# The pixel readout of Micro Patterned Gaseous Detectors

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**Abstract**. The use of pixel readout chips as highly segmented anodes of gaseous detectors offers high granularity and low noise at the input of each channel. This readout can be applied to TPCs for high energy particle tracking as well as for low energy recoil detection where a small charge is created in the gas volume. Detectors combining GEM or Micromegas amplification stages with pixel readout chips will be presented and their tracking capabilities described.

#### 1. Introduction

The use of pixel readout chips as highly segmented anodes of micro-patterned gaseous detectors offers a few tens of microns granularity and a low noise at the input of each channel allowing the detection in three dimensions of single electrons with a potentially very good spatial resolution, with high rate capability and efficiency.

These detectors are well suited for the detection of polarized photons and axions, as both radiations eventually end in a few-keV photo-electron conversion. The photo-electron being absorbed in the gas, its energy can be measured by counting the detected primary electrons; and its track may be resolved thanks to the fine segmentation of the anode. In the same way, the direction and energy of double- $\beta$  decay electrons could be measured, as well as the small ionization of low energy nuclear recoils from WIMP or neutrino interactions. This readout can also be applied to TPCs for high energy physics experiments. In that case, the particle identification (dE/dx) could be improved by counting the primary clusters of electrons along a track and  $\delta$ -rays can be identified and isolated in the analysis.

This paper will summarize the progress in Micromegas and GEM based pixelized detectors, describing their combination with the MediPix2 and TimePix pixel readout chips. Meanwhile, emphasis will be put on the on-chip integration of amplification and discharge protection structures.

# 2. Two dimensional imaging inside small gas volumes

### 2.1. The Medipix2 chip

The Medipix2 [1] is a pixel readout chip designed in 0.25- $\mu$ m CMOS technology and segmented in a 14 mm<sup>2</sup> matrix of 256 x 256 55 x 55  $\mu$ m<sup>2</sup> pixels; the total area being slightly larger (14 x 16 mm<sup>2</sup>) because of I/O pads. The pixel circuitry includes a preamplifier-shaper, 2 discriminators, a 14 bit counter and communication logic. The Medipix2 was originally intended for single photon counting by means of a X-ray semiconductor sensor coupled to the chip. Therefore, every pixel is covered with an 11 x 11  $\mu$ m<sup>2</sup> octagonal bump bonding pad made of aluminium. In the application described in this paper, the chip is placed in a gas volume without any semiconductor sensor or bumps, but with a gas amplification structure above it.

# 2.2. The Medipix2/Micromegas detector

A 5  $\mu$ m thick copper Micromegas mesh [2] with a hole pitch of 60  $\mu$ m is maintained 50  $\mu$ m above the chip by means of insulating pillars. A cathode foil placed parallel above the mesh defines a 14 x 14 x 14 mm<sup>3</sup> drift volume where primary electrons from ionizing tracks are generated. These electrons drift towards the mesh, pass through the holes and enter the amplification region defined by the Micromegas and the chip. The Micromegas being held at high negative voltage with respect to the chip (kept at ground potential), every electron initiates an avalanche in the strong electric field.

In a mixture of helium and 20 % isobutane, gains of some  $2.10^4$  enabled the detection of single electrons from cosmic muons with a high efficiency as most of the signals were high enough to activate the pixel circuitry (the low threshold was set around 3000 electrons). In this way, several images of minimum ionizing cosmic muon tracks were recorded (Figure 1) [3]. From these data the single electron detection efficiency was deduced to be better than 90% [3-4].

As any gaseous chamber operated at high gain, gas discharges occasionally occur between the electrodes. In this detector, discharges occurred between the chip and the Micromegas and could therefore damage the readout electronics. Moreover the difference between the mesh hole pitch and the pixel pad pitch results in a periodic variation of the detection efficiency (so called Moiré effect). These issues will be addressed in part 3.



Figure 1: Image of a muon track, the active area is  $14 \times 14 \text{ mm}^2$ . Note the  $\delta$ -ray.

# 2.3. The MediPix2/GEM detector

A stack of three 10 x 10 cm<sup>2</sup> GEM foils [5] of 70  $\mu$ m hole diameter and 140  $\mu$ m hole pitch is placed 1 mm above the chip. The distance between the GEMs is 2 mm and the drift space is set to 6 mm. This configuration permits a decoupling of the amplification and the readout because high fields are confined within the GEM holes where the electron avalanches develop while a low field extracts the electrons from the bottom GEM to the chip. In that case, the probability of a discharge close to the electronics is reduced compared to the Micromegas detector.

In a mixture of argon  $CO_2$  70/30 the detector could be triggered to record 3.5 MeV electron tracks from a <sup>106</sup>Ru source (Figure 2) [6]. The gain was  $6.10^4$  and the threshold approximately 1000 electrons. The large transversal spread of the charge clouds on the MediPix2 chip surface is explained by the transverse diffusion in the different gaps and depends therefore on the gap sizes and the field strengths. Because the transversal size of the charge cloud is larger than the pixel pitch, it is likely that the charge per pixel is not enough to activate the pixel circuitry resulting in a single electron detection efficiency of some 20 %. The detector is thus sensitive to large clusters of electrons that merge during the amplification.



Figure 2: "Raw" image of a 3.5 MeV electron track in argon  $CO_2$  70/30 (left). Straight line fit to the centers of clusters after a noise suppression procedure (right). The axis units are in number of pixels and the active area is 14 x 14 mm<sup>2</sup>.

# 3. Wafer scale post-processing of CMOS pixelized chips

# 3.1. InGrid

By means of wafer post-processing [7] the Micromegas grid can be integrated directly on top of Silicon wafers [8]. With this technology it will be possible to precisely cover CMOS chip wafers with an amplification grid, resulting in a fully integrated readout device for gaseous detector. The grid holes can be accurately aligned with the pixel pads and the pillars can fit in between the grid holes as their diameter can be shrunk to  $30 \,\mu m$  (Figure 3), resulting in optimal detection efficiency.

Several 180 mm<sup>2</sup> InGrids of various geometries were realized on 10 cm diameter Silicon wafers and tested by means of <sup>55</sup>Fe quanta. For some of them, energy resolutions of 13 % FHWM and gain uniformities better than 3 % RMS were recorded [9]. The next step concerns the post processing of wafers of pixel readout chips which will be realized soon.



Figure 3: Top view of an InGrid. Note the insulating pillars centered between the grid holes.

### 3.2. A protection against discharges

3.2.1. Introduction. The issue of discharges in the Micromegas/MediPix2 detector was addressed in section 2. Gaseous discharges are initiated when an electronic avalanche grows so large that it evolves into a streamer (i.e. thin plasma filament) that extends towards the negatively charged electrode (in our case the grid). Once the streamer reaches the grid, a short is made between the two electrodes and the discharge occurs, resulting in a high current through a localized spot on the chip. This high current density can melt or evaporate the chip material. To limit the spark current, it has been proposed to make one or both electrodes highly resistive. The InGrid technology is not mature enough to propose highly resistive grids, however it is feasible to cover the chip surface by a thin layer of hydrogenated amorphous Silicon (*a*-Si:H).

3.2.2. The SiProt chamber. The effect of a *a-Si:H* covered anode on discharge signals was investigated by means of two Micromegas detectors placed in the same gaseous chamber. Both anodes were made of a 15 x 15 mm<sup>2</sup> aluminium covered silicon substrate; one of them was further covered by a 4 µm thick *a-Si:H* layer, the resistivity of which is of the order of 10<sup>11</sup>  $\Omega$ .cm. During the deposition process [10], the temperature can be kept around 200 °C which is considered safe for CMOS wafer post-processing. A thorium container was added on the gas line (argon/isobutane 80/20) to induce 5 MeV  $\alpha$ -decays in the chamber. The resulting large charge deposits sometimes induced discharges that could be recorded via a dedicated electronic chain by a fast oscilloscope. Signals from the uncovered anode show a fast rise of few ns and a long tail while the "protected" anode (SiProt) signals exhibit a smaller amplitude and are spread in time (Figure 4). The calculated current was found to be attenuated by a factor of 4 in the "protected" detector, establishing a current limiting capability of a *a-Si:H* electrode.



Figure 4: Typical discharge signals from uncovered (left) and covered (right) anode detectors.

# 4. Three dimensional imaging with the TimePix chip

### 4.1. The TimePix chip.

The Medipix2 microchip was not designed for radiation tracking in gases. A dedicated new design was made for TPC applications, called Timepix [11]. MediPix2 readout detectors record projections of tracks without time information. Furthermore of the 14 available bits of the pixel counters, typically only one is used. For the Timepix design it was thus proposed that these bits would be used to count clock pulses according to two different modes. Every pixel that detects a signal crossing the threshold counts clock pulses until the signal crosses the low threshold again or until the end of a user defined time window (shutter time). These two counting modes are respectively called the "Time over Threshold" mode (TOT) and the "Timepix" mode. The first gives information on the signal height i.e.

the total charge, while the Timepix mode provides the drift time. These two modes cannot be used at the same time on the same pixel but can be mixed by applying a "mask" to the pixel matrix.

# 4.2. The TimePix/GEM detector.

The Timepix chip was applied as the readout of a triple GEM detector. The detector was installed in a 5 GeV/c electron beam at DESY. The geometry, bias voltages and gas mixture were as described in section 2.3. Several electron tracks were recorded in TOT and Time modes. Because of the large spread of the charge over the pixels, the mixed mode is here particularly interesting to provide as much information as possible. The mode mixing is illustrated on Figure 5 and suggests the good two-track separation capability of the detector. In Time mode, every "fired" pixel counts until the end of a shutter time, therefore a track passing close to the chip will record a larger number of counts than a track passing further away. A mixture of He/CO<sub>2</sub> 70/30 was also used, resulting in a noticeable decrease of primary ionization (Figure 6).



Figure 5: Two electron tracks detected in mixed mode in Argon  $CO_2$  70/30. Note the different colours in Time mode (right picture).



Figure 6: Electron tracks detected in mixed mode in He/CO<sub>2</sub> 70/30.

# 5. Conclusions

The proof of principle of pixelized gaseous detectors has been demonstrated by combining GEM or Micromegas with the MediPix2 chip. The performance of these detectors depends mainly on the pixel size and on how close to the chip the amplification structures can be brought. In the case of Micromegas, the transverse diffusion in the amplification gap is smaller than the pixel pitch, assuring that one electron avalanche is collected on one pixel; making the detector single-electron sensitive. GEM based detectors suffer from the small pixel pitch and are sensitive to large electron clusters where the charge clouds from several avalanches may merge.

The novel TimePix chip designed as a "time counting" MediPix2 will permit to reconstruct tracks in 3D by measuring the drift time or to measure the total charge collected on a pixel. Reconstruction can be on-board in the front-end electronics.

By means of post-processing technology it is possible to integrate the Micromegas onto the chip (InGrid) while minimizing the pillar diameter and aligning precisely the grid hole with the pixel pads. These two points will reduce dead regions to a minimum and maximize the detection efficiency. Another important development consists in the deposition of a spark protection layer onto the chip (SiProt). Both InGrid and SiProt will be soon applied to the TimePix chip. This combination will form a high precision 3D tracking detector suitable for ionization statistics (cluster densities, Fano factors) and gain fluctuations studies.

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# References

- [1] X. Llopart, M. Campbell, *First test measurements of a 64k pixel readout chip working in single photon counting mode*, Nucl. Instr. And Meth. A 509 (2003) 157.
- [2] Y. Giomataris, et al., *MICROMEGAS: a high-granularity position-sensitive gaseous detector* for high particle-flux environments, Nucl. Instr. And Meth. A 376 (1996) 29.
- [3] M. Campbell, et al., *Detection of single electrons by means of a Micromegas-covered MediPix2 pixel CMOS readout circuit*, Nucl. Instr. And Meth. A 540 (2005) 295.
- [4] A. Fornaini, et al., *The detection of single electrons using a Micromegas gas amplification and a MediPix2 CMOS pixel readout*, Nucl. Instr. And Meth. A 546 (2005) 270.
- [5] F. Sauli, *GEM: A new concept for electron amplification in gas detectors*, Nucl. Instr. And Meth. A 386 (1997) 531.
- [6] A. Bamberger, et al., *Readout of GEM detectors using the Medipix2 CMOS pixel chip*, arXiv:physics/0611229, accepted to Nucl. Instr. And Meth. A.
- [7] J. Schmitz, *Adding functionality to microchips by wafer post-processing*, Nucl. Instr. And Meth. A, in print (2007).
- [8] M. Chefdeville, et al., An electron-multiplying 'Micromegas' grid made in silicon wafer postprocessing technology, Nucl. Instr. And Meth. A 556 (2006) 490.
- [9] V. Blanco Carballo, et al., *On the geometrical design of integrated micromegas detectors*, Nucl. Instr. And Meth. A, accepted.
- [10] N. Wyrsch, et al., Proceedings of the MRS Symp., Vol 869, pp. 3-14, 2005.
- [11] X. Llopart, et al., Proceedings of the VCI 2007.