Development of the X-ray polarimeter using CMOS imager: polarization sensitivity of a 1.5 \( \mu \text{m} \) 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 \( \mu \text{m} \) manufactured by Canon and that with a pixel size of 2.5 \( \mu \text{m} \) manufactured by Gpixel. We measure the modulation factor of the sensors. The obtained modulation factors of the 1.5 \( \mu \text{m} \) 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 \( \mu \text{m} \). 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.

For the details of imaging, see Poster 154 (T. Tamba)

- Photoelectrons tend to be emitted to the polarization angle of incident photons: \((\text{deidi}) \propto 1 + \cos 2\phi\) (Fig. 1; Heitler 1954).
- Tracking the photoelectrons with a micro-pixel sensor (Fig. 2)

Figure 1: Schematic of photoelectric absorption.

- Our objective to evaluate modulation factor (MF) of CMOS sensors

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

\[
\text{MF}_{\text{MDP}} = \frac{9.52 \pm 0.71}{\text{MF}_0} \quad \text{(Kislat et al. 2015)}
\]

\[
\text{MF}_{\text{MDP}} \propto \text{the minimum detectable polarization on 99\% confidence level}
\]

\[
\text{MF}_0 : \text{the total detection counts}
\]

Experiments

<table>
<thead>
<tr>
<th>Sensors</th>
<th>1.5 ( \mu \text{m} ) sensor (Canon)</th>
<th>2.5 ( \mu \text{m} ) sensor (Gpixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>1.5 ( \mu \text{m} \times 1.5 \mu \text{m} )</td>
<td>2.5 ( \mu \text{m} \times 2.5 \mu \text{m} )</td>
</tr>
<tr>
<td>1.5 ( \mu \text{m} ) sensor</td>
<td>higher photoelectron tracking accuracy</td>
<td>MF is expected to be larger</td>
</tr>
</tbody>
</table>

Figure 3: 1.5 \( \mu \text{m} \) sensor  
Figure 4: 2.5 \( \mu \text{m} \) 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

- Rotated the stage to change the incident polarization angle
- Acquired data at multiple energies

Analysis procedure

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

\[
M_2(\phi) = \frac{\sum_i Q_i \cos^2(\phi)}{\sum_i Q_i}
\]

\( Q_i \): charge of the pixel \( i \), \( \phi = (x_i - \bar{x})\cos \phi + (y_i - \bar{y})\sin \phi \) where \( (x_i, y_i) \) are the coordinates of the pixel \( i \), and \( (\bar{x}, \bar{y}) \) 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)

Results

• Utilizing a 1.5 \( \mu \text{m} \) sensor resulted in an improved MF

Table 2: MF of CMOS sensors

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>1.5 ( \mu \text{m} ) sensor</th>
<th>2.5 ( \mu \text{m} ) sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 keV</td>
<td>9.52 ( \pm ) 0.71 %</td>
<td>5.17 ( \pm ) 0.39 %</td>
</tr>
<tr>
<td>22 keV</td>
<td>17.6 ( \pm ) 1.3 %</td>
<td>14.0 ( \pm ) 1.0 %</td>
</tr>
</tbody>
</table>

The required detection count: \( 9 \times 10^7 \) @ 10 keV, \( 3 \times 10^7 \) @ 22 keV to detect 5\% polarization with 99\% confidence using the 1.5 \( \mu \text{m} \) sensor

Conclusion

• Utilizing a 1.5 \( \mu \text{m} \) 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

- Heitler, W., 1954
- Kislat F., Clark B., Beilicke M., Krawczynski H., 2015, APJ, 68, 45.
- Odaka H., Kasuga T., Hatauchi K., et al., 2020, SPIE, 11444, 114445V.