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The detection of single electrons using a Micromegas gas amplification and a MediPix2 CMOS pixel readout

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Abstract

By placing a Micromegas gas gain grid on top of a CMOS pixel readout circuit (MediPix2), we developed a device which acts as a pixel-segmented direct anode in gas-filled detectors.

With a He/Isobutane 80/20 mixture (capable of achieving gas gain factors up to 20×10^3) and employing a drift length of 15 mm, signals from radioactive sources and cosmic radiation were measured. Single primary electrons originating from the passage of cosmic muons through the gas volume were detected with an efficiency higher than 90%.

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Keywords: MediPix2; Micromegas; Pixel segmented anode; Pixel; CMOS pixel detector; Single electron detection

1. Introduction

Our goal is to develop a new readout system to be employed in gas-filled detectors for use in high-energy physics experiments. Such a readout system will be based on a CMOS chip segmented into a pixel matrix, each pixel being equipped with a preamplifier, discriminator and time-stamp circuitry. A gas gain grid will be integrated directly onto the chip itself by means of wafer-scale post-processing techniques.

This detector can replace traditional readout systems (usually composed of wires or gas gain

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grid, charge-collecting pads and readout circuitry) in gaseous chambers. This approach offers many advantages, the most important of which are the following:

- Gaseous detectors will be simpler to build and maintain, since all the gas gain and readout components are integrated in one single element.
- The small pixel size (of the order of $100\,\mu m \times 100\,\mu m$, opposed to typical pad sizes of several mm^2) not only offers a better resolution but opens the way for several additional measurements, for instance dE/dx measurement and δ-ray recognition and suppression.

The first step is to prove that a CMOS pixel detector employed in a gaseous environment is capable of detecting single electrons created by a charged particle traversing the gas volume. The proof-of-principle has been successfully realized with a MediPix2 chip in combination with a Micromegas mesh.

2. The MediPix2/Micromegas gas detector

The MediPix2 chip [1–3] has been employed as a segmented anode in our readout system. MediPix2 is a chip designed in $0.25\,\mu m$ CMOS technology, optimized for single-photon counting, and contains a square matrix of 256×256 pixels, with pixel dimensions $55\,\mu m \times 55\,\mu m$. Each pixel contains a charge-sensitive preamplifier, a discriminator, a 14-bit counter and communication logic. On each pixel an octagonal aluminum pad is present (covering about 20% of the total pixel surface—see also Fig. 1), and it is usually employed for bump-bonding with a semiconductor X-ray converter, segmented in a corresponding array.

In our application the MediPix2 chip is not connected to any semiconductor sensor. Instead, a Micromegas [4] mesh is mounted on top of it. The Micromegas foil that we use has a grid of $5\,\mu m$ thick copper, with $35\,\mu m$ diameter holes repeated in a square pattern with a pitch of $60\,\mu m$. The grid is kept at a distance of $50\,\mu m$ from the surface of the Medipix2 chip by means of insulating spacers (80–140 μm diameter, 840 μm pitch). This structure is mounted on a printed circuit board and inserted in our gas chamber through a slot in the baseplate of the chamber.

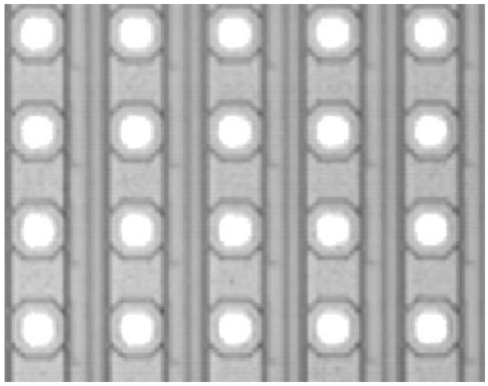

Fig. 1. Each pixel is provided with an octagonal aluminum pad for bump-bonding to the semiconductor sensor.

The gas chamber has a drift length of 15 mm. We expect the drifting volume to be hit by a cosmic ray particle about once every minute.

Several gas mixtures have been tested, based on argon, helium and CF4. The higher values for the gas gain (together with lesser risks of HV breakdown) have been achieved with an He/Isobutane 80/20 mixture.

A (weak) electric drift field is created above the Micromegas mesh. A voltage (200–450 V) is then applied between the Micromegas and the anode plane (which coincides with the Medipix2 plane): electrons entering this region create additional electrons via gas-avalanche mechanisms. Gas gains of up to 20×10^3 have been reached. We observe that in this way, very high electric fields (up to 7000 V/mm) reach the Medipix2 chip, which did not prevent it from working properly.

A schematic view of our MediPix2-Micromegas setup is given in Fig. 2.

3. Single electron detection

As a first test, the chamber was irradiated using several radioactive sources (^{55}Fe, ^{90}Sr and ^{241}Am). The detection of cosmic muons was also investigated. No trigger system was available; data

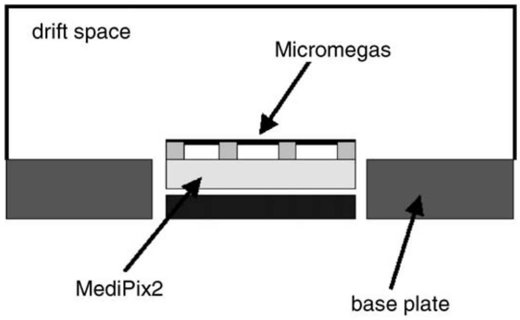

Fig. 2. A schematic view of the MediPix2-Micromegas prototype gas detector.

collection was then performed in the following way: the MediPix2 acquisition window was opened for a fixed amount of time (typically 10 s or 15 s), and all the charge collected during this period is recorded. Subsequent data analysis can reveal the presence of muon tracks.

Fig. 3 gives an example of raw data acquired in this way. In this particular image, a δ-ray can clearly be seen, which confirms the δ-ray recognition capability of our pixel-based readout system.

We collected a data sample of about 6000 images. A pattern-recognition algorithm was run on this data sample: noisy pixels were eliminated and cosmic tracks were reconstructed. The following cuts were applied:

- The track length in the detector plane is required to be larger than 50 pixels.
- More than 5 pixel clusters per track are required.
- The transverse rms is required to be less than 4 pixels.
- The number of pixels associated to the track must be larger than 80% of the total number of pixels hit.
- The number of associated pixels per millimeter of 3D track length should be less than 4.

A total of 164 tracks were identified in our data sample; an example of a selected event is given in Fig. 4.

The efficiency of our system for single electron detection was studied in the following way: for each selected track, the number of charge clusters

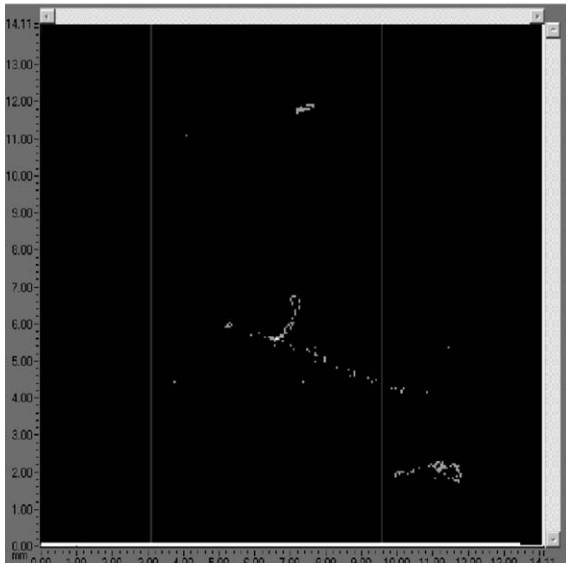

Fig. 3. Raw image of a cosmic muon track. A δ-ray originating from the track is visible. The dimensions of the image are 14.11 mm × 14.11 mm, corresponding to the Medipix2 pixel matrix.

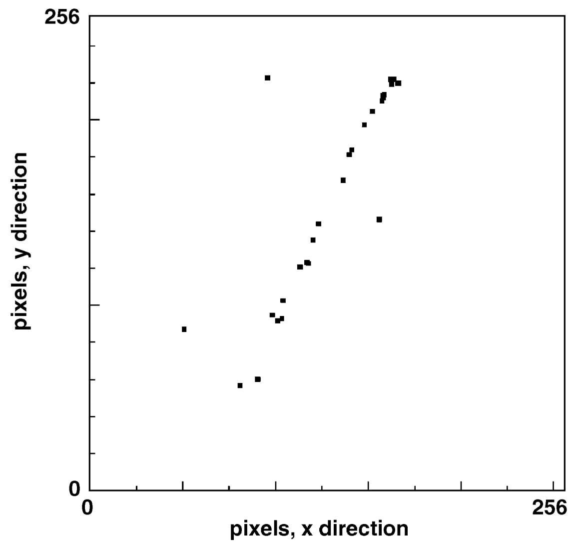

Fig. 4. An example of a selected cosmic-charged particle event. The selection criteria and noise filtering are described in the text. The dimensions of the image are 14.11 mm × 14.11 mm.

associated with the track was counted. Since the track length can be calculated, this gives us information about the number of detected single primary electrons per unit length. This number can be compared with the expected number of primary electrons released by a minimum ionizing particle in a specific gas mixture [5], and the ratio between these two quantities gives us an estimate of the efficiency for single electron detection. The efficiencies that we calculated in this way were above 90% (with some fluctuations depending on the particular gas gain and threshold settings used for each data set).

4. Discharge damage on the Medipix2 chip

Due to electrical discharges, several Medipix2 chips were damaged during the tests and they could not be operated anymore. The Medipix2 chip has no protection circuitry at its pixel input pads other than the source and drain diffusions of the transistors responsible for leakage current compensation. We noticed some damage of the pixel pads, probably due to an high temperature in the discharge region.

In future versions of our detector we intend to reduce the risks of discharge damage in the following ways:

- Covering the bottom of the Micromegas with a (high) resistive layer, limiting the participating charge.
- Covering the anode pads with a (high) resistive layer.
- Including a protective network in the circuitry of each pixel, connected to the corresponding anode pad.

5. Conclusions and future plans

By using a gas chamber based on a MediPix2/Micromegas system, the possibility to detect single primary electrons from cosmic muon tracks with high efficiencies (of above 90%) was proved. Our next goal is to design a new fully optimized CMOS pixel chip, and to integrate the gas gain grid directly on the chip by means of wafer-scale post processing techniques.

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