 (blue arrow)
- 20.77 (yellow arrow)
- (26)
- 59.45 (green arrow)

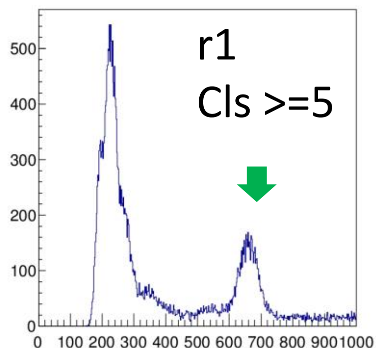
NCZ

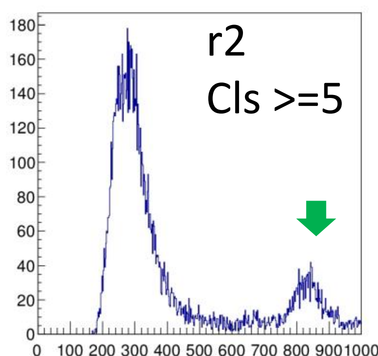


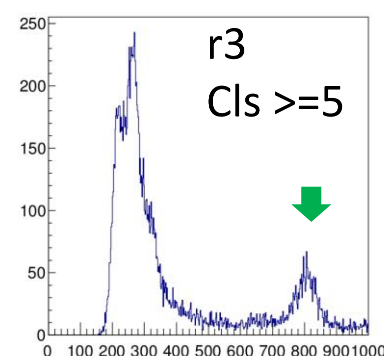




NFZ







DSOI