Nuclear Instruments and Methods in Physics Research A 594 (2008) 188–195

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Evaluation of a hybrid photon counting pixel detector for X-ray polarimetry

T. Michel *, J. Durst

Erlangen Centre for Astroparticle Physics (ECAP), Erwin-Rommel-Strasse 1, 91058 Erlangen, Germany

ARTICLE INFO

Article history:
Received 15 April 2008
Received in revised form
11 June 2008
Accepted 15 June 2008
Available online 2 July 2008

Keywords:
X-ray
Polarization
Polarimetry
Photon counting
Medipix
Timepix

ABSTRACT

It has already been shown in literature that X-ray sensitive CCDs can be used to measure the degree of linear polarization of X-rays using the effect that photoelectrons are emitted with a non-isotropic angular distribution in respect to the orientation of the electric field vector of impinging photons. Up to now hybrid semiconductor pixel detectors like the Timepix-detector have never been used for X-ray polarimetry. The main reason for this is that the pixel pitch is large compared to CCDs which results in a much smaller analyzing power. On the other hand, the active thickness of the sensor layer can be larger than in CCDs leading to an increased efficiency. Therefore hybrid photon counting pixel detectors may be used for imaging and polarimetry at higher photon energies. For irradiation with polarized X-ray photons we were able to measure an asymmetry between vertical and horizontal double hit events in neighboring pixels of the hybrid photon counting Timepix-detector at room temperature. For the specific spectrum used in our experiment an average polarization asymmetry of $(0.96 \pm 0.02)\%$ was measured. Additionally, the Timepix-detector with its spectroscopic time-over-threshold-mode was used to measure the dependence of the polarization asymmetry on energy deposition in the detector. Polarization asymmetries between 0.2% at 29 keV and 3.4% at 78 keV energy deposition were determined. The results can be reproduced with our EGS4-based Monte-Carlo simulation.

1. Introduction

Charge coupled devices (CCDs) can be used [1] to measure the degree of linear polarization of X-rays. Due to their small depletion depth, CCDs can preferably be used for soft X-ray polarimetry. Due to the fact that the pixel pitch of 55 μm of hybrid photon counting pixel detectors such as Medipix2 [2,3] or Timepix [4] detector are typically larger than the pixel sizes of commercial CCDs together with the fact that the range of photoelectrons in silicon is much smaller than the pixel size, the analyzing power is significantly lower compared to CCDs. On the other hand the typical sensor thickness is significantly larger than the sensitive thickness of a CCD leading to higher efficiency for harder X-rays.

Future developments of highly brilliant polarized X-ray sources like synchrotron or free electron laser facilities, also extending their energies to higher values, offer interesting possibilities of using polarized X-ray beams to study material properties. There is a continuous need for X-ray polarimeters with imaging capabilities.

Measurements of the degree of linear X-ray polarization of celestial objects would give valuable insights into the production mechanisms or scattering geometries. A very promising and efficient device to measure the degree and orientation of linear polarization using the photoelectric effect in a gaseous detector is described in Ref. [5]. This device has a very high analyzing power and high efficiency for low photon energies of 2–10 keV. It should be able to measure even small values of the degree of linear polarization in the low energy range of weak sources in reasonable measuring times. A pixel detector with a semiconductor sensor, like it is presented here, cannot compete with the device described in Ref. [5] at low photon energies due to a lack of analyzing power.

Further studies are needed to clarify which performance an optimized semiconductor photon counting pixel detector is able to achieve in X-ray polarimetry in specific applications. Nevertheless, the higher efficiency of the semiconductor sensor for higher photon energies, the high readout speed and the space for improvements in the analyzing power of the hybrid photon counting pixel detector make investigations on its polarimetric performance interesting.

The ASIC of the Timepix-detector has been developed to be used in Time-Projection-Chambers. Bump-bonded to a silicon sensor (like the Medipix) it also serves as a tracking detector for charged particles or as an imaging detector for X-rays. This publication shall show that measurements of the degree of linear X-ray polarization can be performed with such a hybrid photon counting pixel detector as a side-effect although the detector is not designed nor optimized for such measurements.

* Corresponding author. Tel.: +49 9131 8527121.
E-mail address: Thilo.Michel@physik.uni-erlangen.de (T. Michel).

0168-9002/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2008.06.024

For the first time, a hybrid semiconductor photon counting pixel detector has been used to measure polarization asymmetries. The aim of this publication is to show that the hybrid detector is able to measure the degree of linear polarization of X-rays in the energy regime between 27 and 84 keV. In this contribution we will describe a measurement principle of the degree of linear X-ray polarization with the Timepix-detector in counting and in its spectroscopic time-over-threshold mode, prove the applicability in test measurements, compare the measured values to simulation results and discuss advantages and disadvantages of the Timepix for a use in X-ray polarimetry.

2. Polarization signatures of the photoelectric effect and the Compton effect

For X-ray energies below about 58 keV the total cross-section of the photoeffect is larger than the total cross-section of Compton scattering in silicon. The ability of the Timepix-detector to measure the degree of linear polarization using the photoeffect is restricted to an energy band where the energy of released photoelectrons is sufficient to cause significant track lengths in silicon and where the photoeffect still significantly contributes to absorption.

The polarized radiation that we needed to test the ability of the Timepix to measure the degree of linear polarization was produced by Compton scattering. Therefore we describe the important polarization dependent properties of both effects.

2.1. Photoelectric effect

The differential cross-section for the ejection of an electron following photoabsorption of the X-ray photon with energy E_0 in the K-shell is given by [6]

$$\frac{d\sigma}{d\Omega} = r_0^2 Z^5 \alpha^4 \left(\frac{m_e c^2}{E_0}\right)^{7/2} \frac{4\sqrt{2}\cdot \sin^2\theta \cdot \cos^2\phi}{(1-\beta\cos\theta)^4} \tag{1}$$

where ϕ is the polar angle of the momentum of the emitted electron to the y-axis in the reference frame. The reference frame is defined by the direction of the electric field vector of the incoming X-rays (y-axis), the direction of the incoming photon (z-axis) and the direction which is perpendicular to both (x-axis). The angle θ is the azimuthal angle of the electron momentum to the z-axis of this frame. r_0 is the classical electron radius, Z the charge of the nucleus, m_e the electron rest mass, α the fine structure constant and $\beta = v/c$ is the electron velocity. According to this formula the electron is ejected preferably in the direction of the electric field vector of the incoming X-rays.

2.2. Compton effect

The differential cross-section for Compton scattering of a linearly polarized photon beam off a free electron is described by the Klein–Nishina formula:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \frac{E^2}{E_0^2}\left(\frac{E}{E_0} + \frac{E_0}{E} - 2\sin^2\theta \cdot \cos^2\phi\right) \tag{2}$$

where the energy E of the scattered photon is given by

$$E = \frac{E_0}{1 + (E_0/m_e c^2)(1-\cos\theta)} \tag{3}$$

and θ is the scattering angle, which is the angle between the momentum vectors of the incoming and the scattered photon and the azimuthal angle ϕ is the angle between the electric field vector of the incoming photon and the scattering plane. One can see that for X-ray photons with energies $E_0 \ll m_e$ and scattering angles $\theta \approx 90^\circ$, where $E \approx E_0$, the scattered X-radiation is almost completely linearly polarized.

3. The Medipix2 and Timepix-detector

The Medipix2 [2,3] and its derivative, the Timepix [4], comprise a sensor layer which is pixelated with a pitch of 55 μm. The Medipix has been designed for X-ray imaging. Each sensor pixel electrode is connected to one electronics cell of the readout ASIC via a bump-bond of a lead–tin alloy. The ASIC has been developed by the Medipix collaboration with its seat at CERN. The pixel cells are organized in a quadratic matrix of 256 rows and 256 columns giving a total side length of about 1.4 cm. Each electronics pixel cell contains an integrating charge sensitive preamplifier, two discriminators in the Medipix2, one discriminator in the Timepix and a pseudo-random counter with a depth of 14 bit. The minimum threshold that can be applied is about 3 keV. If an X-ray photon interacts in the sensitive volume of a sensor pixel the charge carriers, released by the ejected electron, drift towards the pixel electrode. The charge is collected, transferred to the pixel electronics cell and converted into a voltage signal proportional to the amount of collected charge in the preamplifier. If the collected charge, which is a measure of the energy deposition in the pixel volume, exceeds threshold, the photon is counted. This operation mode is called the photon counting mode. It is available in the Medipix2 and the Timepix ASIC. The Medipix2 offers the possibility to count the number of events with energy depositions in an energy window whereas the Timepix-detector can only be operated with one single analogue threshold. The Timepix offers two additional operation modes: the time-over-threshold and the time-to-shutter mode. In the time-over-threshold mode the counter counts the number of clock pulses of a clock signal during the time of the discriminator input pulse being above threshold. This time is proportional to the amount of collected charge and thus proportional to the energy deposition in the sensor pixel. In the time-to-shutter mode the counter of the Timepix counts the number of clock pulses from the moment of detection until the end of the frame. The Medipix2 and Timepix are operated with a shutter signal which stops the detection processes in the pixel matrix at the same time. After having finished all counting activity, the matrix is read out with the pseudo-random-counters acting as shift registers. The whole matrix can be read out serially in about 9 ms or in parallel in about 265 μs thus offering frame rates from several tens of Hertz up to more than a kHz with tolerable dead times.

The ASIC is connected to a printed circuit board with a heat conducting glue that contains a significant amount of silver. X-rays which transmit the sensor or even the ASIC can be absorbed in this glue or in the bump-bonds and thus produce fluorescence photons which can be detected again in the sensor layer. Thus the energy deposition spectrum measured with the detector shows strong contributions at the energies of the fluorescence photons of silver and tin. This is important for the interpretation of the energy deposition spectra in this publication.

4. Measurement principle of the degree of linear polarization exploiting the photoelectric effect

The measurement principle of the degree of linear polarization with semiconductor pixel detectors can be based on the fact that the first few microns of the photoelectron track in the sensor material contain information about the original direction of emission of the photoelectron which is correlated with the