Radiation Hardness of a P-Channel Notch CCD Developed for the X-ray CCD Camera onboard the XRISM Satellite

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# X-ray CCD for astronomical use

## History of standard focal-plane detectors in Japan

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Period</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASCA</td>
<td>1993-2001</td>
<td>417</td>
</tr>
<tr>
<td>SUZAKU</td>
<td>2005-2015</td>
<td>1700</td>
</tr>
<tr>
<td>HITOMI</td>
<td>2016</td>
<td>2700</td>
</tr>
<tr>
<td>XRISM</td>
<td>2021-</td>
<td></td>
</tr>
</tbody>
</table>

### New Satellite

**XRISM (2021-)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>N-ch FI CCD</td>
<td><img src="image1" alt="CCD Cross-section" /></td>
</tr>
<tr>
<td>N-ch BI CCD</td>
<td><img src="image2" alt="CCD Cross-section" /></td>
</tr>
<tr>
<td>P-ch BI CCD</td>
<td><img src="image3" alt="CCD Cross-section" /></td>
</tr>
<tr>
<td>P-ch BI CCD (w/ notch)</td>
<td><img src="image4" alt="CCD Cross-section" /></td>
</tr>
</tbody>
</table>

200um n-type Si p-channel

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**Notch Structure**
Radiation damage in space

For space application, radiation hardness is one of the most important properties.

- A CCD in space is severely exposed to cosmic rays.
- These particles produce lattice defects -> worsen the efficiency of charge transfer.

- In the case of XRISM, ~100 MeV protons in SAA are the major source of irradiation damage.
- If the camera body is simplified into 20mm thick Al, The dose rate of the CCD is **260 rad/year**.
An indicator of the radiation damage is **Charge Transfer Inefficiency (CTI)**. 

- CTI is defined as the fraction of charge loss in a single pixel transfer, and which is measured by fitting pulse height (PHA) as a function of the number of transfers (Y).

\[
\text{PHA}(Y) = \text{PHA}_0 \times (1 - \text{CTI}_1) \times (1 - \text{CTI}_2) \times \cdots \times (1 - \text{CTI}_Y)
\]

- Y: the number of transfers
- \(\text{PHA}_0\): pulse height w/o charge-transfer loss
- \(\text{CTI}_y\): CTI in a transfer from \(y\) to \(y - 1\)

If CTI is independent of \(Y\), the function is simplified into:

\[
\text{PHA}(Y) = \text{PHA}_0 \times (1 - \text{CTI})^Y \quad (\text{CTI}_y = \text{const.} =: \text{CTI})
\]

If an imaging area damaged uniformly, CTI remains constant. If **damaged non-uniformly**, CTI changes as \(Y\) increases.
CTI degradation

An indicator of the radiation damage is **Charge Transfer Inefficiency (CTI)**.

- CTI is defined as the fraction of charge loss in a single pixel transfer, and which is measured by fitting pulse height (PHA) as a function of the number of transfers (Y).

\[
PHA(Y) = PHA_0 \times (1 - CTI_1) \times (1 - CTI_2) \times \ldots \times (1 - CTI_Y)
\]

\[
= PHA_0 \times \prod_{y=1}^{Y} (1 - CTI_y)
\]

- \( Y \): the number of transfers
- \( PHA_0 \): pulse height w/o charge-transfer loss
- \( CTI_y \): CTI in a transfer from \( y \) to \( y - 1 \)

If CTI is independent of \( Y \), the function is simplified into:

\[
PHA(Y) = PHA_0 \times (1 - CTI)^Y
\]

If an imaging area damaged uniformly, CTI remains constant. **If damaged non-uniformly, CTI changes as Y increases.**
Mitigation of radiation damage effects

In order to reduce radiation damage effects, we applied some methods to our device.

- One of them is a Charge Injection (CI) technique.

- This technique was adopted for the Hitomi CCD, and is also used to the XRISM CCD.
Notch channel technology

The notch structure is newly employed to improve radiation tolerance.

- By increasing the implant concentration in the narrow region of the buried-channel, a notch is formed at the bottom of the channel potential. -> reduce the probability of charge interaction with traps
- For space application, we need to know the radiation hardness of new device and whether the notch structure works as expected.
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CCDs used in the experiment

We fabricated two mini-CCDs (w/ notch and w/o notch) for the experiment

- The storage area was covered when irradiation
- These devices differ from the flight model in terms of imaging area size & format

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### Specifications of the mini-CCD

<table>
<thead>
<tr>
<th>Type</th>
<th>Frame-transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>$24 \times 24 \ \mu m^2$</td>
</tr>
<tr>
<td>Binning</td>
<td>$2 \times 2$</td>
</tr>
<tr>
<td>Clocking</td>
<td>2 phase (H &amp; V)</td>
</tr>
<tr>
<td>Exposure cycle</td>
<td>4 sec/frame</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>$-110 \ ^\circ C$</td>
</tr>
<tr>
<td>Imaging area size</td>
<td>$7.7 \times 6.1 \ mm^2$</td>
</tr>
<tr>
<td>Format</td>
<td>w/o binning $320(H) \times 256(V)$</td>
</tr>
<tr>
<td></td>
<td>w/ binning $160(H) \times 128(V)$</td>
</tr>
</tbody>
</table>
Proton irradiation in HIMAC

The experiment was performed in HIMAC

- HIMAC is a synchrotron facility for heavy ion therapy.
- The beam directly entered imaging area of unpowered CCD under atmospheric pressure at room temperature.
- After irradiation, the devices were delivered to a lab and exposed X-rays with $^{55}$Fe for CTI measurement.

Summary of the experiment

<table>
<thead>
<tr>
<th>date</th>
<th>2018/4/24-29</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam line</td>
<td>HIMAC PH1</td>
</tr>
<tr>
<td>nuclide</td>
<td>p</td>
</tr>
<tr>
<td>energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>radiation dose</td>
<td>1,118 rad (w/ notch)</td>
</tr>
<tr>
<td></td>
<td>676 rad (w/o notch)</td>
</tr>
</tbody>
</table>
Since the beam width is smaller than imaging area, the damage is not uniform

- The irradiation was concentrated around the center of the imaging area
- We had to consider the non-uniform radiation damage. --> CTI becomes a function of Y row
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We defined two damage area.

- The Severe damage area is defined: $40 < X < 80$
- the events in the severe damage area apparently & non-linearly lost charges as $Y$ increases.
  - This means CTI is a function of $Y$ row.
CTI as a function of the number of transfers

We measured non-uniform CTI as below.

- Pulse height (PHA) is a function of $Y$ (with considering the binning):
  \[
  \text{PHA}(Y) = \text{PHA}_0 \times (1 - \text{CTI}_1)^2 \times (1 - \text{CTI}_2)^2 \times \cdots \times (1 - \text{CTI}_Y)^2 \\
  = \text{PHA}_0 \times \prod_{y=1}^{Y} (1 - \text{CTI}_y)^2
  \]

- We assumed that $\text{CTI}_y$ is a Gaussian function because the beam distribution can be approximated as 2D Gaussian function.
  \[
  \text{CTI}_y = c \exp \left\{ -\frac{(y - Y_0)^2}{2\sigma^2} \right\} + cti_{\text{const}}
  \]
  - $Y_0$ : $Y$ coordinate of the center of the beam
  - $\sigma$ : beam width
Measurement of CTI

The fit results are below:

- All of the data are well described by the CTI model.
- The CTI degradation of w/ notch CCD is smaller than that of w/o notch CCD.

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Estimation of radiation dose at Y row

In order to know the relation of CTI and radiation dose, we need to estimate the dose amount of each Y row pixels.

The radiation dose of Y row pixels:

\[
dose(y) = c \int_{Y=y}^{Y=y+1} \int_{X=40}^{X=80} f(X, Y) dX dY
\]

- dose\((y)\): the radiation dose of y row pixels
- c: the total radiation dose
- f: beam distribution function

- Since the total radiation dose was measured, we were able to estimate the radiation dose by integration of the beam distribution over each Y row pixels.

In the beam distribution, we assumed that:

1. the distribution is approximated as a 2D Gaussian function.
2. The vertical and horizontal widths are estimated from CTI and horizontal profile of PHA, respectively.
1. **CTI of w/ notch CCD is significantly reduced in comparison with those of conventional CCDs.**
   -> the new notch CCD is radiation tolerant for the space application with a sufficient margin.

2. It is confirmed that the CI technique is effective for both types of CCDs.

3. Although w/o notch CCD is the same as the Hitomi CCD, the black dots are located between two lines.
Considering the difference of initial CTI

Since initial CTI is dependent on lot number, we considered the difference of initial CTIs between this result and the past one for comparison.

- Assuming the same initial CTIs between the new CCDs and the Hitomi CCD, the above results are obtained. 
  -> The initial CTIs seem a factor of the apparent difference of these results.
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Summary

• We performed a proton irradiation experiment on a new type of p-channel notch CCD for the XRISM satellite.

• The radiation doses of the w/ notch device and w/o notch device are 1,118 rad and 676 rad, respectively.

• The result shows that w/ notch CCD has the significantly higher radiation hardness than w/o notch CCDs including the one adopted for Hitomi.

• This proves that the new CCD is radiation tolerant for the space application with a sufficient margin.