Pushing the Limits of Kyoto’s SOI Pixel Sensor for X-ray Astronomy with the Pinned Depleted Diode

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FORCE Satellite Mission

Focusing On Relativistic universe and Cosmic Evolution

Wideband Hybrid X-ray Imager

- < 20 keV Si sensor
- > 20 keV CdTe sensor

★ Wide energy range : 1 - 80 keV (Requirement)
★ Si + CdTe hybrid detector

 Requirement of Si sensor

- Energy resolution of < 300 eV (FWHM) @ 6 keV
- Time resolution of < 10 μs for anti-coincidence

We have been developing X-ray Si sensor for FORCE mission.

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SOI Pixel Detector “XRPIX”

general XRPIX structure

“XRPIX” = series of SOI pixel sensors for X-ray detection

XRPIX Advantages

* No mechanical bump bonding
  → High Density, Low Parasitic Capacitance, High Sensitivity
* Standard CMOS circuit can be built
  → Trigger output function for good time resolution
* Based on industrial standard technology

Previous devices have two known problems related to charge collection efficiency.

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Spectrum Resolution Difference at Sub-Pixel

Energy spectrum folded in one pixel at 5 keV.

- Tail structure near pixel boundaries.
- The energy resolutions at pixel boundaries are ~ 4 times larger than that at the pixel center.

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We define $T_{\text{STORE}}$ as exposure time after the trigger comes out.

- $T_{\text{STORE}} \approx 320$ ns
- $T_{\text{STORE}} \approx 1.2$ µs
- $T_{\text{STORE}} \approx 10$ µs
- $T_{\text{STORE}} \approx 100$ µs
- $T_{\text{STORE}} \approx 1$ ms

FORCE mission requires $T_{\text{STORE}} < \approx$ µs

- Fake peak appears when the $T_{\text{STORE}}$ is short.
- We speculate that the charge collection efficiency is different at X-ray incident position in the same pixel.
We speculate that both of those problems are due to the signal charges are trapped at the interface between the sensor layer and SiO₂ layer.
Pinned Depleted Diode Structure (PDD) Structure (Kamehama+2018) is employed to mitigate the issues in our previous devices.

* Highly doped buried p-well acts as shield layer to reduce noise.
* Signal charges are transported through stepped buried n-well to the sense node without touching the interface between the sensor layer and SiO₂ layers.

To solve those problems we have developed XRPIX6E with PDD structure.
Placing a thin metal mesh with evenly spaced holes, the hole pitch is multiple to the detector pixel size, parallel to the detector surface and tilted by a small angle. →The hole shadows on the detector gradually shift positions from pixel to pixel.
Mesh Experiment

- X-ray incident position on the detector is restricted by the mesh hole.
- Large number of pixels represent an expanded one pixel structure.
- We can easily determine the incident position on the pixel from the hole shadow on the detector.

This technique enables us to evaluate the sub-pixel resonance.
Experimental Setup

- **X-ray tube**
- Thermostatic Chamber (-15°C)
- Readout boards
- XRPIX6E
  - Pixel size: 36 μm x 36 μm
- Mesh
  - Pitch: 108 μm
  - Hole diameter: 4 μm

Output spectrum from X-ray Tube taken by SDD

- W-Lα: 8.4 keV
- W-Lβ: 9.71 keV
- W-Lγ: 11.28 keV
Spectrum Resolution as Sub-Pixel

previous device (XRPIX3b)

Energy spectrum folded in one pixel at 8.4 keV.

XRPIX6E

- No tail structure is seen near pixel boundaries of XRPIX6E
- Energy resolutions near pixel boundaries are ~ 2 times larger than that at the pixel center.
Spectrum Shape is Related to $T_{\text{STORE}}$

**XRPIX6D**
- $T_{\text{STORE}} \sim 320$ ns
- $T_{\text{STORE}} \sim 1.2$ µs
- $T_{\text{STORE}} \sim 10$ µs
- $T_{\text{STORE}} \sim 100$ µs
- $T_{\text{STORE}} \sim 1$ ms

**XRPIX6E**
- $T_{\text{STORE}} \sim 320$ ns
- $T_{\text{STORE}} \sim 500$ ns
- $T_{\text{STORE}} \sim 750$ ns
- $T_{\text{STORE}} \sim 1$ µs
- $T_{\text{STORE}} \sim 10$ µs

Fake peak not appears at the pixel center and pixel boundaries when the $T_{\text{STORE}}$ is short.

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Summary

* We performed the mesh experiment to evaluate the X-ray response at the sub-pixel level for XRPIX6E with the PDD structure.

* No tail structure is seen near pixel boundaries of XRPIX6E.

* Energy resolution at the pixel center is about 190 eV.

* Energy resolutions near pixel boundaries are ~ 2 times larger than that at the pixel center.

* Fake peak not appears at the pixel center and pixel boundaries.

* These results indicate that charges are efficiently collected even near pixel boundaries. We thus conclude that the PDD structure of XRPIX6E solved the previously-known problems related to the charge collection efficiency.