Proton Radiation Damage Experiment for X-Ray Pixel Detectors

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We have been developing XRPIX which is a monolithic active pixel sensor based on Silicon On Insulator (SOI) CMOS technology for future satellites. XRPIX has time resolution shorter than 10 micro seconds. Furthermore, XRPIX has similar energy resolution to the CCDs because of small parasitic capacitance owing to SOI technology.

In low earth orbit, there are many cosmic rays which are composed primarily of high energy protons. By interacting with the cosmic rays, semiconductor detectors are damaged, and their performance such as energy resolution gets worse. Thus, to examine their radiation hardness is one of important issues.

We used heavy ion accelerator at National Institute of Radiological Science in Chiba to perform our proton radiation damage experiment for XRPIX. We irradiate 6MeV proton to XRPIX2bFZ. With 410rad irradiation, whose equivalent time in orbit is 3.5 years, degradations of gain and energy resolution are less than 0.2% and 0.5%, respectively.
After more proton irradiation, specifically at 4000rad, gain increases by 0.7% and energy resolution gets worse by 10% than those with no damage.
In addition, we found out that damage of source follower increased fluctuation of output and this is one of cause which worsened energy resolution.

XRPIX

XRPIX is CMOS image sensor for next generation X-ray satellites based on SOI technology. X-ray satellites commonly load X-ray Charge Coupled Devices (CCDs). But CCDs time resolution (~4sec) is regarded as a problem. XRPIX's energy resolution is equivalent to CCDs, and shorter time resolution (<10μs) owing to trigger function.

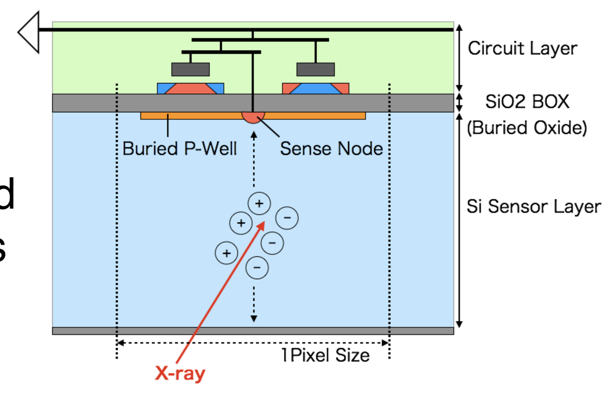


Figure1: Schematic drawing of XRPIX

Radiation damage of Semiconductor detector

In the space radiation environment, performances of semiconductor detectors degrade year by year due to lattice detect or total ionizing dose.
Lattice defect or Total Ionizing Dose (TID) is suspected as the reason for this.
We fear that XRPIX is suffered by the same effect, so we have to assess quantitatively and investigate damage mechanism.

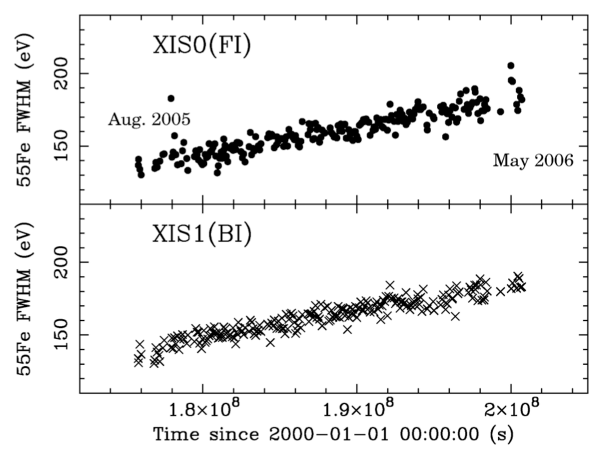


Figure2: Time variation of XIS energy resolution

Proton radiation experiment

We irradiated a XRPIX with proton beam and examined the effect of radiation damage.
We experimented on condition as shown below.

Table1: Detector Information

Detector	XRPIX 2b FZ
Sensor Thickness	500 μm
Pixel Size	30 μm × 30 μm
Pixel Number	144 × 144
Resistivity	5.0 kΩ·cm

Proton didn't go through XRPIX.
But proton beam irradiated from XRPIX's thin circuit layer, so we could damage sensor layer as well as circuit layer.

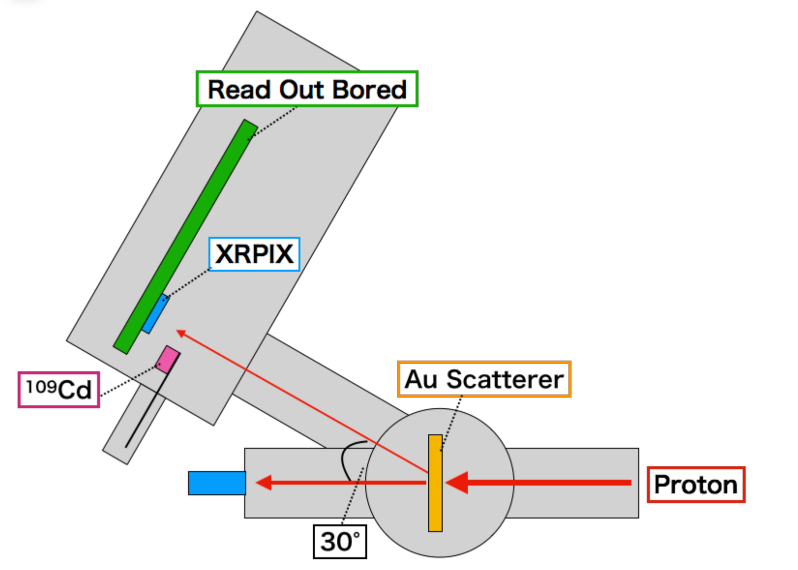


Table2: irradiation conditions

Place	HIMAC
Proton Energy	6 MeV
Back Bias Voltage	150 V
Integration Time	100 μs
Irradiated from sensor layer	

Result

One of our purpose is XRPIX can endure 3.5 years operation.
So, we report from two aim. One of them is 410 rad whose equivalent time in orbit is 3.5 years,
and the other is hard damaged 4000rad.

Back Bias Voltage	250 V
Integration Time	100 μs

Energy Spectrum

We irradiated ^{109}Cd X-ray from sensor layer when we examined the XRPIX's performance.
This is spectrum of Single Pixel Event.
Peak at 170 ch is AgKa **characteristic X-ray.**

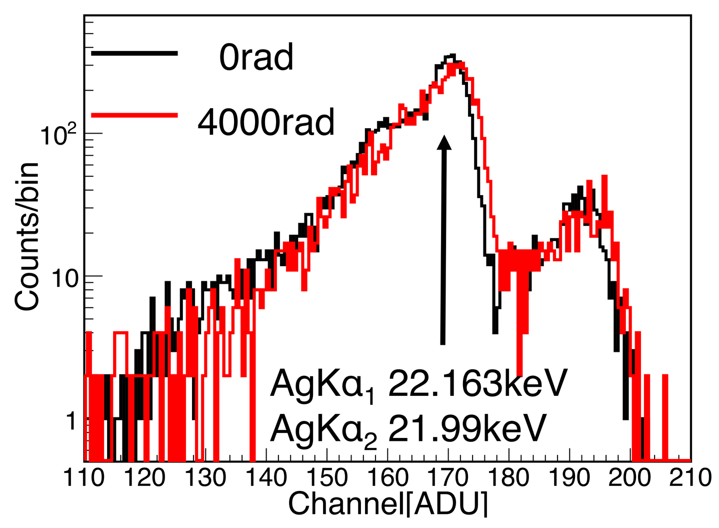


Figure3: Energy spectra at Vbb 250V

Bad Pixel Fraction

We defined bad pixel as the pixel whose output differ 3sigma from average of all pixel's output.
Bad pixel fraction was only 1~2% until 4000 rad.
Since 10000 rad, the fraction increased rapidly.
After 4000 rad, we removed some from evaluation because too large fluctuation of pedestal impeded bad pixel selection.

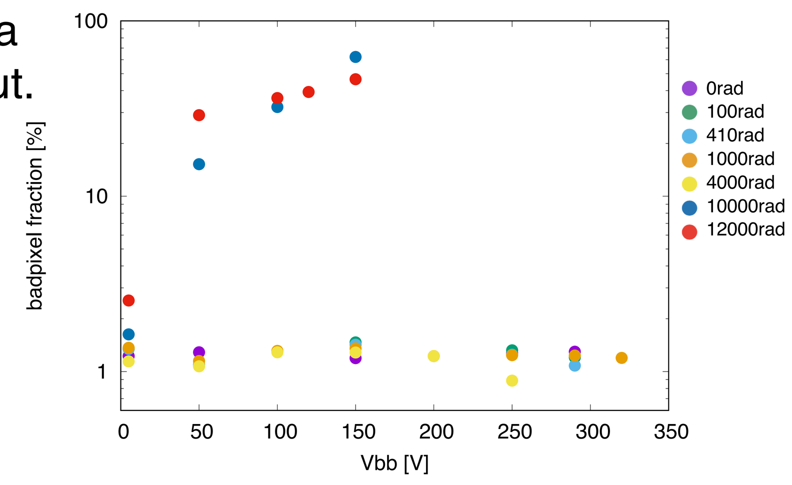


Figure4: Bad Pixel fraction to all pixel number

Leak current

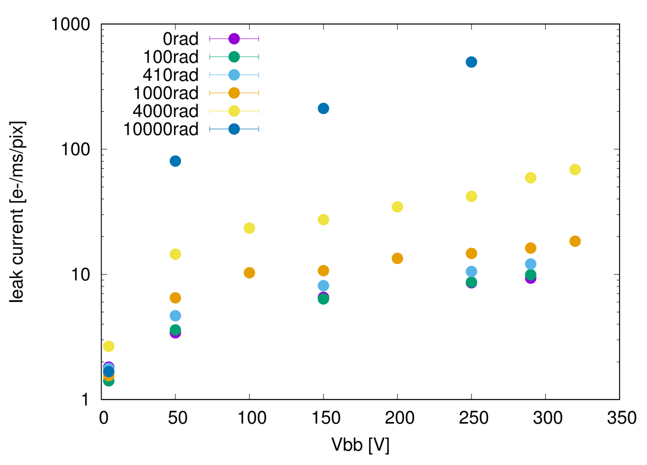


Figure5: I-V characteristics

Gain

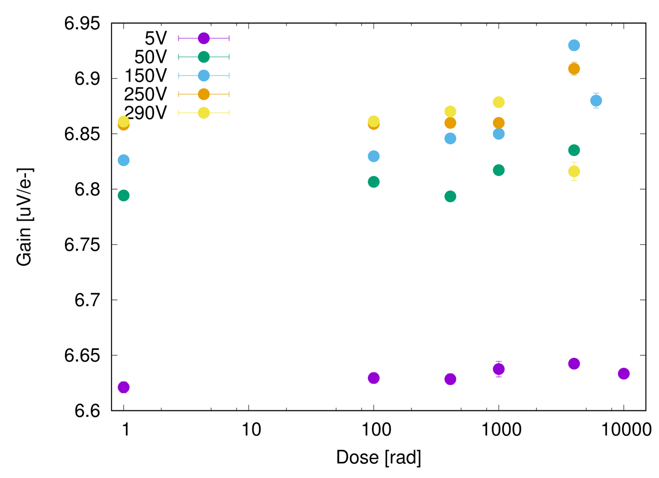


Figure6: Transition of gain

Leak current grew by 20 % at 410 rad. At 4000 rad, leak current increased rapidly to 5 times.
And inclination became steeply since 4000 rad.
Focus on gain at Vbb = 250 V, rate of increase was only 0.2 % at 410 rad.
Significant difference is showed up at 4000 rad but the rate was no more than 0.7 %.

Energy Resolution

Definition from FWHM of ^{109}Cd AgKa1 peak(22.163keV).

FWHM increased at most 5.5% at 410 rad but this was not significant different.
We could see increasing trend when we irradiated to 4000rad.

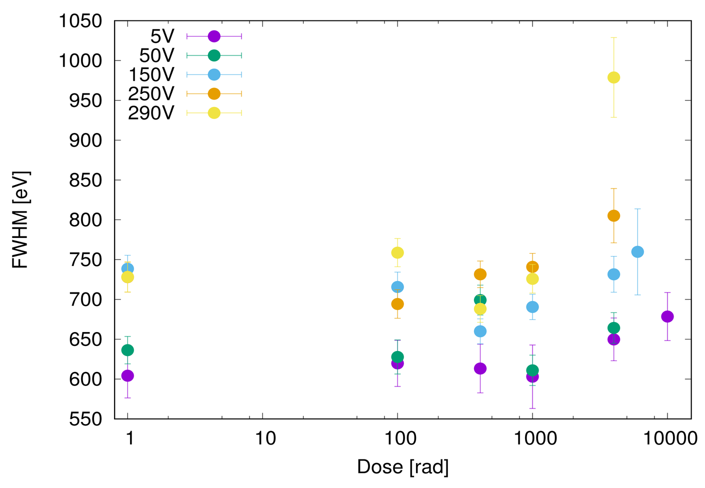


Figure7: Transition of energy resolution

Noise decomposition

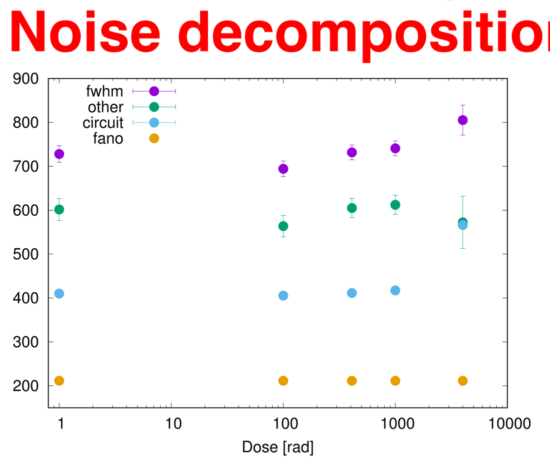


Figure8: Transition of every kind of noise

We could isolate noise to use these expressions.

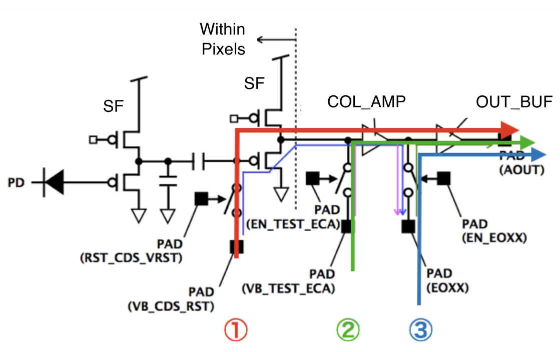
$$\sigma^2 = \sigma^2_{\mathrm{Readout}} + \sigma^2_{\mathrm{Fano}}$$

$$\sigma^2_{\mathrm{Readout}} = \sigma^2_{\mathrm{leakcurrent}} + \sigma^2_{\mathrm{circuit}}$$

But we couldn't recreate FWHM from these expressions, so we introduced other term.

$$\sigma^2 = \sigma^2_{\mathrm{leakcurrent}} + \sigma^2_{\mathrm{circuit}} + \sigma^2_{\mathrm{Fano}} + \sigma^2_{\mathrm{other}}$$

We show this result in left figure. The figure tells us increasing circuit noise made energy resolution worse.
Therefore, an arbitrary voltage was applied to only a part of the circuit, and it was verified whether the output changes with the route.
By comparing with each of various route output, we can detect a cause of increasing circuit noise.



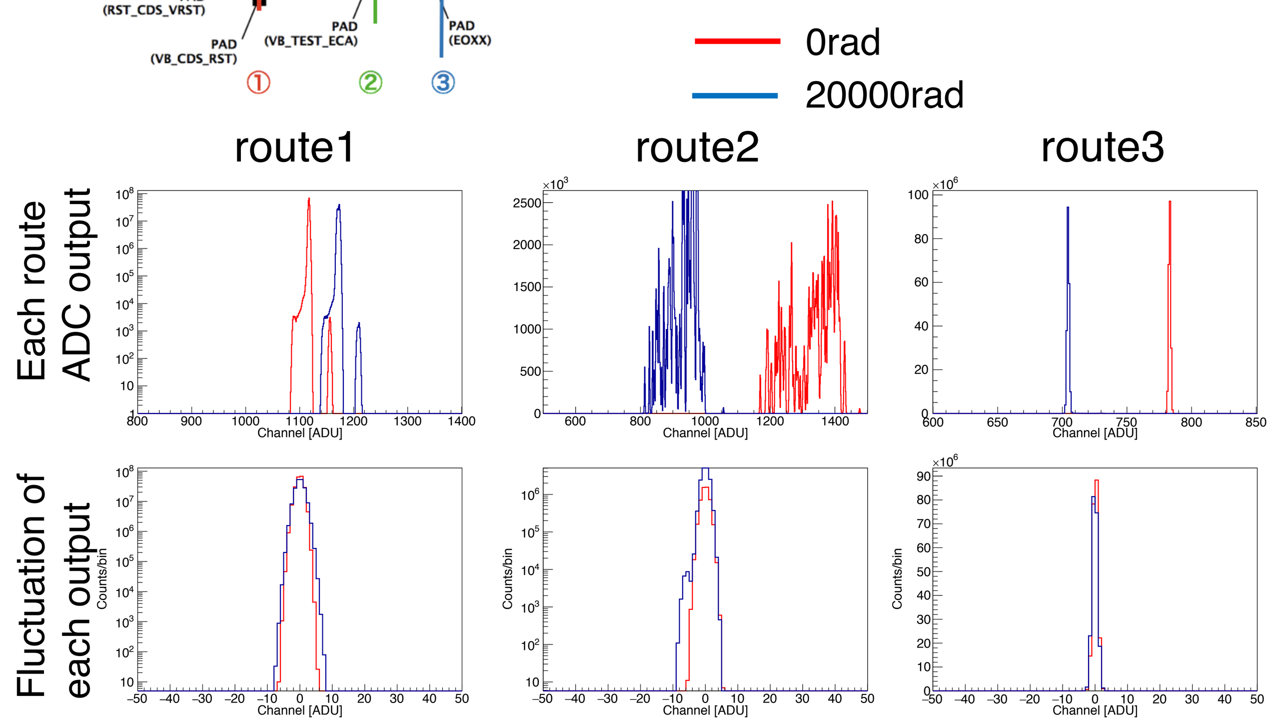


Figure9: Output and fluctuation of each route

In route2 and 3, the level of output became lower after damage. Radiation damage made fluctuation of route1 worse, but output after route2 had same fluctuation level before and after damage.
From this result, we detected that damage of source follower caused output dispersion.
Not only that latest amplifier output lower level after damage.

Conclusion

- XRPIX2b's performance like gain or energy resolution didn't show significant different at 410 rad whose equivalent in orbit is 3.5 years.
- After 4000 rad, leak current and energy resolution showed significant different.
- By comparing of each circuit output, circuit noise increases at source follower.