Imaging with the invisible light

R. Bellazzini, G. Spandre, A. Brez, M. Minuti, L. Baldini, L. Latronico, M.M. Massai, N. Omodei, M. Pesce-Rollins, C. Sgò, M. Razzano, M. Pinchera, J. Bregeon, M. Kuss, A. Bream

Istituto Nazionale di Fisica Nucleare di Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy
University of Pisa and INFN-Pisa, Largo B. Pontecorvo, 3 I-56127 Pisa, Italy
CERN, CH-1211 Genève 23, Switzerland

Available online 1 August 2007

Abstract

We describe a UV photodetector with single photon (electron) counting and imaging capability. It is based on a CsI photocathode, a GEM charge multiplier and a self-triggering CMOS analog pixel chip with 105 k pixels at 50 μm pitch. The single photoelectron produced by the absorption of a UV photon is drifted to and multiplied inside a single GEM hole. The coordinates of the GEM avalanche are reconstructed with high accuracy (4 μm rms) by the pixel chip. As a result the map of the GEM holes, arranged on a triangular pattern at 50 μm pitch, is finely imaged.

PACS: 25.6; 34.8.a; 52.70.−m

Keywords: UV photodetector; Single photon counting; Pixelized CMOS analog chip

1. Introduction

The idea of position sensitive gas detectors with CsI photocathodes was introduced and developed by Charpak’s group [1] at the end of the 80s when the first parallel-plate chamber with a CsI photocathode was successfully tested. Soon afterward solid photocathodes were coupled to wire chambers [2] and, with the introduction of new detector construction technologies as photo-lithography and advanced PCB, to new types of charge amplification structures such as MSGC [3–5], MGC [6], GEM [7–9].

Since the beginning, these types of detectors found great interest and widespread applications in several, different fields, from high energy physics, to nuclear physics, astrophysics, industry, plasma diagnostic and medical imaging and for this reason, in the last two decades, a large number of different types of “gaseous photomultipliers” have been developed and successfully tested. In the development of photon detectors the main requests are for detection efficiency, particularly to single photons, localization accuracy and time stability. The use of GEMs in gaseous photodetectors with CsI photocathode, has allowed, due to the shadowing effect provided by the GEM itself, to efficiently reduce the avalanche-induced photon and ion feedback that spoils the performance and limits the gain and the lifetime of the detector.

In this work we describe a UV photodetector based on a single GEM charge multiplier coupled to a custom CMOS VLSI pixel array which is, at the same time, the charge collecting electrode and the analog, self-triggering, read-out electronics. The fine pitch of both the read-out system and of the amplification structure (50 μm) and the possibility to work in single photon detection allows reaching avalanche reconstruction accuracy of 4 μm.

2. The UV photon detector

Two different photocathode configurations have been studied: the so-called semitransparent mode (Fig. 1, left...
panel), obtained by evaporating \(~100 \text{ Å}\) CsI film onto the quartz window that closes the gas volume of the detector and the \textit{reflective} mode (Fig. 1, right panel) in which the UV photon converter layer (1000 Å) is deposited onto the top side of the GEM. With this last method the photoelectrons extracted from the CsI are focused, by the electric field at the top GEM surface, into the nearest GEM hole and here multiplied. The \textit{reflective} approach allows the use of thick photocathodes which are easier to handle and have higher quantum efficiency \((10-20\% \text{ at } 150 \text{ nm})\) compared to the semitransparent ones but, on the other hand, a photodetector operating in this configuration needs a special gold pre-coating on the GEM which introduces a lower geometrical efficiency \((\sim 50\% \text{ in our case})\) and a lower gas gain.

With respect to the reflective mode of operation the detector with a semitransparent photocathode is simpler to fabricate, has a higher gas gain and geometrical efficiency but the low thickness of the CsI coating prevents to obtain high Q.E. Fig. 2 shows a sketch view of the detector assembly and the UV-lamp adapter.

The brass frame in Fig. 2 houses the quartz window and defines the 1 mm drift region. The transfer gap between the GEM bottom and the charge collection pads of the VLSI ASIC has also 1 mm thickness. This chip is the third generation \([10,11]\) of a series of custom CMOS ASICs of
increasing complexity, larger size, reduced pitch and improved functionality (Fig. 3). In the top metal layer of the chip, 105,600 hexagonal pixels are arranged at 50 $\mu$m pitch in a $300 \times 352$ squared matrix of $15 \times 15$ mm$^2$ active area (corresponding to a pixel density of 470 mm$^2$). A full electronics chain (pre-amplifier, shaping amplifier, sample and hold, multiplexer) is integrated under each pixel in the remaining metal, polysilicon and oxide layers of the 0.18 $\mu$m CMOS technology. The chip integrates more than 16.5 million transistors and it is subdivided in 16 identical clusters of 6600 pixels (22 rows of 300 pixels) or alternatively in 8 clusters of 13,200 pixels (44 rows of 300 pixels) each one with an independent differential analog output buffer.

A new feature implemented in the chip is a customizable internal self-triggering capability with independently adjustable thresholds for each cluster. Groups of four contiguous pixels (mini-cluster) contribute to a local trigger with a dedicated amplifier whose shaping time ($T_{\text{shaping}} \approx 1.5 \mu$s) is roughly a factor of two faster than the shaping time of the analog charge signal. In self-trigger operation the read-out time and the amount of data to be transferred result vastly reduced (at least by a factor 100) with respect to the standard sequential read-out mode of the full matrix (which is still available, anyway). This is due to the relatively small number of pixels (400–500) within the region of interest. The main characteristics of the VLSI chip are summarized in Table 1.

To exploit the high granularity of the read-out plane, a non-standard gas amplification structure (GEM) with a pitch of 50 $\mu$m that matches the read-out pitch has been manufactured at CERN. Optimal spatial resolution and imaging capability have been obtained. The technological challenge in the fabrication of this type of GEM has been the precise and uniform etching of the very narrow biconical multiplication holes, only 33 and 15 $\mu$m diameter, respectively, at the top and in the middle of the kapton layer. With this gas multiplier, large effective gains at voltages at least 70 V less than with standard 90 $\mu$m GEM have been reached. A gas gain of around 1000 has been obtained in 50% Ne–50% DME at 450 V across the GEM. This is likely due to the higher field lines density inside the very narrow amplification holes. A photo of the detector ready to be mounted on the control motherboard is shown in Fig. 4.

A custom and very compact DAQ system to generate and handle command signals to/from the chip (implemented on Altera FPGA Cyclone EP1C240), to read and digitally convert the analog data (ADS5270TI Flash ADC) and to storage them temporarily on a static RAM, has been developed. By using the RISC processor NIOS II, embedded on Altera FPGA, and the self-triggering functionality of the chip it is possible, immediately after the event is read-out, to acquire the pedestals of the pixels in the same chip-defined event window (region of interest).
The pedestals can be read one or more times (user-defined). The average of the pedestal readings is used to transfer pedestal subtracted data to the off-line analysis system. This mode of operation has the great advantage of allowing the real time control of the data quality and to cancel any effect of time drift of the pedestal values or other temperature or environmental effects. The disadvantages are a slight increase of the channel noise (at maximum a factor $\sqrt{2}$, for the case of 1 pedestal reading only) and an increase of the event read-out time. For most of the applications we envisage, this will not be a real problem given the very large signal-to-noise ($S/N$) ratio (well above 100) and the very fast window mode operation.

Nonetheless, the standard mode of operation with the acquisition of a set of pedestal values for all the 105k channels at the beginning or at the end of a data taking run is still possible. The instrument control and data acquisition is done through a VI graphic interface developed in LabVIEW. The VI performs a bidirectional communication through a 100 Mbps TCP connection between the DAQ and a portable PC running Windows XP.

Fig. 5 shows a snapshot of the Control Panel of the VI.

3. Laboratory tests and single photon operation

The detector has been tested in both configurations, semitransparent and reflective; in particular the capability to operate in single photon detection has been studied.

Data were acquired in self-trigger configuration and the detector was illuminated with a UV lamp operating in DC mode. The gas filling utilized is a mixture of 50% neon–50% DME.

The use of a GEM with a much finer pitch than usual (pitch and thickness have now equal size) that matches the
50 μm read-out pitch, has allowed not only to push forward the 2D reconstruction capability of the device but also to obtain high gas gain with reduced voltages across the GEM. Fig. 6 shows the measured effective gain as a function of the GEM voltage, with the typical exponential dependence, as derived from the charge distributions of Fig. 7. The gain values reported in Fig. 6 have been obtained by fitting (Fig. 8) the corresponding distribution with a Polya function of the type:

\[ P\left( \frac{G}{G_0} \right) = \frac{N_m}{\Gamma(m)} \left( m \frac{G}{G_0} \right)^{m-1} e^{m(G/G_0)} \]

where \( G_0 \) is the average effective gas gain.
The detection efficiency of the device has been evaluated by measuring the trigger rate as a function of $\Delta V_{\text{GEM}}$ (Fig. 9). From an exponential fit to the curve an efficiency of $\sim 82\%$ at 560 V across the GEM has been obtained.

The characteristics of the detector of very low noise, high gain and read-out granularity, allows operating in single photon detection and, under this condition, a very high intrinsic spatial resolution has been measured. With the UV light intensity kept sufficiently low, the device can detect one photon at a time, each producing a single electron.

This electron drifts into a single GEM hole where it knocks out further electrons from atoms in an avalanche effect. The avalanche started from the single electron is then extracted and collected onto the fine-pitch pixel CMOS analogue chip which provides a direct reading of the GEM charge multipliers. If the resolution is good and the noise is low, the centre of gravity corresponds to the centre of the GEM hole.

A cumulative map of several hundreds of thousands of such events produces a kind of self-portrait of the GEM amplification structure with individual dots only 50 $\mu$m apart (Fig. 10).

A cut through the GEM holes of the 2D image, allows to estimate the intrinsic resolution of the read-out system, in response to a single primary electron, of only 4 $\mu$m (Fig. 11). The picture shown in Fig. 10 has been obtained with the CsI photocathode in semitransparent configuration, but similar, highly resolved, images have been obtained in reflective mode, as shown in Fig. 12 where a set of small washers and nuts, the smallest one being an hexagonal nut with 1 mm internal diameter, has been imaged by illuminating the detector from above with the UV lamp.

At least three facts demonstrate that the detector can operate in single photon detection:

- After a first strong attenuation of the light flux by filtering, no significant change of the mean value and of the shape of the charge distribution has been observed by further reduce of the trigger rate; at this point a final reduction of the flux of more than a factor five has been performed by adding UV filters and by moving the UV lamp far away from the entrance window.
- Even at higher rate, double events, recognizable in the one-dimensional plot of the pixel charge (Fig. 13), are very rare and clearly distinguishable; in the 2D
reconstruction they are in fact treated as two single photons. The 2D cumulative histogram of Fig. 14 shows the first 50 triggers registered by the detector. All the 50 reconstructed photoelectron clusters are well separated.

- The spots, corresponding to the GEM holes, in the baricenters distribution of Fig. 11 are very well resolved; only the detection of a single photon cluster can lead to such a resolving power. Detecting two or more unresolved photons would make impossible to associate the baricenter with a GEM hole.

4. Conclusions

A UV photodetector based on a semitransparent or reflective CsI photocathode, followed by a Gas Electron Multiplier foil and a large area, custom, analog CMOS VLSI ASIC has been reported. The detector has shown excellent imaging capability and single electron sensitivity. The high granularity and low noise of the read-out electrode allows to reconstruct with a 4 μm resolution the centroid of the single electron avalanche. The position resolution of the device is, at the moment, limited by the 50 μm pitch of the GEM foil.

The main problem of such device is the control on the ion back-flow that can limit the lifetime of the detector, but various possible solutions exist and are now under development.

The performance obtained with this device allow to state that the class of Gas Pixel Detectors is now a mature technology with a level of integration, compactness, operational simplicity and resolving power up to now typical of solid state detectors only. It is also important to remark that this kind of device is very robust and after several months of intensive operation, no die or single pixel has been lost for electrostatic or GEM discharges, or for any other reason.

Fig. 11. An horizontal cut through the bi-dimensional map of the baricenter positions allows to estimate the intrinsic resolution of the detector. The peak-to-peak distance corresponds to the GEM pitch. A gaussian fit of an individual peak distribution gives a width (rms) of less than 4 μm.

Fig. 12. Reconstructed image of a sets of small mechanical components obtained by illuminating the detector from above with the UV lamp. The smallest object is a nut with internal diameter of only 1 mm.
References