A gas pixel detector for x-ray polarimetry

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Even though lacking of solid experimental verifications, X-ray polarimetry is strongly established as a deep diagnostic tool for probing the emission mechanisms in astronomical sources of high energy radiation. The recent development of new, more efficient instrumentation, as well as the renewed interest of the theoreticians, has drawn a significant attention to the field. Particularly, the exploitation of the photoelectric effect for deriving polarization information seems to promise a great advance in sensitivity with respect to the conventional techniques.

To this aim we have designed, produced and tested a CMOS VLSI array of 2101 pixels (with 80 μm pitch), to be directly used as the charge collecting anode of a Gas Electron Multiplier (GEM). Each pixel is fully covered by a hexagonal metal electrode and each of these electrodes is individually connected to a full electronics chain, built immediately below it; in this sense detector and read-out electronics become virtually the *same* thing.

Even though we focus our attention on the polarimetric applications, our achievements are highly significant for the whole field of development of gas detectors, which for the first time reach the level of integration and resolution typical of solid state detectors.

1. INTRODUCTION

X-ray polarimetry has been extensively discussed over more than 30 years since the first pioneering detection from the Crab Nebula - which represents, to date, the only solid experimental result in this branch of X-ray astronomy.

So far, the main reason which has prevented the polarimeters flown on-board of rockets and satellites from providing more than a few week upper limits, resides in the intrinsically poor polarimetric sensitivity of the standard techniques; namely, Bragg diffraction at 45° and Thomson scattering at 90°.

On the other hand, physicists have been trying for a long time to exploit the photoelectric effect as an "analyzer" of polarization: in principle it can provide a strong polarization signature (the photoelectron is emitted with a $\cos^2$ distribution around the electric vector of the absorbed photon) and, moreover, it generally constitutes the physical process with the greatest cross section in the "few keV" energy band, which is extremely interesting for X-ray astronomers. The main limitation is that, at these energies, electrons propagate in matter less than photons. Nevertheless, finely segmented Micro Pattern Gas Detectors (MPGDs) have demonstrated that nowadays it is possible to implement such an approach, opening wide perspectives for a new generation of highly efficient X-ray polarimeters.

2. THE DETECTOR

The basic concept of the detector dates back to about three years ago [1,2]. A full 2D track reconstruction, performed by means of a finely-segmented pixel read out, allows to identify the original direction of emission of the photoelectrons, thus deriving the information about the polarization angle and degree of the incoming radiation. A GEM [3] provides the gas gain (as well as the trigger for the read-out electronics) preserving at the same time the directional information thanks to the high granularity achievable in the multiplication process.

In our first implementation the read out plane was manufactured using advanced PCB (Printed Circuit Board) techniques; 512 pixels, arranged in a honeycomb array with a pitch of 260 μm (for a total active area of few mm^2), were connected to the external front-end electronics through a complex multi-layer fan-out. We demonstrated the polarimetric capabilities of the detector in terms of modulation factor and, at the same time, we realized that major improvements in terms of sensitivity would have been only possible through radical technological changes. In fact, the PCB approach intrinsically limits the number of independent channels that can be brought to the peripheral electronics, as well as the minimum achievable pitch. Moreover, the crosstalk between adjacent channels - running close to each other for several cm - and the noise due to the high input capacitance to the preamplifier can become not negligible.

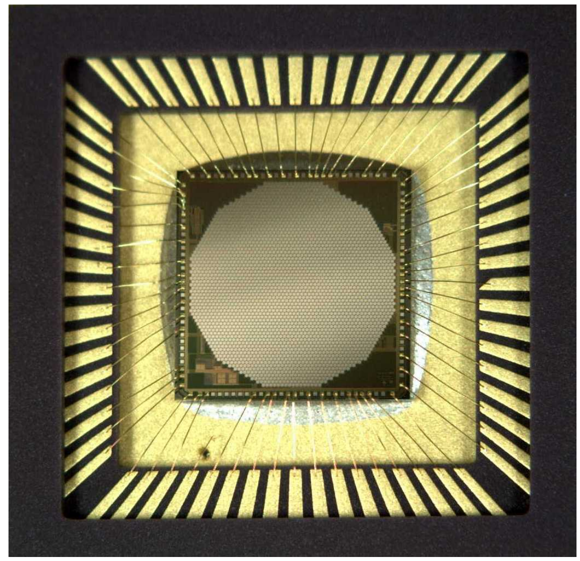

Figure 1. Microscope photograph of the ASIC, wire bonded to the ceramic package used for the assembly on the control board.

2.1. The CMOS VLSI collection/read-out chip

The VLSI ASIC we have recently designed, produced and tested completely reverses our previous approach, overcoming all of the intrinsic limitations described in the previous paragraph; instead of bringing the signal from the read-out plane out to the front-end electronics, the electronics itself is brought right under the pixels [4].

Figures 1 shows a photograph of the chip. The array, directly used as a charge collecting anode, consists of 2101 hexagonal pixels (arranged in a triangular matrix with 80 μm pitch) and has been manufactured using a standard 0.35 μm CMOS technology. Each metal pad is *individually* connected to a full electronics chain (charge amplifier, shaper, sample and hold, multiplexer) which is built immediately *below it*.

Thanks to the negligible input capacitance to the preamplifiers ($\simeq$ 0.1 pF) and the optimal shaping time ($\simeq 3.5\ \mu s$) the noise level is incredibly low (typically $\simeq$ 100 electrons ENC), allowing to achieve a high sensitivity to the single primary electron even with a moderate gas gain ($\simeq$ 1000, easily achievable by the GEM). In normal operation, upon activation of an external asynchronous trigger the maximum of the shaped signals is searched within a 10 μs window and the 2101 analog values of the charge - stored within the pixels - are then serially transferred to an external flash ADC for digitization. At the typical system clock of 5 MHz the time needed for the read-out sequence to be completed is 400 μs.

2.2. Test results

Before the assembly of the actual detector (figure 2), the ASIC has been electrically tested and characterized exploiting the internal calibration system. A noise level perfectly consistent with specifications and a gain uniformity as good as 3% RMS throughout the whole chip have been measured; at the same time, due to the fact that all the signal processing occurs within the pixel, no trace of cross-talk between adjacent channels has been found.

The MPGD has been tested with 5.9 keV photons coming from a ^{55}Fe source both with a

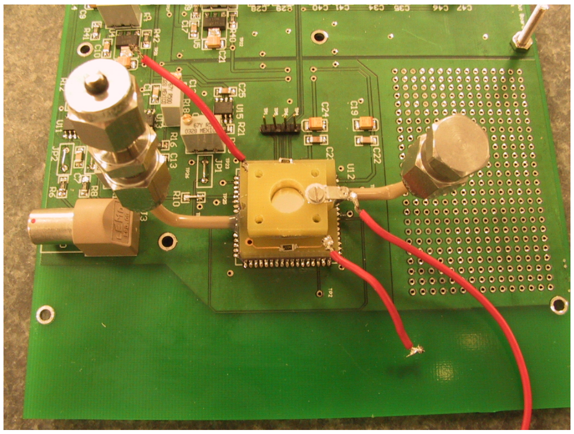

Figure 2. MPGD fully assembled on the control board and ready for tests.

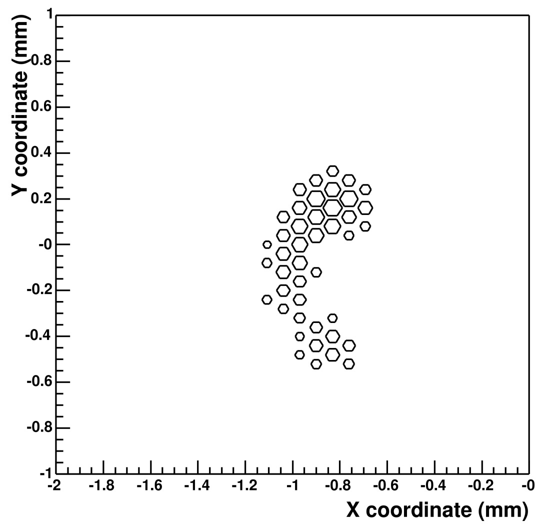

Figure 3. Sample photoelectron track collected irradiating the MPGD with 5.9 photons coming from a ^{55}Fe source.

standard 50 μm thick GEM (90 μm holes pitch) and with a 25 μm thick GEM (50 μm holes pitch)specifically manufactured for this application. Figure 3 shows a sample track of a 5.0 keV photoelectron + 0.9 keV Auger electron in Ne/DME 80/20 gas mixture at atmospheric pressure. It is worth to note that, even thought the total amount of charge collected on the read-out plane in this particular event is less than 40000 electrons, subdivided over more than 40 pixels, the track is perfectly clean. The Bragg peak toward the end of the track and the small excess of energy deposited on the opposite side by the Auger electron can be clearly recognized; all these informations are fully exploited by the reconstruction algorithm in order to identify the initial part of the photoelectron path, enhancing the angular accuracy.

3. MONTE CARLO SIMULATION AND POLARIMETRIC SENSITIVITY

A full Monte Carlo simulation has been developed as to evaluate the polarimetric sensitivity of different realistic configurations (based on the current detector implementation) in terms of Minimum Detectable Polarization, which is somehow the key parameter - depending on the modulation factor, detection efficiency, effective area and observation time.

The simulation of photoelectron tracks is based on a code originally developed for electron microscopy (and hence tuned on the description of low energy electrons) [5], modified as to deal with arbitrary gas mixtures. All the parameterizations used for the transport of the ionization within the detector and the gas multiplication have been worked out by means of the "standard" toolkits for simulation of gaseous detectors, such as Maxwell (a commercial finite elements program for the solution of electrostatic problems) and Garfield (a free program, including interfaces to Magboltz and Heed, developed at CERN) [6].

Figure 4 shows the results of our simulations, performed in two different configurations respectively optimized for "low" and "high" energies, for Her-X1, which is one of the most interesting potential target for a future X-ray polarimetric mission. For these source the MPGD could detect a polarization degree as low as $\simeq 1\%$ in a typical integration time of one day.

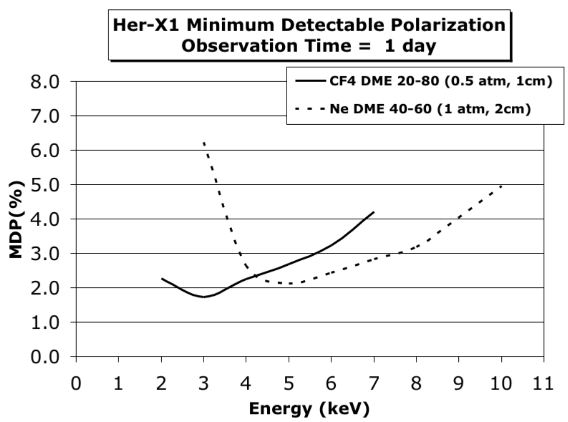

Figure 4. Minimum Detectable Polarization - in several energy bins - for 1 day observation of Her-X1 ($\simeq$ 100 mCrab source). A 1000 cm^2 mirror collecting area - in the 1 - 10 keV energy band - is assumed. The two curves refer to two different configurations (CF4/DME 20/80, 0.5 atm, 0.5 cm absorption gap and Ne/DME 40/60, 1 atm, 2 cm absorpion gap), optimized for different energies.

4. FUTURE PERSPECTIVES

The design of the second generation of ASICs to be used as charge collecting anodes of MPGDs has been finished and it has been already submitted for the fabrication. This new chip implementation will include $\simeq$ 22000 pixels, with 80 μm pitch, for a total active area of about 11x11 mm. In order to have 1 kHz source rate capability, 8 independent parallel analog buses, feeding 8 different ADCs, are foreseen, for a total read-out time as low as 280 μs.

5. CONCLUSIONS

The last decade has seen a renewed interest in the possibility of exploiting the photoelectric effect for astronomical X-ray polarimetry in the 1-10 energy range. To this aim, we have designed, produced and tested a custom VLSI ASIC, including 2101 independent electronics channels, to be used as a charge collecting anode for a standard Gas Electron Multiplier. Our approach allows a very fine segmentation of the readout plane and a high density of channels, which is critical for the application; at the same time the low noise of the system provides high sensitivity to the single primary electron even with a moderate gas gain. The polarimetric sensitivity of the detector, evaluated in the case of an astronomical source of real interest, is presented.

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