Development of the X-ray polarimeter using CMOS imager: polarization sensitivity of a $1.5\ \mu m$ pixel CMOS sensor

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Abstract

We are developing an imaging polarimeter using a micro-pixel complementary metal–oxide–semiconductor (CMOS) image sensor and a coded mask to realize polarimetry in the hard X-ray band of 10–30 keV. We call the project cipher (Coded Imaging Polarimetry of High Energy Radiation; Odaka et al. 2020). In this study, we evaluate the polarization sensitivity of a CMOS image sensor with a pixel size of 1.5 μm manufactured by Canon and that with a pixel size of 2.5 μm manufactured by Gpixel. We measure the modulation factor of the sensors. The Obtained modulation factors of the 1.5 μm sensor were $9.52 \pm 0.71\ \%$ at 10 keV and $17.6 \pm 1.3\ \%$ at 22 keV, which were higher than that of the sensor with a pixel size of 2.5 μm. These results show that the modulation factor can be improved by using a finer-pixel sensor.

Introduction

- **X-ray polarimetry in astrophysics** is a promising approach to studying the structure of the celestial objects.
  - Synchrotron radiation ➡ Magnetic field
  - Scattering ➡ Geometrical structure
- We are developing a hard X-ray imaging polarimeter using **a micro-pixel CMOS sensor**.

  The project is called cipher (Coded Imaging Polarimetry of High Energy Radiation; Odaka et al. 2020).

  For the details of imaging, see Poster 154 (T. Tamba)
- Photoelectrons tend to be emitted to the polarization angle of incident photons: $(d\sigma/d\Omega) \propto 1 + \cos 2\phi$ (Fig. 1; Heitler 1954).
- Tracking the photoelectrons with a micro-pixel sensor (Fig. 2)

  ➡ information on polarization

Charge distribution of events
⬇
Emission directions of the photoelectrons
⬇
The distribution of the photoelectron directions
⬇
Polarization degree and angle

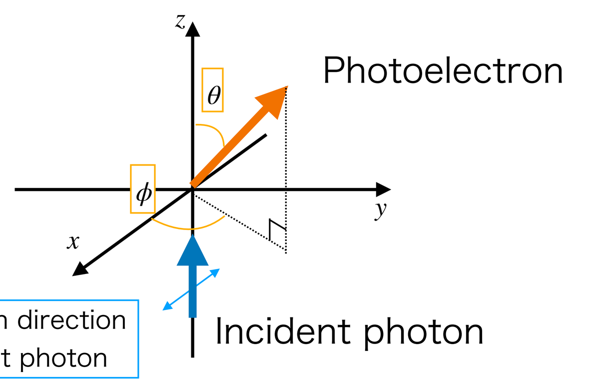

Figure 1: Schematic of photoelectric absorption.

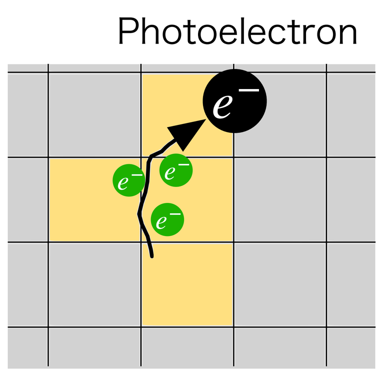

Figure 2: Schematic of the principle of photoelectron tracking.

- Our objective

  to evaluate **modulation factor (MF) of CMOS sensors**

  *MF: modulation amplitude for perfectly polarized incident radiation

  MF is an important parameter to calculate the sensitivity for a polarimeter

$$\mathrm{MDP}_{99} \simeq \frac{4.29}{\mathrm{MF}\sqrt{N}}$$ (Kislat et al. 2015)

MDP_{99}: the minimum detectable polarization on 99% confidence level
N: the total detection counts

Experiments

Sensors

Table 1: CMOS sensor

	$1.5\ \mu m$ sensor (Canon)	$2.5\ \mu m$ sensor (Gpixel)
Pixel size	$1.5\ \mu m \times 1.5\ \mu m$	$2.5\ \mu m \times 2.5\ \mu m$

- $1.5\ \mu m$ sensor

  Smaller pixel size

  ➡ higher photoelectron tracking accuracy

  ➡ **MF is expected to be larger**

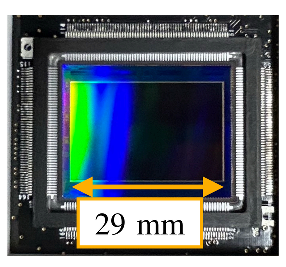

Figure 3: 1.5 μm sensor

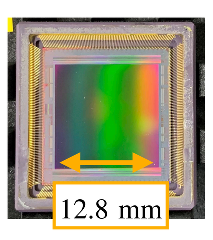

Figure 4: 2.5 μm sensor

Beam experiments to measure MF

- We conducted beam experiment at SPring-8 and PF-KEK to measure MF (Fig. 5)

  *SPring-8: the synchrotron radiation facility

  *PF-KEK: the Photon Factory of the High Energy Accelerator Research Organization
- Irradiated almost 100% polarized monochromatic beam to the CMOS sensors
- Rotated the stage to change the incident polarization angle
- Acquired data at multiple energies

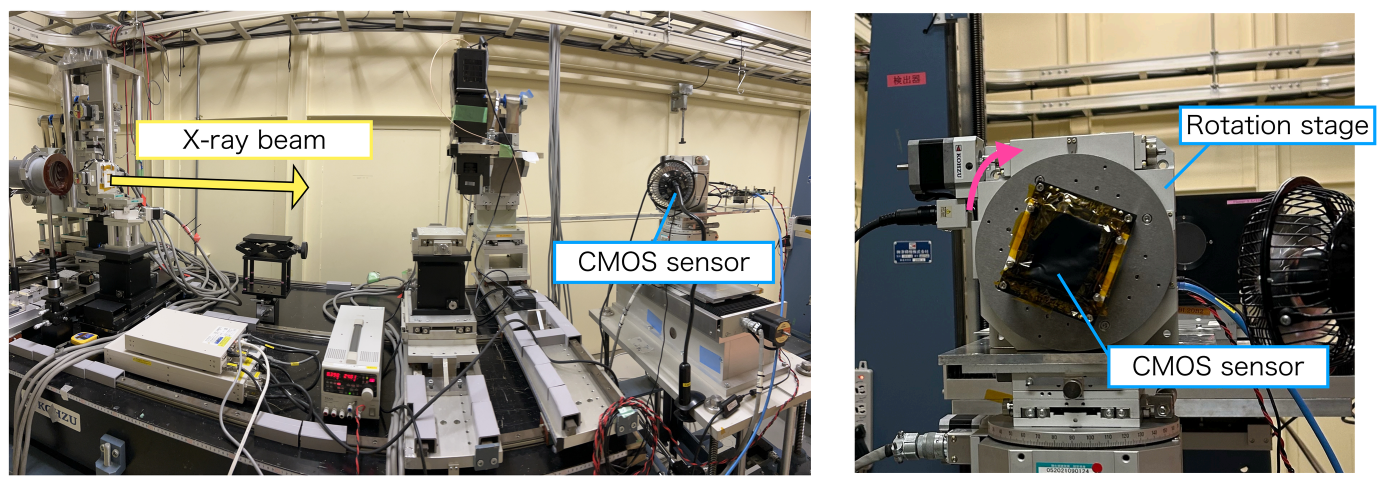

Figure 5: beam experiment

Analysis procedure

- Estimate the emission direction of photoelectron by **maximizing the second moment of the charge distribution, $M_2(\phi)$** (Fig. 6)

$$M_2(\phi) = \frac{\sum_i Q_i x_i'^2(\phi)}{\sum_i Q_i}$$ (Bellazzini et al. 2003)

*Q_i: charge of the pixel i, $x_i'(\phi) = (x_i - x_b)\cos\phi + (y_i - y_b)\sin\phi$ where (x_i, y_i) are the coordinates of the pixel i, and (x_b, y_b) is that of the barycenter

- Correct the distribution of the photoelectron direction (modulation curve; Fig. 7)
  - Subtract spurious modulation due to the instrument:
  - Recreate the scenario with two sensors positioned at a 45° rotation to correct for differences in modulation due to the incident polarization angle:
- The corrected distributions were fit with sine curve to determine the MF (Fig. 7)

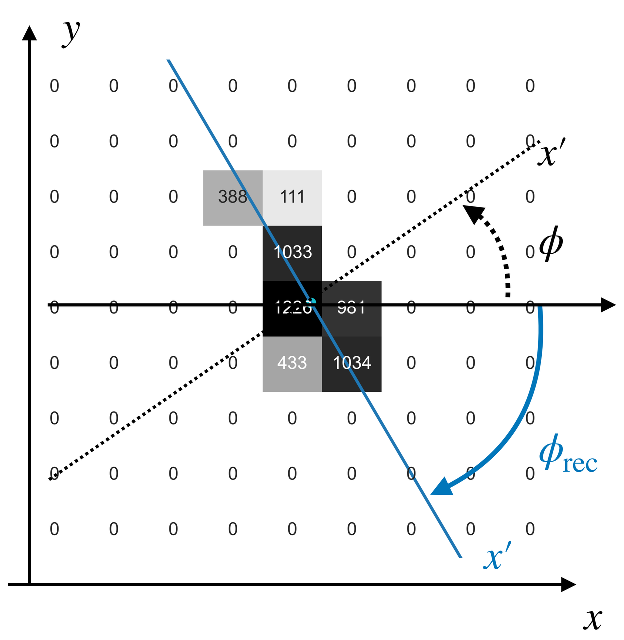

Figure 6: charge distribution and the direction which maximize the second moment

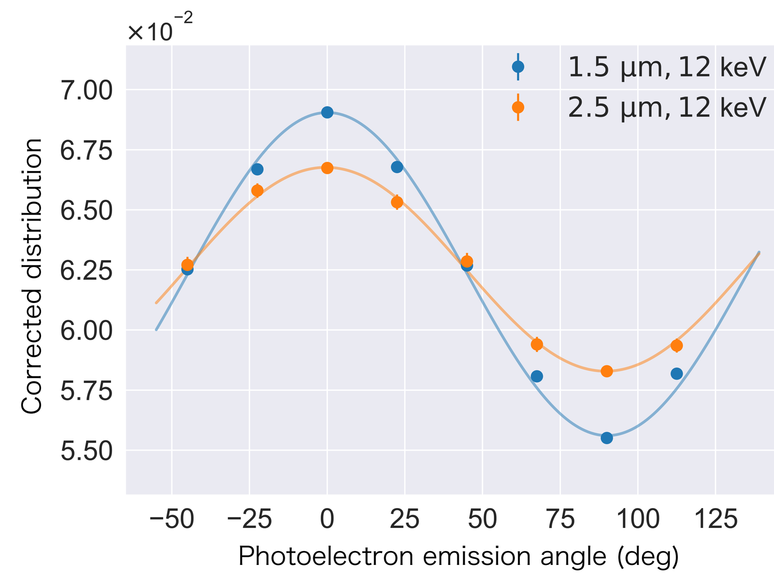

Figure 7: modulation curves

Results

- Utilizing a 1.5 μm sensor resulted in an **improved MF**

Table 2: MF of CMOS sensors

	$1.5\ \mu m$ sensor	$2.5\ \mu m$ sensor
10 keV	$9.52 \pm 0.71\ \%$	$5.17 \pm 0.39\ \%$
22 keV	$17.6 \pm 1.3\ \%$	$14.0 \pm 1.0\ \%$

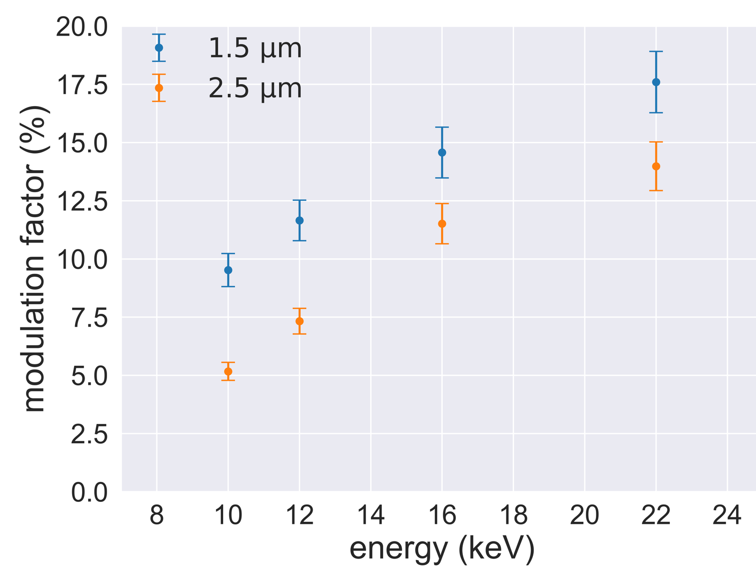

Figure 8: the energy dependence of the MF

⬇

The required detection count: 9×10^5 @ 10 keV, 3×10^5 @ 22 keV to detect 5% polarization with 99% confidence using the 1.5 μm sensor

Conclusion

- Utilizing a 1.5 μm sensor resulted in an improved modulation factor (MF) with values of $9.52 \pm 0.71\ \%$ at 10 keV and $17.6 \pm 1.3\ \%$ at 22 keV.

Reference

- Bellazzini R., Angelini F., Baldini L., et al., 2003, SPIE, 4843, 383.
- Heitler, W., 1954
- Kislat F., Clark B., Beilicke M., Krawczynski H., 2015, APh, 68, 45.
- Odaka H., Kasuga T., Hatauchi K., et al., 2020, SPIE, 11444, 114445V.