High-gain DC-mode operated Gaseous Photomultipliers for the visible spectral range

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Abstract

We shortly describe recent progress in photon detectors combining bi-alkali photocathodes and cascaded patterned gas-avalanche electron multipliers. It permitted the development and the first feasibility demonstration of high-gain gaseous photomultipliers sensitive in the visible spectral range, operated in DC mode with single-photon sensitivity.

Key words: gaseous photomultipliers, gas multiplication, bi-alkali photocathodes, micropattern detectors, visible-sensitive photon detectors, GEM, MHSP

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1. Introduction

Gaseous photomultipliers (GPM) have been widely employed since a few decades for single-photon imaging in the UV spectral range - mainly in Cherenkov detectors. Their main advantage is the possibility of conceiving large-area atmospheric-pressure devices, with low sensitivity to magnetic fields, having multiplication factors that permit efficient imaging of light at single-photon levels. In recent years there has been a considerable progress in the development GPM concepts with advanced Micropattern electron multipliers, as reviewed in [1]. In most cases these were coupled to CsI UV-sensitive photocathodes. Intensive R&D efforts have been motivated by the necessity to overcome some basic limitations of wire-chamber multipliers; others were directed towards the possible extension of GPMs’ sensitivity from the UV to the visible spectral range. Here the main difficulties are the photocathodes’ (e.g. bi-alkali) chemical reactivity, as well as gain limitations due to ”feedback effects” caused by photon- and ion-mediated secondary-avalanches. The very high reactivity of visible-sensitive photocathodes results in very short lifetimes in gases, even with impurity levels in the fraction of ppm range. Therefore, visible-sensitive GPMs can operate only in sealed containers, as shown in [2]. Efforts were made to coat bi-alkali photocathodes with thin protective films [3,4], as to allow for gas-flow operation; these resulted, at best, in residual QE-values of 4-5 fold lower than that of bare photocathodes [5]. Feedback effects limit the detector’s gain and its single-photon detection efficiency; they affect time and position resolutions and damage the photocathode. The ion-induced secondary-electron emission is particularly important in GPMs with visible-sensitive photocathodes; their low electron-emission threshold clearly limits the avalanche gain
in DC mode [2]. Visible-sensitive GPMs reached however high gains ($\sim 10^6$) with pulsed ion-gating in cascaded GEMs [6]. The present success in their stable DC operation, at gains of $10^5$, resulted from an efficient avalanche-ion blocking with advanced patterned hole-multipliers [7,8]. The various approaches of multiplier-concepts for visible-sensitive GPMs are reviewed in [1]. More information about sealed visible-sensitive GPMs, bi-alkali photocathode production and high-gain gated operation is provided in [9].

2. Visible-sensitive GPM with cascaded patterned hole-multipliers

In cascaded gaseous "hole-multipliers" of different structures, discussed in [1], the avalanche develops in successive multiplication stages and is confined within the holes. Cascading several successive multipliers results in total avalanche gains above $10^5$ - adequate for efficient single-photon detection. Most of the avalanche-induced secondary photons originating from the last avalanche in the cascade are efficiently screened by the cascade elements, thus preventing photon-feedback effects. Ion-feedback reduction is by far more difficult and challenging. It is inherently difficult to prevent avalanche ions from back-drifting to the photocathode while maintaining high multiplier’s gain and full photoelectron collection and detection efficiencies; this is because the ions follow the same field lines (though in an opposite direction) as the avalanche electrons. Efficient methods were recently developed that permit a very significant reduction of the Ion Back-flow Fraction (IBF), e.g. the fraction of total avalanche-generated ions reaching the photocathode in a GPM [7,8].

Fig. 1. Photographs of gaseous electron hole-multipliers used in this work. a) the GEM, with two identical faces and b) the MHSP strip-patterned face; its other face is GEM-like.

The lowest ever attained IBF-values, of $3 \cdot 10^{-4}$, were reached, at gains of $10^5$ and with full single-photon electron collection efficiency [8] combining Gaseous Electron Multipliers (GEM) [10] and other patterned hole-multipliers: Micro Hole & Strip Plates (MHSPs) [11] (Fig. 1a, Fig. 1b). Both have micro-holes (typically 50-70 microns in diameter) densely etched in a thin double-sided metal-clad 50 microns thick polyimide. In GEM, multiplication occurs under high electric fields within the holes. The MHSP has thin anode- and cathode-strips patterned on the GEM-like electrode; the anode strips either multiply electrons (following the initial hole-multiplication) or, with reversed strip polarity, trap ions - preventing them from drifting backwards to the photocathode [7,8]. In the ion-defocusing mode, the MHSP strips can either point towards the successive cascade elements, in reversed-bias MHSP (R-MHSP) mode, trapping their ions, or to point towards the photocathode; in the latter, the so-called flipped reverse-bias MHSP (F-R-MHSP), the strips also trap the avalanche ions generated within this multiplier’s holes. In both cases conditions were found for efficient ion blocking under full photoelectron collection efficiency [7,8]. Based on the recently measured ion-induced electron emission probabilities from bi-alkali photocathodes, the low IBF value of $3 \cdot 10^{-4}$ fulfills the requirement for stable DC operation of visible-sensitive GPMs at gains of $10^5$ [1].

Fig. 2. The gaseous visible-sensitive photomultiplier (GPM) comprising: a) a semitransparent bi-alkali photocathode followed by 3 different cascaded hole-multipliers: F-R-MHSP, GEM and MHSP (with 4 avalanche stages). The arrows show possible avalanche-ion paths.

Following this successful ion blocking, a first proof of principle was recently made in the DC-mode operation of a visible-sensitive GPM. The detector comprised a semitransparent K-Cs-Sb bi-alkali photocathode coupled to a cascaded hole-multiplier composed of a F-R-MHSP followed by a GEM and an MHSP, described above (Fig. 2). The QE of this...
GPM in Ar/CH$_4$ (95/5) at 700 Torr was estimated, on the basis of electron-backscattering data [12], from the vacuum-QE measured after the bi-alkali-photocathode production (Fig. 3). Values of 24% were estimated at 400 nm.

Stable operation at gains of $10^5$ (not the detector’s limit) was reached in DC mode, at 700 Torr of Ar/CH$_4$ (95/5) (Fig. 4). The response of a GPM composed of 2 cascaded GEMs coupled to a bi-alkali photocathode is shown for comparison; notice the gain “divergence” in the bi-alkali/double-GEM GPM, occurring already at gains above 100, compared to the regular exponential behavior curve obtained with the cascaded GPM of Fig. 2. This validated the hypothesis that an efficient ion blocking (here IBF$=3 \times 10^{-4}$) permitted, for the first time, operating a visible-sensitive gaseous photomultiplier at such high gains. In addition to the curves with bi-alkali photocathodes (data points), lines fitted to the data measured with CsI UV-photocathodes are shown in Fig. 4 under the same conditions; the stable operation with CsI is due to the lack of ion-feedback. Large-area UV-sensitive cascaded-GEM GPMs with CsI photocathodes are already in use for single-photon imaging in Cherenkov detectors [113].

The ageing of semitransparent K-Cs-Sb photocathodes under avalanche-ion impact was recently investigated [11]. The measurements showed typically a QE decay of $\sim 20\%$ after an accumulated charge (avalanche ions) of 1-2 $\mu$C/mm$^2$ on the photocathode. In terms of a photon detector with a bi-alkali PC, operating at a gain of $10^5$ and assuming an IBF value of $3 \times 10^{-4}$, a 20% QE drop would occur after 46 years of operation at a photon rate of 5 kHz/mm$^2$. For comparison, due to the high ion-backflow in a MWPC-based photon detector, the photocathode would only survive 5 days under the same operation conditions [11].

3. Summary

Following an intensive and long R&D program, we demonstrated, for the first time, the possibility of operating gaseous photomultipliers (GPM) sensitive in the visible spectral range, at high gains, in DC mode. The stable operation, free of ion-feedback gain-limitations, was reached with cascaded hole-multipliers combining three different electron-multiplier elements: a F-R-MHSP, a GEM and a MHSP. The 3 different multipliers permitted reaching high gains, with 100% photoelectron collection efficiency and with unprecedented ion-blocking capability. The latter was reached by ion trapping with strips patterned on the surfaces of the MHSP-like elements. Due to the small hole-size and pitch, cascaded GEM and GEM-like GPMs offer 2D single-photon localization resolutions in the 100 micrometer range [131,130]. Large-area photon detectors could also use the more recent Thick-GEM (THGEM) cascaded multipliers [17] with patterned ion-blocking electrodes. These economically manufactured devices have larger holes but
still sub-millimeter resolutions \[18\]. Such devices would require low-outgassing substrate-materials (e.g. polyimide, ceramic, glass etc.) when applied to visible-sensitive GPMs. The prospects of producing economically large-area, sealed flat visible-photon detectors of this kind, with single-photon sensitivity and good localization and timing properties, capable of operation at MHz/mm\(^2\) rates - should be very challenging to industry! These would pave ways towards numerous potential applications.

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