Evaluation of the X-ray SOI pixel detector with on-chip ADC

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Outline

Introduction
  X-ray astronomy
  Concepts of future X-ray detector & XRPIX

Results of evaluations
  Unit test of the on-chip ADC
    Integral non-linearity
    Differential non-linearity
  Noise from on-chip ADC
  XRPIX end-to-end test
    obtain X-rays spectrum from XRPIX
X-ray astronomy

We can study high-energy physics through X-ray observations

Example: High energy celestial objects

<table>
<thead>
<tr>
<th>Neutron stars</th>
<th>Vicinity of Black holes</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="" alt="Neutron stars" /></td>
<td><img src="" alt="Vicinity of Black holes" /></td>
</tr>
</tbody>
</table>

Current standard X-ray detector: CCD

**Pros**: Energy resolution: 150 eV @ 6 keV
  Good spatial resolution: 20 ~ 30 um

**Cons**: Time resolution: several seconds
  Unsuitable for celestial objects rotating in seconds
Concepts of future X-ray detector

Energy range: 0.5 – 80 keV
- Adopted Si sensor (<20 keV) and CdTe sensor (>20 keV)
- Capable of wide-band X-ray research

Observation targets: High energy celestial objects

Low background above 10 keV
- Reduce non-X-ray events by active shields
- Capable of low luminosity celestial objects

Good time resolution ~ a few us

Future Si detector’s Requirements

\[ \Delta E < 140 \text{ eV} @ 6 \text{ keV} \]
- It catches X-rays less than 20 keV
- Time resolution ~ a few us

This talk theme: Future Si detector XRPIX
**Future X-ray detector : XRPIX**

XRPIX is the *new* X-Ray detector made with SOI technology.

- **Combine CMOS Layer and Sensor**
- **SiO2 (Insulation layer)**
- **CMOS layer**
- **Sensor layer**
- **X-rays**

**Trigger function**
- Measure the moment when X-rays hit

**Good time resolution**
- Each pixel has trigger function
- Time resolution <10 us

**Energy resolution**
- $\Delta E < 300$ eV at 6 keV
- Goal : $\Delta E < 140$ eV at 6 keV

**Thick sensor layer**
- High detection efficiency for X-rays

**It will be installed on X-ray satellites**
XRPIX’s current status

We’ve been researching and developing

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
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<tbody>
<tr>
<td>Model</td>
<td>XRPIX1</td>
<td>XRPIX1b</td>
<td>XRPIX2b</td>
<td>XRPIX3</td>
<td>XRPIX3b</td>
</tr>
<tr>
<td>Size</td>
<td>1.0 mm</td>
<td>1.0 mm</td>
<td>4.6 mm</td>
<td>1.0 mm</td>
<td>1.0 mm</td>
</tr>
<tr>
<td></td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>6.0 mm</td>
<td>2.9 mm</td>
<td>2.9 mm</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Charge Sensitive Amplifier</td>
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</table>

2015 | 2016 | 2017 | 2018
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>XRPIX5</td>
<td>XRPIX6G</td>
<td>XRPIX6C</td>
<td>XRPIX6E</td>
</tr>
<tr>
<td>13.8 mm</td>
<td>4.45 mm</td>
<td>6.0 mm</td>
<td>4.6 mm</td>
</tr>
<tr>
<td>24.6 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pixel Structure</td>
<td>D-SOI Structure</td>
<td>Structure</td>
</tr>
</tbody>
</table>

This talk

XRPIX6E
FWHM~240 eV at 6.4 keV

Sensor: Good spectral performance

We are currently working on digitalization

Harada et.al 2019
Previous designs and problems

**Previous XRPIX**

**XRPIX with on-chip ADC**

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**Future objective**

Install on future X-ray satellites

**Problem in X-rays satellites**

Require a large imaging area in a limited space

**ADC mounted on XRPIX for Compactness**

NEXT : Details of XRPIX with on-chip ADC
XRPIX with on-chip ADC

XRPIX9
The first XRPIX to output digital signal

- Pixel area: 36 um x 36 um
- Sensor layer: ~300 um
- Capable of wide-band detection: 1.0 - 40 keV

XRPIX9 on-chip ADC

- Type: Cyclic ADC
- High speed (6 us)
- Small size (20 um)

Advantages:
- Number of bits: 14 bits
- Voltage range: 0.4-1.5 V
- Total units: 16 units
- 1 column has 2 ADC

Goal: Evaluate the performance of its on-chip ADCs and inspect that XRPIX9 has the same performance of previous XRPIX
Unit test of the on-chip ADC

Input ramp wave or constant voltage into ADC

Analog signal

XRPIX9 on-chip ADC

14 bits Digital signal

Function generator
Result1: Integral Non-Linearity (INL)

Input ramp wave into on-chip ADC

- Ideal ADC steps one at a time
- Actual ADC: Vertical deviation occurs

Methods:
Fitted actual ADC outputs with straight line calculated residuals between the line and ADC outputs

INL (LSB)

- Single ADC
- Averaged 2ADCs

INL: 6 LSB (=36 eV, 0.036 %)

Negligible level for resolution 300 eV

2ADC are used for 1 column
Averaged 2ADCs

ADC Outputs
**Result 2: Differential Non-Linearity (DNL)**

**Methods**:
- Histogram the number of AD outputs
- Evaluate deviation from ideal ADC

**Actual ADC**
- Ideal AD
- Lateral deviation

**<Result>**
- single ADC
- averaged 2ADCs

**Averaged ADC’s DNL < 0.4 LSB**
**Single ADC’s DNL < 0.7 LSB**
**NO MISSING CODE**

**DNL (LSB)**

**AD output**

![Diagram showing ideal and actual ADCs with DNL analysis](image-url)
Result3: Noise

**Methods**: Input constant voltage into on-chip ADC

1. Histogram AD outputs
2. Fitted hist with Gauss

Histograms of AD outputs

![Histograms of AD outputs](image)

Evaluated width (@1 σ)

![Evaluated width](image)

Width of noise at each ADC

![Width of noise at each ADC](image)

Noise width ~ 3 LSB (= 5 e)  
Negligible level for 300 eV
XRPIX9 end-to-end test

Irradiated X-rays on XRPIX

55Fe (5.9 keV) & 109Cd (22.1 keV)

XRPIX9

Spectrum from on-chip ADC

- 5.9 keV FWHM ~ 300 eV
- 22.1 keV FWHM ~ 400 eV
- 3.1 keV
- 6.4 keV
- 25.0 keV

XRPIX 9 single pix
Temperature -60 °C

Red: 55Fe
Black: 109Cd

Successfully obtained spectra from on-chip ADC
Comparison with external ADC

Comparison on-chip ADC with external ADC

55Fe (5.9 keV)

XRPIX9

Pixels

on-chip ADC

external ADC

Previous XRPIX
We've used external ADC

compare their 1σ

investigate performance difference between external ADC and on-chip ADC

Spectrum

55Fe (5.9 keV)
external ADC
on-chip ADC
XRPIX 9
single pix
temperature -60 °C
on-chip ADC vs external ADC

Fitted X-ray spectrum with gaussian and compared these width of 1 $\sigma$

Most of plots are along $\sigma_{on\ chip} = \sigma_{external}$
Almost the same performance
But plots are slightly above it

to go over the noise of on-chip ADC
Fitted plots with $\sqrt{\sigma_{external}^2 + \sigma_{additional}^2}$

Results: contains unrecognized noise of 45 eV

Future task: Evaluate noise & improve performance
Objective
XRPIX aims to be installed on future X-ray satellites as detector

Future task: Digitalization

Detector needs to be compact

We developed on-chip ADC

Result: Unit test of on-chip ADC

1. Integral Non-Linearity: 0.036 % (6 LSB, 36 eV)
2. Differential Non-Linearity: NO MISSING CODE (DNL< 0.7 LSB)
3. Noise: 3 LSB (5 e)

Result: XRPIX9 end to end test

We successfully obtained spectrum from on-chip ADC
(FWHM@5.9 keV ~ 300 eV, FWHM@22.1 keV ~ 400 eV)

No crucial differences between on-chip and external

Problem: Noise(1σ) = 45 eV

Future task & improve it
Back up
Cyclic ADC

XRPIX9 adopted cyclic ADC

How to work cyclic ADC

Process of AD conversion

Digital output

Analog signal input

Voltage

1. compare \( V_{\text{in}} \) with \( V_{\text{ref}} \)

If \( V_{\text{in}} > V_{\text{ref}} \) → 1 = MSB

2. Subtract \( V_{\text{ref}} \) from \( V_{\text{in}} \) & \( V_2 = 2 \times (V_{\text{in}} - V_{\text{ref}}) \)

compare \( V_2 \) with \( V_{\text{ref}} \)

If \( V_2 < V_{\text{ref}} \) → 0 = MSB-1

3. Repeat process for 14 times → 14 bit Cyclic ADC

Advantages: small size and high speed
1.5 bit cyclic ADC

Actually, We have used 1.5 bit ADC.

1 bit ADC
So far, ADC to determine 0 or 1

1.5 bit ADC
Bit is determined by 00, 01 or 10

- V_{\text{ref}}
- 10 \rightarrow \text{Vin} - \text{V_{\text{ref}}}
- 01 \rightarrow 2\times\text{Vin}
- 00 \rightarrow \text{Vin} + \text{V_{\text{ref}}}

Voltage
Advantages of Future satellite

1. Low background (from CXB)

- active shield
- Detector
- NXB
- DXB

X-ray from source

introduce anti-coincidence methods

アクティブシールドは10 kHzで反応
時間分解能10 usが必要

最終的にこの程度まで低減
Pixel pattern

single pixel event

4 pixel event

double pixel event
Purpose of digitalization

XRPIX

XRPIX9 output digital signals

external ADC

previous version
How to work ADC
About ADC

How to work cyclic ADC

Process of AD Conversion

Digital Output

Analog signal input

Voltage

1. compare Vin with V_reff
If Vin > V_reff → 1 = MSB

2. Subtract V_reff from Vin
& V_2 = 2×(Vin-V_reff)
compare V_2 with V_reff
If V_2 < V_reff → = MSB-1

3. Repeat process for 14 times
→ 14 bit Cyclic ADC
Purpose of Digitalization

X-rays create electron pairs
電圧に変換される
しかし、衛星搭載を目指していることや
スペクトル解析などデータ解析にはデジタル化が必須となる→ADCの利用

省電力、高速、高分解能
XRPIX9ではCyclic ADCを採用

Cyclic ADC搭載
XRPIX’s current status

We’ve been researching and developing

2010 2011 2012 2013 2014

First Model
Event-driven readout

Middle Size
6.0 mm
Buttable

Charge Sensitive Amplifier

2015 2016 2017 2018 2020

XRPIX6
XRPIX6b
5.0 mm
4.4 mm

XRPIX10
XRPIX11
4.6 mm
6.0 mm

XRPIX12
XRPIX13
2.9 mm
2.9 mm

XRPIX14
XRPIX15
4.6 mm
6.0 mm

24.6 mm
24.6 mm
15.3 mm
15.3 mm

608 x 384 pixels
608 x 384 pixels
608 x 384 pixels
608 x 384 pixels

36 μm sq. pixel
36 μm sq. pixel
36 μm sq. pixel
36 μm sq. pixel

Sensor: Good spectral performance

Future task: Digitalization

XRPIX6E
FWHM~240 eV at 6.4 keV

From Ayaki Takeda

KyotoU Harada

This meeting

Counts

Pulse Height [ADU]

6.4 keV
13.9 keV
17.8 keV
20.8 keV

ΔE ~ 240 eV (FWHM)
ΔE ~ 400 eV (FWHM)
Purpose of on-chip ADC

Previous XRPIX: Converts **analog signals** with external ADC

Problem: X-ray satellites require a large imaging area in a limited space

ADC mounted on XRPIX for compactness (on-chip)
ADC readout process

Signal Sampling Phase (2C)

Amplification Phase

Reset Phase

Sampling Phase
X-ray astronomy

We can study high-energy physics through X-ray observations.

Example: High energy celestial objects

Neutron Stars

Vicinity of Black Holes

X-rays are fairly absorbed in atmosphere

Need to launch satellites

Atmospheric opacity

0 %

100 %

0.1 nm

wavelength

1 m

credit:NASA

credit:NASA

credit:MASA

credit:NASA
Purpose of Digitalization

X-ray signals are Analog

Digitalization is necessary for these objectives
Also, ADC is necessary for Digitalization

Digital-Analog Converter

NEXT : About ADC & How does it work ?
Purpose of on-chip ADC

Previous XRPIX

XRPIX

Analog signal

ADC

Digital signal

XRPIX9 on-chip ADC

ADC mounted on XRPIX for Compactness

Type: Cyclic ADC
Low Energy Consumption
High Speed (50 MHz)
Small Size (20 um)

Advantages

Number of bits: 14 bits
Voltage range: 0.4-1.5 V
Total Units: 16 units

Goal: Evaluate on-chip ADC

<Problem in X-rays Satellite>
Require a large imaging area in a Limited space
Future X-Ray satellite and detector

<Concepts of future X-ray satellite>
Energy range: 0.5 - 80 keV (Wide band)
Observation targets: Black hole, Neutron star...
Low non-X-ray background above 10 keV
Good time resolution ~ a few us

<How to work CMOS X-ray detector>
1. X-rays create electrons
2. Sense nodes catch electrons

This talk theme
Future detector XRPIX
external ADC’s INL & DNL

ADC : 12 bits

AD output
How to make SOI wafer

From SOITEC