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Development of gaseous PMT with micropattern gas detector

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Abstract

We have developed gaseous photomultiplier tubes (PMTs) with a bialkali photocathode combined with micropattern gas detectors (MPGDs) such as a glass capillary plate (CP), a gas electron multiplier (GEM) and a Micromegas detector. Gaseous PMTs with two different gas mixtures of Ar (90%) + CH₄ (10%) and Ne (90%) + CF₄ (10%) were investigated at a gas pressure of 1 atm. Quantum efficiencies of up to 12% were obtained for both neon and argon gas mixtures. A new glass CP made of Pyrex glass has been developed for a hole-type MPGD. The glass is well suited for the high level of cleanliness and reaction conditions required for the production of bialkali photocathodes. A gain of up to $1.5 \times 10^4$ and an energy resolution of 23% were obtained for 5.9 keV X-rays. This latest result and the basic performance of the gaseous PMTs are described.

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Keywords: gaseous PMT, glass capillary plate, micropattern gas detector
1. Introduction

In the last few years, there has been considerable effort devoted to the development of gaseous photomultiplier tubes (PMTs) with a micropattern gas detector (MPGD) sensitive to light in the region ranging from vacuum ultraviolet (VUV) to infrared (IR) wavelengths (see refs [1-7] and references therein). The potential advantage of the gaseous PMT is that it can achieve a very large effective area with moderate position and timing resolutions. In addition, it can be easily operated under a very high magnetic field compared with the conventional vacuum-based PMT. In the VUV range, a ring imaging Cherenkov detector (RICH), which consists of a cesium iodide (CsI) photocathode coupled to a multiwire proportional chamber (MWPC), has been successfully and widely utilized in the field of high-energy physics for particle identification (see refs [8, 9] and references therein). However, it has been suggested that the open geometry of the MWPC limits the sensitivity and lifetime of the CsI photocathode due to both photon and ion feedback [8]; almost all the photons and ions produced during the electron multiplication reach the photocathode, where they cause secondary and successive avalanches by interacting with the photocathode. Therefore, the maximum achievable gain is limited to approximately $10^5$ due to the feedbacks from the interaction of the MWPCs with the CsI photocathodes [8].

Concerning gaseous PMT that are sensitive to visible light, the effect of the feedback is more serious because the work function of the bialkali is lower than that of the CsI photocathode [3]. It is expected that the photon and ion feedback cause faster degradation of the bialkali photocathode than that of the CsI photocathode. Hence, the maximum achievable gain is limited to approximately 100 due to the feedback [10]. Several recent developments have been achieved using hole-type MPGDs such as the gas electron multiplier (GEM) [11] and glass capillary plate (CP)
Attacks to develop MPGDs with a CsI photocathode seem to be feasible since the geometry of the hole-type MPGDs plays the roles of both masking photons and absorbing ions [13, 7]. However, to develop a gaseous PMT with a bialkali photocathode, attention must also be paid to the high chemical activity of the bialkali metal. Thus, the selection of the material of the MPGD is crucial, in particular, the material should be well suited to the high level of cleanliness and reaction conditions required for the production of bialkali photocathodes. To evaluate the MPGD in a gaseous PMT sensitive to visible light, we have investigated the characteristics of sealed gaseous PMTs with a bialkali photocathode combined with MPGDs such as a glass CP, a GEM, and a Micromegas detector [14]. In this paper, we describe the basic performance of the gaseous PMTs, particularly the production of the photocathode, quantum efficiency, gain and photon and ion feedback.

2. Basic properties of the gaseous PMT

2.1. Quantum efficiency in gas mixtures

To begin the first study on the production of a bialkali photocathode, we constructed a double Micromegas detector in a gaseous PMT following the previous work [15]. A photograph and schematic view of the double Micromegas detector with a bialkali photocathode are shown in Fig. 1. The glass vessel, electrode and insulator are the same as those used in the vacuum-type PMT developed at Hamamatsu Photonics K.K. Each Micromegas detector is made of Ni mesh with square holes of 43 μm × 43 μm with 78 μm mesh spacing. The space between the first and second meshes is 600 μm, and that between the second mesh and the anode plate is 500 μm. The fabrication of the bialkali photocathode (K-Cs-Sb) was
performed at Hamamatsu Photonics K.K. by the same process used to produce the conventional vacuum-type PMT.

The gaseous PMT was filled with Ar (90%) + CH₄ (10%) or Ne (90%) + CF₄ (10%) gas mixtures at 1 atm. The photocathode was irradiated with photons from a tungsten lamp at the temperature of black-body radiation, 2856 K, and the luminous flux ranged from 10⁻⁵ to 10⁻⁹ lm. The quantum efficiency (QE) was determined by measuring the photoelectron currents using current meters at the photocathode (I_{cathode}) and the first mesh (I_{mesh1}) as shown in Fig. 1 b).

The QEs of the gaseous PMT with a bialkali photocathode are shown in Fig. 2 as a function of wavelength for the gas mixtures of Ar (90%) + CH₄ (10%) and Ne (90%) + CF₄ (10%). The electric field at the collection area between the photocathode and the first mesh was set to 150 V/cm for the QE measurements. The QE for the neon gas mixture is similar to that for the argon gas mixture. The maximum QEs are 14 and 12% for the neon and argon mixtures at wavelengths of 350 and 420 nm, respectively. The quantum efficiencies of the same PMT in a vacuum environment are also shown in Fig. 3 before and after filling the argon gas mixture. The QE in the evacuated PMT was approximately 20% before the gas filling at wavelengths between 300 and 500 nm. The deterioration of QE after filling the gas can be explained by the effect of photoelectron backscattering due to collisions with the gas molecules. Although the QE was degraded to approximately 12% upon filling the gas, it recovered its original value when the gas was evacuated again. Moreover, there was no deterioration of the QE over one and half years for the sealed gaseous PMT filled with the argon gas mixture. From these results, it is confirmed that there is no degradation of the bialkali photocathode resulting from the inefficient sealing of the glass vessel and the escape of gas from the PMT.
2.2. Gain of the gaseous PMT with double Micromegas detector

The gain of the gaseous PMT with the double Micromegas detector was studied by measuring the signal currents at the anode (I_{anode}), first mesh (I_{mesh1}), second mesh (I_{mesh2}) and the photocathode (I_{cathode}) while varying the applied voltage of the first and second meshes. The voltage between the first and second mesh is fixed at the difference in voltage ($\Delta V_{\text{mesh}}$) between the second mesh and the anode. The electric field between the photocathode and the first mesh is kept at 170 V/cm. Fig. 4 shows the dependence of the signal currents on $\Delta V_{\text{mesh}}$ above 450 V. The current at the photocathode is less than 0.1 nA throughout the entire measurement. It is clear that almost all the ions produced at the double Micromegas are collected by both meshes. The ion feedback, defined as the ratio of $I_{\text{cathode}}$ to $I_{\text{anode}}$, is estimated to be less than $2.5 \times 10^{-3}$ when $\Delta V_{\text{mesh}} = 495$ V. This value is about 100 times larger than that required for the practical application of single-photoelectron detection.

The gain of the gaseous PMT was obtained by measuring the ratio of $I_{\text{anode}}$ to $I_{\text{cathode}}$ ($\Delta V_{\text{mesh}} = 0$ V). Fig. 5 shows the gain as a function of the applied voltage ($\Delta V_{\text{mesh}}$) for the Micromegas detector; the gain reached $2 \times 10^3$ without a large deviation from the exponential curve, indicating photon and ion feedback [16]. However, unexpected signals resulting from the operation of the double-mesh structure appear at a gain above $2 \times 10^3$ for the neon gas mixture. This secondary effect was also observed in the previous measurement with a gas mixture of Ar (90%) + CH$_4$ (10%) at a gain of approximately $6 \times 10^3$ [15]. Therefore, we concluded that it is not appropriate to apply the gaseous PMT with the double Micromegas detector to a single-photon detector, for which a gain of over $5 \times 10^5$ is necessary for practical operation. Thus, we started to develop a gaseous PMT with a bialkali photocathode using the combination of a hole-type MPGD and a Micromegas on the basis of previous works [7, 15].
3. Evaluation of bialkali photocathode for gaseous PMT with hole-type MPGD

3.1. Material of the hole-type MPGD

Because the bialkali photocathode is chemically very unstable, the materials inside the PMT must satisfy the high level of cleanliness required for the production of a bialkali photocathode. At present, the main materials of hole-type MPGDs are Kapton and lead glass, which are used the substrate of the GEM and the glass CP, respectively. Using these materials, we attempted to fabricate gaseous PMTs with a bialkali photocathode combined with the hole-type MPGD. We tested two types of hole-type MPGDs having different substrates; a glass CP made of lead glass and a GEM made of Kapton (Kapton GEM). The other materials and parts as well as the configuration of the gaseous PMTs are identical to those used for the measurement by the double Micromegas detector except for the first mesh. The CP has a thickness of 0.4 mm and an individual capillary diameter of 100 μm. The hole diameter and the hexagonal array pitch of both GEM are 70 and 140 μm, and the thicknesses is 50 μm.

3.2. Fabrication of bialkali photocathode

The fabrication of the bialkali photocathode (K-Cs-Sb) was performed by the process used for the production of the gaseous PMT with a double Micromegas detector; a thin layer of Sb is deposited on a substrate of Koval glass, and is activated by bialkali metals (K-Cs). First we observed the colors of the surface on Koval glass after fabricating the bialkali photocathode. For the glass CP, the surface was light brown similar to that of vacuum-type PMT. In contrast, it was colorless for the Kapton GEM. These results imply that the bialkali K-Cs vapor react with the material of the GEM. We performed an additional experiment to investigate the chemical reaction. Piece of Kapton was set in glass ampoules filled with the bialkali K-Cs or K vapor. After a while, the color of Kapton were gradually changed to grey as K
evaporated then to dark brown as soon as the Cs started to evaporate. These changes in the color are attributed to an absorption reaction between the bialkali metals and the organic material in the GEM.

The photocathode sensitivity $S_k$, defined as the ratio of the cathode current $I_{\text{cathode}}$ to the incident flux ($\Phi$), was measured to investigate the quality of the production of the bialkali photocathode. The photocathode was illuminated with focused visible light from a tungsten lamp. $S_k$ was 56.3 $\mu$A/ lm for the gaseous PMT with the glass CP, which is consistent with that for the gaseous PMT with a double Micromegas detector. $S_k$ was 1.5 $\mu$A/ lm for the gaseous PMT with the Kapton GEM, which is less than 3% of that of the glass CP. The experimental results clearly show that the material of GEM chemically reacts with the bialkali metals and affect the production of the bialkali photocathode on the substrate of the Koval glass.

3.3. Pyrex glass capillary plate

In contrast, the production of the bialkali photocathode seems to be problem-free for the PMT with the lead glass CP. However, our experiment shows that the conductivity on the surface of the wall of the lead glass changed after the production of the bialkali photocathode. This result indicates that a chemical reaction between the lead glass and the bialkali metal occurs at the surface of the wall. Indeed, the photoelectrons cannot enter the electron multiplication region in the CP, since the penetration of the bialkali metal causes the deterioration of the electric field in the drift region. Therefore, we started to develop a hole-type MPGD with Pyrex glass that allows the problem-free production of bialkali photocathode. A micrograph of the Pyrex glass CP is shown in Fig. 6. Its thickness is 300 $\mu$m, and the diameter and pitch of each capillary are 160 and 300 $\mu$m, respectively. The electrodes are made of
Al fabricated onto the two flat surfaces of a plate. Each hole has a double-conical shape with 124 μm diameter at the centre of the glass.

Basic performance tests of the Pyrex CP gas detector were carried out with an X-ray source using the experimental setup described in ref. [17]. Fig. 7 shows the gain for the Ne (90%) + CF− (10%) gas mixture as a function of the voltage across the glass CP electrodes. The gain was obtained by measuring the amplitude of the charge output from the CP anode using a digital oscilloscope. Gains of up to $1.5 \times 10^4$ were safely achieved using a single CP. The gain obtained with the lead glass CP with thickness and hole diameter of 400 and 100 μm, respectively, is also indicated for comparison. At the same gas gain, the operating voltage for the Pyrex glass CP was ~80 V higher than that for the lead glass CP. The typical pulse height spectrum for 5.9 keV X-rays is shown in Fig. 8. The energy resolution is 23%, which agrees with the result obtained using the lead glass CP gas detector [17]. Following the successful operation of the Pyrex glass CP upon X-ray irradiation, we are currently developing the gaseous PMT with bialkali photocathode.

4. Summary and discussion

The potential advantages of the gaseous PMT are very large effective area with moderate position and timing resolutions. It can also be easily operated under a very high magnetic field, compared with the conventional vacuum-based PMT. The characteristics are important in experiments in elementary particle physics using accelerators and in clinical applications using a combination of positron emission tomography (PET) and magnetic resonance imaging (MRI). To develop a gaseous PMT, we have investigated the basic characteristics of gaseous PMTs with a bialkali
photocathode combined with MPGDs with a glass CP, a GEM, and a Micromegas detector.

Quantum efficiencies of up to 12% were obtained for the gaseous PMT with a bialkali photocathode filled with neon and argon gas mixtures. Although these efficiencies were lower than that in vacuum due to photoelectron backscattering, there was no deterioration of the efficiency over more than one and half years for the gas within the sealed glass vessel. From the investigation of the production of the bialkali photocathode in the gaseous PMT, we found that Pyrex glass is a more suitable material as a hole-type MPGD than other materials such as lead glass and Kapton. The Pyrex glass CP gas detector was operated with a gas mixture of Ne (90%) + CF₄ (10%) at 1 atm. We successfully obtained a gain of up to 1.5 × 10⁴ and an energy resolution of 23% for 5.9 keV X-rays. A high gain of above 5 × 10⁵ is required for practical applications including single-photelectron imaging. To satisfy this requirement, the development of a gaseous PMT with cascaded MPGD is under way.

5. Acknowledgements

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References


Figures

Fig. 1 Photograph a) and schematic view b) of the sealed gaseous PMT with a bialkali photocathode and double Micromegas detector.

Fig. 2 Quantum efficiencies of the sealed gaseous PMT with a bialkali photocathode and double Micromegas detector for the gas mixtures of Ar (90%) + CH₄ (10%) and Ne (90%) + CF₄ (10%) at 1 atm as a function of wavelength.

Fig. 3 Quantum efficiencies of the gaseous PMT with a bialkali photocathode and double Micromegas detector measured in vacuum before and after filling the argon gas mixtures. The maximum QE in the evacuated PMT is approximately 20% at wavelengths between 300 and 500 nm. The QE of the sealed gaseous PMT for Ar (90%) + CH₄ (10%) at 1 atm is indicated as solid a thick line (blue).

Fig. 4 Electrode currents (I_{cathode}, I_{mesh1}, I_{mesh2}, I_{anode} and their sum) of the sealed gaseous PMT with a bialkali photocathode and double Micromegas detector as a function of $\Delta V_{mesh}$ between the second mesh and the anode. The filled gas is Ne (90%) + CF₄ (10%) at 1 atm.

Fig. 5 Gain of the sealed gaseous PMT with a bialkali photocathode and double Micromegas detector for Ne (90%) + CF₄ (10%) at 1 atm as a function of $\Delta V_{mesh}$.

Fig. 6 Photograph of the Pyrex glass CP a), a micrograph b) and a scanning electron microscope image of the cross section of the glass plate c). The thickness of the CP is 300 μm, and the diameter and pitch of each capillary
are 160 and 300 μm, respectively. Each hole has a double-conical shape with 124 μm diameter at the centre of the glass.

Fig. 7  
Gain as a function of the voltage across the Pyrex glass CP electrodes for Ne (90%) + CF (10%) gas mixture at 1 atm obtained with 5.9 keV X-rays. The gain for the lead glass CP with a thickness of 400 μm and a hole diameter of 100 μm is indicated for comparison.

Fig. 8  
Pulse height distribution of the charge signal of the Pyrex glass CP gas detector for a collimated 55Fe source. The energy resolution is 23% (FWHM) for 5.9 keV X-rays.
Fig. 1

Fig. 2

Fig. 3
Fig. 4

Fig. 5

Fig. 6
Fig. 7

Fig. 8