Gas Pixel Detectors

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Polarimetry: The Missing Piece of the Puzzle

Imaging: Chandra

Timing: RXTE

Spectroscopy: AstroE2, Constellation-X, Chandra

Polarimetry: ?
The only polarized source already known

Positive measurement: of X-ray polarization of the Crab Nebula without pulsar contamination (by lunar occultation, Weisskopf et al., 1978).

\[ P = 19.2 \pm 1.0 \% \]
\[ \theta = 156.4^\circ \pm 1.4^\circ \]

But this is only the average measurement. The structure is much more complex!

With XPOL we can perform the separate polarimetry, imaging, spectroscopy and timing of details of the major structures.
The photoelectric effect is very sensitive to photon polarization!

Simple analytical expression for photoemission differential cross section (k-shell photoelectron in non-relativistic limit):

$$\frac{\partial \sigma}{\partial \Omega} = r_o^2 \frac{Z^5}{137^4} \left( \frac{mc^2}{h \nu} \right)^{\frac{7}{2}} \frac{4\sqrt{2} \sin^2(\theta) \cos^2(\phi)}{(1 - \beta \cos(\theta))^4}$$

If we project on the plane orthogonal to the propagation direction...

$$\frac{\partial \sigma}{\partial \Omega} \propto \cos^2 \phi$$
Photoelectron and Auger angular distributions

Photoelectron emission angular distributions

\[ \frac{\partial \sigma}{\partial \theta} \propto \sin^3(\theta) \left(1 - \beta \cos(\theta)\right)^n \]

\[ \frac{\partial \sigma}{\partial \phi} \propto \cos^2 \phi \]

Auger emission directions

Photoelectron emission directions
The principle of detection

A custom CMOS analog chip is at the same time the pixelized charge collecting electrode and the amplifying, shaping and charge measuring front-end electronics of Micropattern Gas Detectors (MPGD) or other suitable charge multiplier.
three ASIC generations of increasing size, reduced pitch and improved functionality have been realized
The collecting anode/read-out VLSI chip

Advantages: asynchronous, fast, low noise

pixel electronics dimension: 80 \( \mu \text{m} \times 80 \ \mu \text{m} \) in an hexagonal array, comprehensive of preamplifier/shaper, S/H and routing (serial read-out) for each pixel

number of pixels: 2101

First ASIC prototype

~3.5 \( \mu \text{s} \) shaping time
100 e- ENC
100 \text{mv/fC} \ input sensitivity
20 fC dynamic range

First ASIC prototype
Tracks reconstruction

1) The track is recorded by the PIXel Imager

2) Baricenter evaluation

3) Reconstruction of the principal axis of the track: maximization of the second moment of charge distribution

4) Reconstruction of the conversion point: major second moment (track length) + third moment along the principal axis (asymmetry of charge release)

5) Reconstruction of emission direction: pixels are weighted according to the distance from conversion point.
From 2k to 22k pixels
Further technological step:
a 0.18 µm CMOS VLSI

The chip integrates more than 16.5 million transistors. It has a 15mm x 15mm active area of 105’600 pixels organized in a honeycomb matrix.

470 pixels/mm²

Matrix organization:
300 (width=300x50µm=15mm) x 352 (height=352x43.3µm=15.24mm) pixels
16 clusters of 300 x 22 = 6600 pixels each or
8 clusters of 300 x 44 = 13200 pixels each
0.18 µm ASIC features

- Peaking time: 3-10 µs, externally adjustable;
- Read-out clock: up to 10MHz;
- Frame rate: up to 10 kHz in self-trigger mode (event window);
- Read-out mode: asynchronous or synchronous;
- Trigger mode: internal, external or self-trigger;
- Pixel noise: 50 electrons ENC;
- Self-trigger threshold: 2300 electrons;
- Full-scale linear range: 30000 electrons;
- Parallel analog output buffers: 1, 8 or 16;
- Access to pixel content: direct (single pixel) or serial (8-16 clusters, full matrix, region of interest);
- Fill fraction (ratio of metal area to active area): 92%

Total power dissipation ~ 0.5 Watt
Self-trigger functionality

- charge sum of mini-cluster of 4 pixels contribute to a local trigger with dedicated s.a.
- threshold < 3000 e⁻ (10% FS)
- individual pixel trigger mask
- independent trigger level for each 16 clusters
- event localization in rectangle containing all triggered mini-clusters + user selectable region of 10 or 20 pixels
- the chip calculates the event ROI \((X_{\text{min}}, Y_{\text{min}} - X_{\text{max}}, Y_{\text{max}})\) for subsequent sequential readout of selected area

Average window size ~700 pixels
Noise and threshold

Self-trigger threshold constrained by pedestal offset more than pedestal fluctuations

ENC ~50 e⁻

Few hertz @ 2300 e⁻
Detector assembly

1 - The GEM glued to the bottom of the gas-tight enclosure
2 - The large area ASIC mounted on the control motherboard

Large effective gas gain around 1000 @450V in Ne(50%)-DME(50%)
(at least 70 V less than in our standard 90 µm pitch GEM)

- GEM pitch: 50 µm
- GEM holes diameters: 33 µm, 15 µm
- Read out pitch: 50 µm
- Absorption gap thickness: 10 mm
- Collection gap thickness: 1 mm
GEM specs

pitch: 50 \( \mu \text{m} \)
holes outer \( \varnothing: 35 \mu \text{m} \)

The matching of readout and gas amplification (GEM) pitch allows getting optimal results and to fully exploit the very high granularity of the device.
The read-out system
On-line monitoring

Real time pedestal subtraction
Imaging capability

$^{55}\text{Fe}$ source Ne(50\%)\text{-DME(50\%)}

Holes: 0.6 mm diameter, 2 mm apart.
Imaging and spectroscopic capability

Argon (50%)-DME(50%)

Holes:
Ø 0.5 mm
pitch 1 mm

Pulse Height

<table>
<thead>
<tr>
<th>PHeight</th>
<th>Entries</th>
<th>$\chi^2$/ndf</th>
<th>Prob</th>
<th>p0</th>
<th>103.2 ± 4.4</th>
<th>p1</th>
<th>1984 ± 16.6</th>
<th>p2</th>
<th>385 ± 16.7</th>
<th>p3</th>
<th>582.6 ± 8.3</th>
<th>p4</th>
<th>4317 ± 6.9</th>
<th>p5</th>
<th>573.9 ± 6.0</th>
</tr>
</thead>
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Signal from GEMtop

$\Delta E/E$ ( @5.9 KeV) ~18% FWHM
Polarizing X-rays

90° Thompson scattering
Track morphology and angle reconstruction

Event Number: 101
Number of Clusters: 1
Cluster Size (largest): 130
Pulse Height: 1228.2
Signal to Noise: 320.1
Baricenter: 2.50 -4.31
Conversion Point: 2.32 -4.01
Second Mom Max: 0.0459
Second Mom Min: 0.0134
Shape (ratio of moments): 3.42
Third Mom Max: -2.8e-03
Phi (iteration 1): -0.9540
Phi (iteration 2): -1.8518

Event Number: 25
Number of Clusters: 1
Cluster Size (largest): 121
Pulse Height: 10625.1
Signal to Noise: 278.9
Baricenter: -0.15 2.95
Conversion Point: -0.53 2.34
Second Mom Max: 0.0475
Second Mom Min: 0.0210
Shape (ratio of moments): 3.25
Third Mom Max: -1.1e-02
Phi (iteration 1): 0.1949
Phi (iteration 2): -0.2401
Modulation factor

Measured with two different gas mixtures: He/DME and Ne/DME

51.11% ± 0.89% @5.4 keV Cr-line energy

54.26% ± 1.24% @6.4 keV Fe energy
Residual modulation

S/N distribution, scatter plot of the two principal axes of the cluster charge and residual modulation, obtained with $^{55}$Fe source in Ne(50%)-DME(50%)
Expected MDP with XEUS optics @ different source fluxes and spectral index

With observations of one day we can measure the polarization of several AGNs down to 1% for 1 mCrab flux.

With 1 h it is possible to get few % with a 10 mCrab flux.
Conclusions

With devices like the one presented the class of Gas Pixel Detectors has reached the level of integration, compactness and resolving power typical of solid state detectors.

Depending on type of electron multiplier, pixel and die size, electronics shaping time, analog vs. digital read-out, counting vs. integrating mode, many applications can be envisaged for this class of detectors.

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*A real breakthrough in X-ray astronomy* if compared with the traditional X-ray polarimeters sensitivity.
An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars
E. Costa, P. Soffitta, R. Bellazzini, A. Brez, N. Lumb, G. Spandre