Available online at www.sciencedirect.com

SCIENCE DIRECT®

Nuclear Instruments and Methods in Physics Research A 513 (2003) 250–255

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Recent advances in gaseous imaging photomultipliers

A. Breskin*, M. Balcerzyk[1], R. Chechik, G.P. Guedes[2], J. Maia[3], D. Mörmann

Department of Particle Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

Abstract

We summarize our recent advances in gaseous photomultipliers (GPMTs) for the UV and visible spectral range. They combine photocathodes and advanced multi-stage Gas Electron Multipliers (GEMs). Principles of operation and properties are discussed, with emphasis on time and localization resolutions, ion-feedback suppression, novel electron multipliers and sealed photon detectors for visible light.

PACS: 85.60.Gz; 29.40.−n; 29.40.Ka; 29.40.Cs

Keywords: Photon detectors; Gas-avalanche detectors; GEM; Visible-light photocathodes

1. Introduction

In recent years there has been considerable progress in the development of gaseous photomultipliers (GPMTs). In parallel to very large-area (m^2) imaging GPMTs, combining CsI UV-sensitive photocathodes and wire-chamber electron multipliers, mostly motivated by applications in Cherenkov Ring Imaging in particle physics [1,2], there have been intensive R&D efforts towards the development of novel GPMT techniques [3,4]. We will concentrate here on GPMTs comprising solid UV- and visible-sensitive semitransparent and reflective photocathodes coupled to cascaded Gas Electron Multipliers (GEM [5]). Large-area multi-GEM imaging GPMTs [6] may compete with available vacuum-based photon detectors: the atmospheric pressure operation in a variety of gases, including noble gases [6], permits conceiving compact flat-geometry devices; they reach multiplication factors exceeding 10^6, thus having single-photon sensitivity; the devices have good 2D localization resolution and ns timing with single photons. Unlike vacuum photon detectors, gas-filled devices can operate in high magnetic fields [1].

We will briefly summarize below the properties of GEM-based GPMTs and demonstrate that these photon detectors became a mature technique in the UV spectral range. We will report on recent progress in gas-sealed visible-photon GPMTs with alkali-antimonide photocathodes and standard Kapton-made GEM electrodes. Further developments in electron multipliers will be discussed.

2. GEM-based photomultipliers

The multi-GEM GPMT has a very similar structure to that of a typical vacuum-operated

*Corresponding author. Tel.: +972-8-934-2645; fax: +972-8-934-2611.

E-mail address: amos.breskin@weizmann.ac.il (A. Breskin).

[1] On leave from Soltan Institute of Nuclear Science, Swierk, Poland.

[2] On leave from COPPE/LIN Rio de Janeiro, Brazil.

[3] On leave from University of Coimbra, Portugal.

0168-9002/$ - see front matter
doi:10.1016/j.nima.2003.08.041

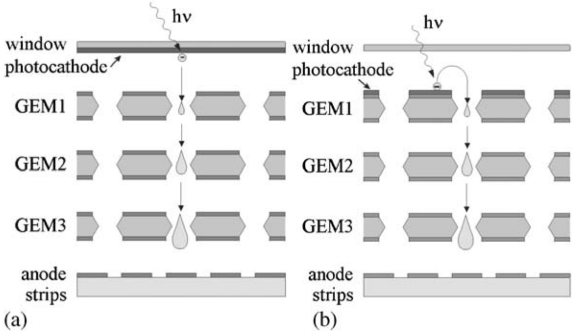

Fig. 1. Schematic view of the multi-GEM gaseous photomultiplier with: (a) a semitransparent photocathode and (b) a reflective photocathode. Signals are recorded at a segmented anode used for photon localization.

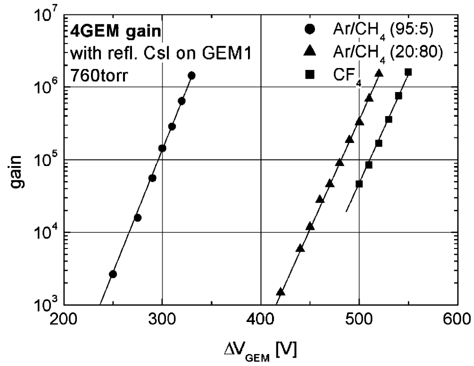

Fig. 2. Gain curves recorded in a multi-GEM photomultiplier with a reflective CsI photocathode, shown in Fig. 1b. ΔV_{GEM} is the voltage across a single GEM.

mesh-dynode photomultiplier. Its schematic view is shown in Fig. 1; in Fig. 1a a cascade of GEM multipliers is coupled to a semitransparent photocathode [6], while in Fig. 1b a reflective photocathode [7,8] is deposited directly on the top surface of the first GEM.

A standard single-GEM electrode [9] is made of 50 μm thick Kapton, with double-sided 5 μm thick copper clad, perforated with an hexagonal array of double-conical holes (diameter 50 μm in Kapton and 70 μm in copper), with a pitch 140 μm. A single GEM has typically a gain of a few times 10^3 in common counting gases, upon the application of a few hundred volts across the holes [10]. Cascaded 3- and 4-GEM CsI-based GPMTs reach gains above 10^5 with single photons, in noble gas mixtures and in Ar-CH_4 [6], and above 10^6 in CF_4 (Fig. 2) [11]. These very high gains, resulting in high sensitivity to single photons, are due to the efficient optical screening of avalanche-induced photon-feedback effects. The "reflective" GPMT has the further important advantage: due to its optimal operation with "zero" drift-field above the photocathode, it is practically insensitive to ionization deposited by background radiation [8]. This is of prime importance in photon imagers (e.g. of Cherenkov detectors) operating under very intense particle background [12,13].

The photon detection sensitivity is dictated by the quantum efficiency (QE) of the photocathode, the photoelectron extraction efficiency into gas and by that of its focusing into a GEM hole. The extraction efficiency depends on backscattering on gas molecules [14], which increases with the electric field; for a given field it is low in noble-gas mixtures, while it reaches values close to that in vacuum in CH_4 and CF_4 [11]. The electron focusing efficiency into the first GEMs hole depends on the detector geometry, the electric field at the photocathode and at the GEM-hole vicinity and on the type of gas. This very crucial single-electron focusing process has been extensively investigated for both GPMT operation modes shown in Fig. 1 [7,8,15]. Conditions were found where each photoelectron extracted from the photocathode is efficiently transferred through the first GEM to the next multiplication elements. This is also summarized in Ref. [12].

To summarize, the photon detection efficiency with GPMTs can reach values close to that reached in vacuum devices, when operating with CH_4, CF_4 and in Ar-CH_4 mixtures, under appropriate electric field conditions [11]. Though the GEM-coated photocathode has about 20% lower active area, due to the holes, its production is simpler and its absolute QE value is superior to that of a semitransparent photocathode.

The 50 μm GEM-foil thickness results in a fast-growing avalanche process across this very short distance. Unlike other gas multipliers, the electron avalanche diffuses very little laterally and longitudinally; typical current pulses have a few ns rise time and 10–20 ns width (Fig. 3), depending upon the gas and the number of GEMs in a cascade

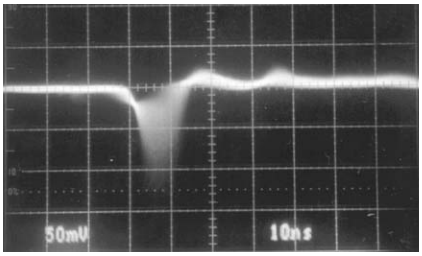

Fig. 3. Typical single-photon fast current pulses recorded in CF4 at a gain of 105.

[6,11]. Therefore, respective rms time resolutions of 1.6 and 0.3 ns were measured for single- and 150-photoelectron bursts [11,16].

The multi-GEM detector offers excellent localization properties with segmented readout anode circuits [17]. The small lateral spread of the avalanche affects the width of the charge induced on the anode; this width can be tailored to a given readout method, by a proper choice of gas and GEM-to-anode avalanche-induction distance [18]. An example demonstrating the 2D localization resolution of a 3-GEM detector operated with soft X-rays is shown in Fig. 4 [19]. The intrinsic resolution with a X–Y strip-anode coupled to a dedicated delay-line readout circuit is of the order of $\sigma = 70-100\,\mu m$.

Similarly to avalanche-induced photon-feedback effects in gas counters, also ion-induced electrons may cause avalanche divergence into discharge. Such ion-feedback effects, discussed in Ref. [20], depend upon ion kinetic and ionization energies (function of: gas, pressure and electric field) and upon the detector surface material (electron affinity, gap energy). In GPMTs, ion-feedback effects occur mostly when ions are neutralized at the photocathode. Efforts have been made to understand and to reduce to minimum such ion-feedback in the multi-GEM multipliers [21–23]. In devices designed to detect charges deposited in gas, ion-feedback effects can be reduced by applying low electric drift-fields at the cathode region [22]. In contrary, the fields at the photocathode surface of a GPMT must be kept high to permit an efficient photoelectron extraction into gas (see above). This naturally makes it very difficult to prevent ions from reaching the photocathode. We have demonstrated that, while keeping high fields at the photocathode surface, ion collection can be reduced in multi-GEM detectors only down to levels of $\sim 10\%$ [16,23]. This is not sufficient, as already discussed in Ref. [24].

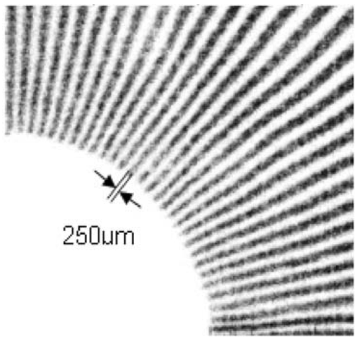

Fig. 4. A 2D X-ray image of a patterned mask of a total size of $18 \times 18\,mm^2$, recorded in a 3-GEM detector with a striped anode and delay-line readout; Ar/CO_2 (70/30), 1 atm.

A solution to the problem is the incorporation of an active ion-gating electrode between the GEM electrodes. It is based on a pulsed alternating-bias wire-plane, similar to that of [25]. We have demonstrated [23] that such a pulsed gate, triggered by the anode avalanche and having good electron transmission, can suppress ions down to 10^{-4} levels, though at the cost of some rate limitations. Another possible solution of feedback-free operation in a non-gated mode is discussed below.

3. Gaseous photomultipliers for the visible spectral range

While it seems that the UV-sensitive multi-GEM GPMT is a mature technique, the real challenge are visible-sensitive devices. In contrary to UV-sensitive photocathodes that are stable under gas multiplication conditions [1–3] and operate in a gas-flow mode, visible-sensitive photocathodes are chemically very reactive and should operate in a sealed mode. In the past we have extensively studied the possibility to couple bialkali photocathodes with a gaseous detector, by coating them with thin protective alkali-halide films [26]. This approach, though successfully demonstrating unprecedented protection against oxygen, involved a significant loss of the QE, by factor 3–7 [26]. The opportunity to operate high-gain multi-GEM detectors with noble gas mixtures, a medium compatible with bialkali photocathodes, opens the possibility of realizing high-QE sealed GPMTs with visible range sensitivity.

Following successful attempts of sealing multi-GEM GPMTs, 60 mm in diameter, with UV-sensitive CsI photocathodes [21], we have been producing sealed devices with semitransparent bialkali photocathodes (Fig. 5). The photocathode is sealed to the detector package by "hot" In-Sn sealing, at 130–150°C; details are provided in Ref. [27]. Having succeeded sealing bialkali photodiodes in argon, which have been kept stable for over 8 months [16], we have proceeded with sealing visible light GPMTs. These comprise a cascade of $30 \times 30\,\mathrm{mm}^2$ standard-geometry Kapton-based GEMs (see above) and an anode. First sealing attempts in 710 Torr of pure Ar yielded rather low QE values, due to elevated sealing temperatures; the QE was stable for two weeks and degraded due to a micro leak. Gas-multiplication studies indicated that in contrary to CsI, a considerable ion feedback appeared with the bialkali photocathode, due to its very efficient secondary electron emission, strongly limiting the gain [16]. Further studies of ion-induced secondary effects on a bialkali photocathode coupled to a GEM were carried out in various gas mixtures [16]. It was surprisingly found that while in pure Ar and CH_4 the feedback is large, resulting in a gain limit of 20 in a single GEM, adding a few percent of CH_4 to Ar raised the gain limit to 1000; with 2–5% CH_4 in Ar ion feedback was not observed at this gain.

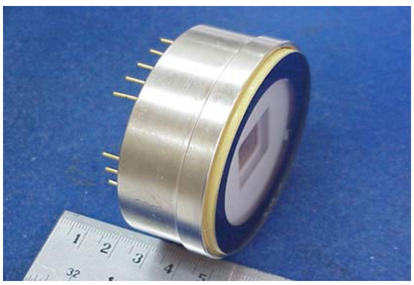

Fig. 5. A photograph of a sealed multi-GEM gaseous photomultiplier.

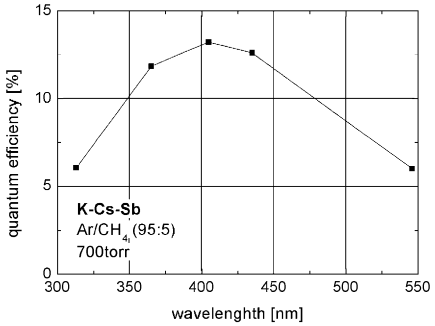

Fig. 6. The absolute quantum efficiency as function of wavelength of a visible-sensitive multi-GEM photomultiplier, sealed in atmospheric Ar/CH4 (95/5).

This interesting observation is yet unexplained and is currently under study.

A GPMT of identical structure, sealed with 710 Torr of Ar/CH_4 (95/5) could be operated with no feedback till gains of 800 on the first GEM; a total gain of 2×10^4 was reached in a two-GEM operation mode. The QE measured in the detector after sealing was peaked at 13% at 435 nm (Fig. 6), which is only ~ 2 times lower than the QE measured in vacuum before sealing.

4. Novel electron multipliers

In parallel to the research described above, focused on GPMTs with multi-GEM electron multipliers, we are in constant search for advanced multiplier concepts and materials. We have recently demonstrated that a novel micropattern multiplier, the Micro Hole & Strip Plate (MHSP) [28,29] could have some interesting properties. The double-stage MHSP multiplier, shown in Fig. 7, is a GEM-like electrode foil, but with the rear-metalized face subdivided into thin anode- and broader cathode-strips; this face is similar to that of a Microstrip gas avalanche chamber (MSGC) [30]. Electrons focused into a hole are preamplified in a GEM-like process; the avalanche electrons are then focused onto the anode strips, where a second multiplication occurs. The total gain of this single-foil, double-stage multiplier exceeded 10^3, in a first, non-optimized detector electrode [29]; it is similar to a single-GEM gain. However, in a GPMT configuration, the MHSP has the

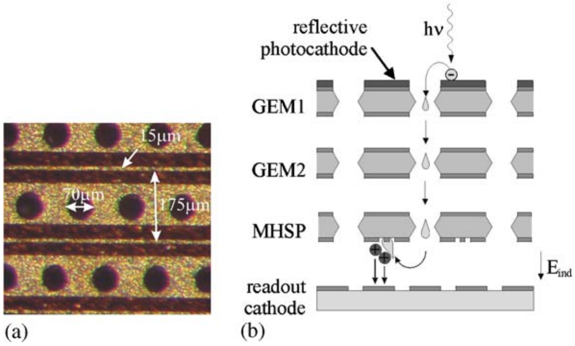

Fig. 7. A photograph of the striped side of an MHSP electron multiplier (a) and a schematic layout of a gaseous photomultiplier comprising a cascaded 2-GEM plus MHSP electron multiplier (b); signals are induced on a segmented cathode, providing photon localization.

following advantages when preceded by a cascade of GEMs:

(a) This geometry will totally screen the photocathode from photon feedback.
(b) Conditions were found where the ion-feedback is considerably reduced compared to GEMs, by collecting the strip-avalanche ions on the nearby cathodes [31].
(c) The readout can be done with a segmented cathode, localizing the pulses induced by the strip-avalanche; the resulting broader charge distribution, compared to that on GEM-anodes [18], may ease the localization procedure.

Though the first results with Kapton-made GEMs sealed with bialkali photocathodes seem encouraging on the short time scale, it is yet unclear if on the long term, possible outgassing of this polymer will not deteriorate the photocathodes. Therefore, other substrate materials for GEMs are currently being investigated, among them glass, ceramic and silicon. Glass-GEMs were recently reported to yield successful operation [32]; we are studying methods for economically producing metalized perforated thin glass sheets. We also investigate production techniques of thin ceramic-made GEMs. A new approach recently initiated in cooperation with scientists of the University of Glasgow is the fabrication of thin silicon-GEMs; Fig. 8 shows an example of a perforated substrate, demonstrating the precisions reached with modern silicon etching techniques. However, the possibility of charge multiplication within holes in a semiconductive material is yet questionable and is under investigation. Other potential multipliers for sealed detectors could be glass capillary plates, studied by other groups [33,34].

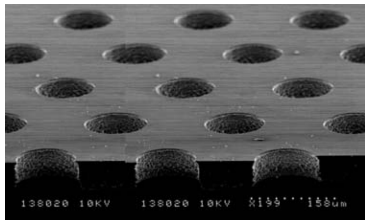

Fig. 8. A photograph of a perforated silicon substrate, studied for future GEM production. Si thickness: 120 μm; hole diameter: 100 μm; spacing: 200 μm.

5. Summary

GEM-based GPMTs have been extensively studied over the past years; they can be made with large surfaces and flat compact geometry; they have excellent timing and localization capabilities and can operate at high magnetic fields. Conditions were found for efficient single-photoelectron detection in a variety of gases, including noble-gas mixtures. While the technique seems mature in the UV spectral range, we get very close to the possible realization of the more challenging dream of detectors for visible light. First attempts, using standard Kapton-made GEMs and bialkali photocathodes, are very encouraging, showing stability over a few weeks and QE values above 10% at 400 nm. Ion-induced feedback effects, distinctive to the bialkali photocathode, could be strongly reduced by either selecting proper gas mixtures or by introducing an active ion-gate electrode. Novel MHSP multipliers may permit further reduction of ion-feedback effects. Though Kapton-made GEMs seem to permit stable operation of visible-sensitive sealed GPMTs, yet demonstrated only on a short time scale, we are investigating other, UHV-compatible GEM-substrates like glass, ceramic and silicon. Long-term stability in sealed mode, photocathode aging under high gain multiplication, ion feedback studies in various gases, single-photon imaging and other topics are under investigations. Large-area fast imaging GPMTs have many potential applications; most important are single-photon imaging in Cherenkov detectors, light recording from solid, liquid and gas scintillators in physics experiments and medical imaging, plasma diagnostics, etc. We are currently developing a large-area thermal-neutron imaging detector comprising thin liquid scintillator coupled to a visible-sensitive GPMT [35].

Acknowledgements

The research on MHSP electron multipliers has been carried out in close cooperation with Prof. J.M.F. dos Santos and Dr. J.F.C.A. Veloso from the University of Coimbra, Portugal; we would like to thank them for their contribution to this topic. We are indebted to Prof. K. Smith, Dr. M. Rahman and Mr. Giulio Pellegrini from the University of Glasgow, for their enthusiastic co-operation in preparing perforated silicon substrates.

This work was partially supported by the Israel Science Foundation. A. Breskin is the W.P. Reuther Professor of Research in the Peaceful use of Atomic Energy.

References

[1] F. Piuz, et al., Nucl. Instr. and Meth. A 433 (1999) 178.
[2] F. Piuz, Proceedings of RICH02, Pylos, Greece, June 2002, Nucl. Instr. and Meth. A 502 (2003) 195.
[3] A. Breskin, et al., Nucl. Instr. and Meth. A 442 (2000) 58 and references therein.
[4] T. Francke, et al., IEEE Trans. Nucl. Sci. NS 49 (2002) 977 and references therein.
[5] F. Sauli, Nucl. Instr. and Meth. A 386 (1997) 531.
[6] A. Buzulutskov, et al., Nucl. Instr. and Meth. A 443 (2000) 164 and A 442 (2000) 68.
[7] D. Mörmann, et al., Nucl. Instr. and Meth. A 471 (2001) 333.
[8] D. Mörmann, et al., Nucl. Instr. and Meth. A 478 (2002) 230.
[9] Produced at the Printed Circuits Workshop-CERN, Geneva.
[10] J. Benlloch, et al., Nucl. Instr. and Meth. A 419 (1998) 410.
[11] A. Breskin, et al., Nucl. Instr. and Meth. A 483 (2002) 670.
[12] R. Chechik, et al., Progress in GEM-based gaseous photomultipliers, Proceedings RICH02, Pylos, Greece, June 02. Nucl. Instr. and Meth. A 502 (2003) 195.
[13] C. Aidala, et al., A hadron-blind detector for PHENIX, Proceedings of RICH02 Workshop, Pylos, Greece, June 2002. Nucl. Instr. and Meth. A 502 (2003) 200.
[14] A. Di Mauro, et al., Nucl. Instr. and Meth. A 371 (1996) 137.
[15] C. Richter, et al., Nucl. Instr. and Meth. A 478 (2002) 528.
[16] D. Mörmann, et al., GEM-based gaseous photomultipliers for UV- and visible-photon imaging, Nucl. Instr. and Meth. A 504 (2003) 93.
[17] A. Bressan, et al., Nucl. Instr. and Meth. A 425 (1999) 254.
[18] G. Guedes, et al., Effects of the induction gap parameters on the signal in double-GEM detector, Nucl. Instr. and Meth. A 497 (2003) 305 and references therein.
[19] G. Guedes, et al., Two-dimensional GEM X-ray imaging detector with delay-line readout, Nucl. Instr. and Meth. A, in press.
[20] R. Chechik, et al., Nucl. Instr. and Meth. A 419 (1998) 423.
[21] A. Breskin, et al., Nucl. Instr. and Meth. A 478 (2002) 225.
[22] A. Bondar, et al., Study of ion feedback in multi-GEM structures, Nucl. Instr. and Meth. A 496 (2003) 325.
[23] D. Mörmann, et al., Evaluation and reduction of ion back-flow in multi-GEM detectors, Nucl. Instr. and Meth. A, in press.
[24] J. Edmends, et al., Nucl. Instr. and Meth. A 273 (1988) 145.
[25] P. Nemethy, et al., Nucl. Instr. and Meth. A 212 (1983) 273.
[26] E. Shefer, et al., Nucl. Instr. and Meth. A 433 (1999) 502 and references therein.
[27] M. Balcerzyk, et al., Methods of preparation and results of sealed gas photomultipliers for visible light, IEEE Trans. Nucl. Sci. NS-50 (2003) 847.
[28] J.F.C.A. Veloso, et al., Rev. Sci. Instr. 71 (2000) 2371.
[29] J.M. Maia, et al., Advances in the Micro Hole & Strip Plate detector, Nucl. Instr. and Meth. A 504 (2003) 364.
[30] A. Oed, Nucl. Instr. and Meth. A 367 (1995) 34 and references therein.
[31] J. Maia, et al., Avalanche-ion back-flow reduction in gaseous electron multipliers based on GEM/MHSP, Nucl. Instr. and Meth. A, submitted for publication.
[32] S.K. Ahn, et al., IEEE Trans. Nucl. Sci. NS-49 (2002) 870.
[33] V. Peskov, et al., Nucl. Instr. and Meth. A 433 (1999) 492.
[34] H. Sakurai, et al., IEEE Trans. Nucl. Sci. NS-46 (1999) 333 and these proceedings.
[35] D. Vartsky, et al., Large area imaging detector for neutron scattering based on boron-rich liquid scintillator, Nucl. Instr. and Meth. A 504 (2003) 369.