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

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

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<td>Ryu et al.</td>
<td>IEEE NSS 2010, Conf. Record</td>
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<td>Ryu et al.</td>
<td>IEEE TNS 60, 465 (2013)</td>
<td>XRPIX1b-CZ-FI, Inter-pixel cross-talk</td>
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<td>Takeda et al.</td>
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<td>Charge Collection Efficiency</td>
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Talk Plan

• “XRPIX”  
  the Kyoto’s X-ray Astronomical SOI pixel sensor

• Spectral Performance

• Depletion Layer

• Trigger output and Event Driven Readout

• Charge loss at the interface between the depletion layer and SiO2 insulator
2.4. Heat Sink and Thermo-Electric Cooler (TEC)

The radiator heat is transferred through a heat pipe to a radiator panel on the cold-end of the TEC is directly connected to the substrate to generate a temperature difference of about 16C. The PPU extracts a charge pattern characteristic of X-rays, while AE/TCE may include a pulse height (PH) offset from the true energy scale of ~3e- (rms). Therefore one line, 90

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

Fano limited spectroscopy with the readout noise ~3e- (rms).

Wide and fine imaging with the sensor size of ~20-30mm pixel size of ~30µm.

High QE by BI and thick depletion (200µm for ASTRO-H).

Non X-ray background of Suzaku XIS (BI)

Due to high energy particles on orbit.
“XRPIX” = **Monolithic** SOI pixel sensor for future X-ray astronomical satellites

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**Sensor**
- (high $\rho$, depleted Si)

**Insulator**
- (SiO2)

**Fast CMOS**
- (low $\rho$ Si)

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**Our SOIPIX (XRPIX)**

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

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**Target Spec.**

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<td><strong>Imaging</strong></td>
<td>area &gt; 25x25mm$^2$, pixel $\sim$ 30-60µm$^2$ (1” @ F=9m)</td>
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<td><strong>Energy Band</strong></td>
<td>0.3-40keV with BI (&lt;0.1µm), and thick depletion (&gt;250µm)</td>
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<td><strong>Spectroscopy</strong></td>
<td>$\Delta E &lt; 140$eV @ 6keV, Fano limit (Req.&lt;10e-, Goal &lt; 3e-)</td>
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<tr>
<td><strong>Timing</strong></td>
<td>&lt;1µsec</td>
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<td><strong>Dark Current</strong></td>
<td>&lt;2pA/cm$^2$ (assuming working T = -40°C)</td>
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<tr>
<td><strong>Function</strong></td>
<td>Trigger signal &amp; pixel address output, built-in ADC (option)</td>
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<td><strong>Non X-ray BGD</strong></td>
<td>5e-5 c/s/keV/10x10mm$^2$ at 20keV (1/100 of CCD)</td>
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XRPIX Series - Road Map -

- XRPIX1
  - 1.0mm
  - 2.4 mm

- XRPIX1b
  - 1.0mm
  - 2.4 mm

- XRPIX2
  - 4.0mm
  - 6.0 mm
  - First Model
  - Trigger
  - Output

- XRPIX2b
  - 4.5mm
  - 6.0 mm
  - Middle Size

- XRPIX3
  - 1.0mm
  - 2.9 mm
  - Buttable
  - Charge Sensitive AMP

- XRPIX3b
  - 1.0mm
  - 2.9 mm

- XRPIX ΔΣ-type ADC
  - 2.4 mm

Years:
- 2010
- 2011
- 2012
- 2013
- 2014
• Measure the depletion thickness by observing the ratio between the counting rates of two energies X-rays having different attenuation lengths.

• CZ: Depletion thickness of 150μm at VBB=100V.

• FZ: Full depletion is achieved at VBB=30V.
Counting Rate of 22keV X-ray (Cd-109) as a function of VBB.

(Attenuation Length = 1200 μm > Physical Thickness = 500 μm.)

The data follow the expected slope of depletion \( \propto VBB^{1/2} \).

Full Depletion of 500 μm is reached at VBB=200V.
**XRPIX2-CZ-F1 (Small Pixel): Spectrum in the frame mode**

**Cu Kα (8.0 keV)**
- **Observed:** 656 eV
- **FWHM:** 548 eV (FWHM)
- **64 e- (rms)**
- **Readout Noise:** 139 eV
- **Fano Noise:** 553 eV
- **Sum:** 620 eV

**Mo Kα (17.4 keV)**
- **Observed:** 800 eV
- **FWHM:** 205 eV
- **ppd Dispersion 1%:** 805 eV

**Cu Kα (8.0 keV) & Mo Kα (17.4 keV)**
- **FWHM:** 19.6 keV

**PH [ADU]**
- **Cu Count:** 100, 200, 300, 400
- **Mo Count:** 100, 200, 300, 400

**Nakashima et al., 2012, NIM A submitted**

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**XRPIX2 Gain**
- **6.5 µV/e⁻**

**XRPIX1 Gain**
- **3.6 µV/e⁻**
A charge sensitive amp (CSA) in every pixel in order to increase the gain and improve energy resolution.

CSA is basically the same that developed in another SOIPIX (PIXOR).

Gain \(~50\ \mu\text{V/e, higher by a factor of } \sim10\).

Readout noise = 64e (rms) \rightarrow Now testing
XRPIX2b-CZ : Event-driven Readout Mode

- Event-driven mode basically operates.
- Capacity of event rate >1kHz.
- The gain is different. There is offset.
- Due to interference between analog and digital circuits

Note: Pixel gain is not calibrated.

Fe-55 (5.9keV)

Preliminary

Preliminary

X-ray Energy (keV)

22keV X-ray detection Cd-109

5.4 μV/e-

7.0 μV/e-

0 5 10 15 20 25 30 35 40
0 50 100 150 200 250 300 350

Takeda et al., IEEE (2013)
**BPW**: Buried p-well

- Suppress the back gate effect of Tr.
- Also act as a part of charge collecting node.
- Increase parasitic capacitance.
- A large BPW reduces node gain.

A part of signal charge is lost somewhere.
The charge loss occurs in the region of pixel boundary.
Charge Loss at interface between Si and SiO₂

- Electric field penetrates into SiO₂ insulator.
- Signal charge moves to the interface region between depleted Si and SiO₂ insulator.
- The signal charge would be trapped and lost at the interface.
- Pencil X-ray beam test in SPring-8.

Y. Ono, master thesis "Research and development of the PIXOR (PIXel OR) semiconductor detector for the high energy experiments based on the SOI technology" (unpublished, in Japanese) http://epx.phys.tohoku.ac.jp/eeweb/paper.html
Summary

• Developing monolithic SOI sensor ‘XRPIX’ for future X-ray Astronomical Satellites.

• Realize the event driven readout mode and very low non-X-ray BGD by the function of the trigger signal output.

• Depletion region ~500μm.

• The readout noise ~60e- → Charge Sensitive Amp.

• The event driven readout basically operates.

• Signal charge would be lost at the interface between the depleted Si and SiO2 insulator. → Pencil X-ray mean test.