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Study of electron focusing in thick GEM based photon detectors using semitransparent photocathodes

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ABSTRACT

The detection efficiency of a GEM based UV sensitive gaseous photomultiplier (GPM) depends on the focusing of electrons from the drift gap to the GEM aperture. We have studied the effect of drift parameters on the efficiency of electron focusing into Thick GEM (THGEM) holes in a GPM with semitransparent UV photoconverter. This study comprises simulation of electron focusing into THGEM holes using GARFIELD for different Ar and Ne based gas mixtures and experimental investigations of the same with P10 gas mixture.

1. Introduction

Thick GEM (THGEM) detectors [1,2] have longer multiplication region and offer higher gain compared to normal GEM in a single stage, which is achieved using larger multiplication voltage. They are used in applications such as UV sensitive gaseous photomultipliers (GPM) [3]. In these detectors, solid photocathode (usually CsI) is used for initial photon conversion. In this process, UV photons release photoelectrons from the solid photocathode into the gas volume of the detector. These photoelectrons undergo avalanche multiplication across the THGEM hole due to high dipole field, achieving gain up to 10^5 and single photoelectron detection [2]. However, single photoelectron detection in stable conditions can be achieved only in triple THGEM configuration [1,4].

THGEM based UV photon detector systems such as in RICH detectors used for relativistic particle identification in high energy physics experiments [6] and more generally GPMs [3] are required to have excellent detection efficiency for single photon. Efficient single photon detection requires,

(i) Maximum photoelectron yield from the photocathode surface. This includes quantum efficiency of the photocathode and the efficiency of photoelectron extraction into the gas medium.
(ii) Efficient charge transfer (photoelectrons) from the photocathode surface to the THGEM hole for multiplication, which is termed as Electron Transfer Efficiency (ETE) in this paper. ETE is the ratio of the number of electrons entering the THGEM hole to the total number of electrons extracted from the photocathode surface.
(iii) Efficient multiplication in the THGEM hole and.
(iv) Efficient charge transfer towards next amplification element.

In THGEM detectors with reflective type of photocathode, electrons are efficiently focused (close to 100% ETE) even at smaller gas gain [4]. When semitransparent (ST) photocathode is used [3,7,8], there are several parameters that affect the transfer of electrons from the photocathode surface to the THGEM holes like the electron transport properties in the drift region between the ST photocathode and the THGEM. The electron transport properties such as drift velocity and diffusion depend on the electric field, gas mixture, pressure and temperature. THGEMs manufactured by mechanical drilling of standard PCBs having thickness 400–1000 μm, holes pitch between 700 and 1000 μm and diameter between 300 and 1000 μm are typically used for UV photon detector applications [4,5]. In the specific case of THGEM applications, the ETE is also affected by geometrical parameters namely drift gap, hole diameter and pitch [2,6,9].

There are several reported works on ETE measurements and also on its simulations. But most of them deals with normal GEM and not THGEM [9,10]. Though GEM and THGEM are both hole-type structures, their geometrical parameters are quite different.

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THGEM is a mechanical expansion of the standard GEM, but its operational properties and operational conditions do not scale accordingly. In the literature, only a few papers deal with electron transfer efficiency in THGEM based UV photon detectors [4,5], but they mainly focus on the study of drift field and dipole field. In the present work, we use Monte Carlo technique with GARFIELD to simulate the electron transport from the photocathode surface to the THGEM hole for various operating conditions and geometrical parameters. Experimental investigations have been carried out for P10 gas mixture to compare with simulation results. Factors affecting the charge transport in the drift region of the THGEM based GPM with ST photocathode are discussed.

2. Modeling and simulation

A schematic of a ST photocathode based GPM is shown in Fig. 1. 3D finite element modeling and electric field computation of the THGEM were carried out using ANSYS while the electron cluster generation and transport properties in various gas mixtures were simulated using GARFIELD program.

The simulation process steps followed are given below,

(i) THGEM structure was modeled in ANSYS. A unit cell was modeled, material properties were assigned to the different parts of the structure and voltages were applied to different electrodes. The model was then subjected to finite element meshing and electrostatic solution generates field map files.
(ii) The field map files were exported to GARFIELD. The unit cell was subjected to mirror symmetric repetition in GARFIELD, which produced full model of the THGEM.
(iii) A gas mixture was defined using MAGBOLTZ program, which has interface with GARFIELD.
(iv) A uniform matrix of large number of electrons was produced in the drift gap on the photocathode plane. Each of the electrons was drifted from their starting point. Monte Carlo technique was used with GARFIELD to simulate the drift path of electrons through the gas medium.
(v) End coordinates of the drifting electrons returned by GARFIELD was used to find out the total number of electrons entering the THGEM hole, backscattered to the photocathode and hitting the top metal electrode.

Snapshot of GARFIELD simulation is depicted in Fig. 2, illustrating the transport of charge in Ar:CO_2 (70:30) gas mixture at 1 atm. In this example, voltage across the THGEM was set at a value of 1000 V and the drift field maintained between the drift electrode and THGEM top electrode was 0.3 kV/cm. Induction field across the induction gap, i.e. the gap between the THGEM bottom electrode and the readout electrode was 4 kV/cm. It can be seen that not all the electrons starting from the drift electrode reach the THGEM hole for multiplication. Many electrons stop at the top metal electrode. Single photon detection efficiency relies not only on the photocathode

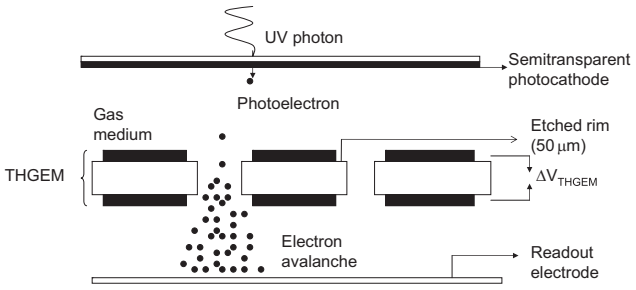

Fig. 1. Schematic of THGEM coupled to a semitransparent photocathode.

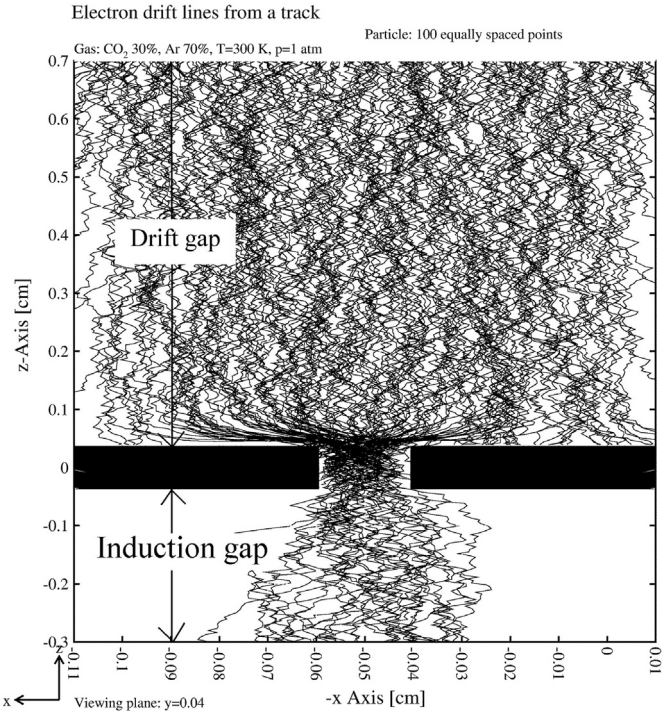

Fig. 2. 2D view of GARFIELD plot showing the end point of electron drift lines at different parts of the THGEM structure for semitransparent photocathode. The gas mixture used was Ar:CO_2 (70:30) at 1 atm.

quantum efficiency, but also on the ETE, i.e. the probability that a photoelectron reaches the THGEM holes. Factors affecting such a probability, namely hole geometry, drift field, drift gap, gas mixture and gas pressure are studied and discussed in the following sections.

2.1. Studies on geometrical parameters

Optical transparency, i.e. the ratio of the open area (THGEM hole area) to the total THGEM area is one of the deciding factors for focusing of electrons into the THGEM aperture. For any THGEM structure with cylindrical holes of diameter D and pitch P, the optical transparency is given by [11],

$$\tau = \frac{\pi D^2}{2\sqrt{3}P^2} \quad (1)$$

Simulation results of ETE for different hole diameter and thickness are shown in Fig. 3. P10 gas at 1 atm was used for simulation of the THGEM with a ST photocathode. The pitch was maintained at 1000 μm. The ratio of dipole field E_{Hole}, and the drift field E_d, was kept constant for different THGEM thicknesses. ETE increases with the optical transparency and this holds for THGEMs of any thickness. While optical transparency and hence ETE can be increased with larger hole diameter, higher operating voltage is required for achieving a particular gain [5]. Diameter of the hole and pitch are decided based on manufacturing limitations and also on position resolution requirements. All these factors impose limitations on optimization of geometrical parameters for maximizing ETE.

3. Experimental apparatus and procedure for ETE measurement

Simulations and experimental studies of ETE dependence on drift parameters were carried out for P10 gas. Geometrical parameters of the THGEM used in these studies were insulator thickness 250 μm, hole diameter 200 μm and pitch 450 μm.

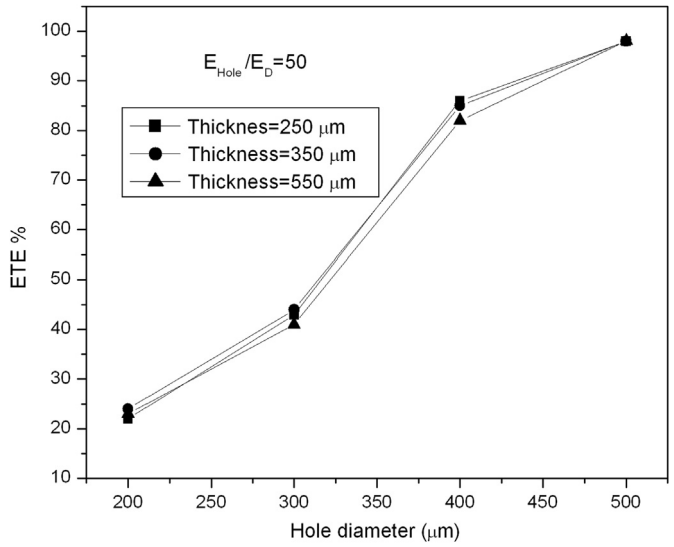

Fig. 3. Effect of THGEM hole diameter on ETE for a ST photocathode configuration. The optical transparencies corresponding to hole diameters 200 μm, 300 μm, 400 μm and 500 μm are 3.6%, 8.1%, 14.5% and 22.6% respectively. The drift field was maintained at 0.3 kV/cm.

A 50 μm rim was provided around each hole for reducing the probability of discharges. This rim was created by chemical etching of copper [5]. The drift gap was varied between 5 and 14 mm for different measurements. A quartz window (2 mm thick) with 4–5 nm chromium layer deposited on it was used as substrate for the ST photocathode. 50 nm thick CsI layer deposited onto the chromium layer was used as the photocathode [5]. CsI coating was carried out using thermal evaporation technique at a vacuum of 10^{-5} Torr. The sample was then annealed at 70 °C for 4 h in vacuum before carrying out the measurements. A low pressure Hg lamp emitting in the range of 100–280 nm was used as UV source for our measurements. At lower ΔV_{THGEM}, below multiplication field, ETE was derived from current measurements [5]. The effective photocurrent due to photoelectrons extracted from the photocathode surface was measured for ST type photocathode using experimental arrangement shown in Fig. 4(a). The current was measured with an electrometer (KEITHLEY 6517 A). Drift field was applied between the photocathode and the THGEM top electrode. No ΔV_{THGEM} was established during the measurement of photocurrent as the top and bottom electrodes of THGEM were shorted. The electrons reaching the THGEM hole and below were measured at the THGEM bottom and readout electrodes together, using experimental arrangement as shown in Fig. 4 (b). The electrical connections were external to the gas detector chamber, so the changes between the measurements were made without disturbing the setup. To ensure stable photon flux from the lamp during all the measurements, experiments were carried out 45 min after switching ON the UV lamp. The ratio of THGEM bottom current and the total photocurrent is the measure of ETE.

Initially the variation of photocurrent with drift field was studied experimentally using setup shown in Fig. 4(a). The results obtained are presented in Fig. 5. As can be seen, the photocurrent increases with the drift field. The increased photoelectron extraction at higher drift field is due to reduced photoelectron backscattering [4].

Fig. 6 shows the current measured at the THGEM bottom electrode and the readout electrode together for various ΔV_{THGEM}. It can be observed that above ΔV_{THGEM} of ~400 V, the current starts increasing gradually and then increases exponentially, due to the onset of avalanche multiplication.

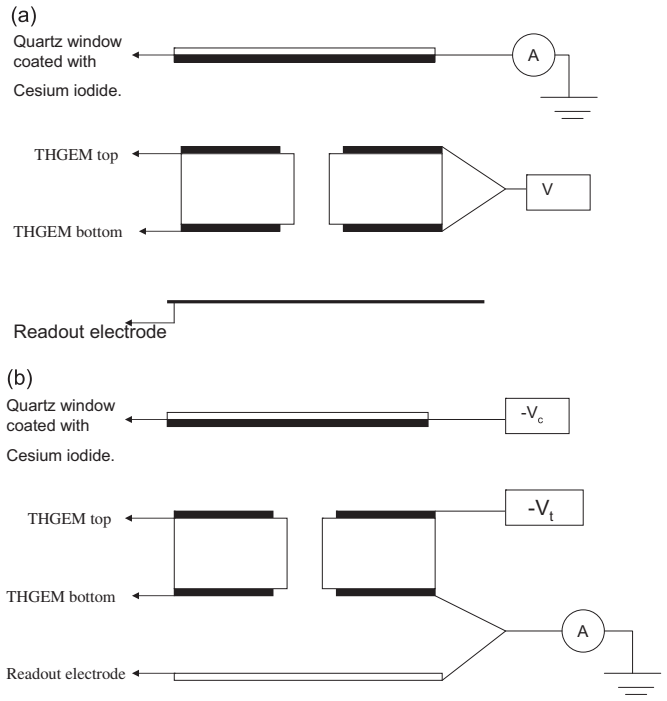

Fig. 4. (a) Photocurrent measurement setup for semitransparent photocathode. (b). THGEM bottom current measurement setup.

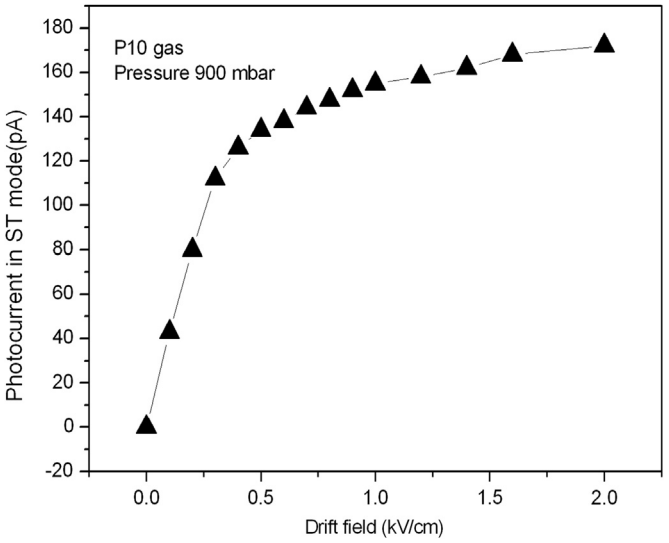

Fig. 5. Photocurrent measured at various drift fields for semitransparent photocathode.

4. ETE dependence on drift field

First we studied the effect of drift field on ETE in absence of avalanche multiplication in the THGEM element. The results shown in Fig. 7(a) indicate that, with the increase of drift field ETE reduces. Transverse diffusion coefficient as calculated by MAGBOLTZ (plotted in the same graph) shows an increase with the increase of drift field. Increase in the diffusion of electrons in gas medium degrades ETE. Experimental and simulation results agree well in our studies for P10 gas. Since backscattering phenomenon [12–16] was involved in these measurements and it also depends on the drift field, we have used simulations to find the fraction of photoelectrons backscattered to the photocathode. Simulation results in Fig. 7(b) show the percentage of photoelectrons focused into the THGEM hole (ETE), backscattered to the photocathode and those lost in the drift region (mainly terminating at the top metal

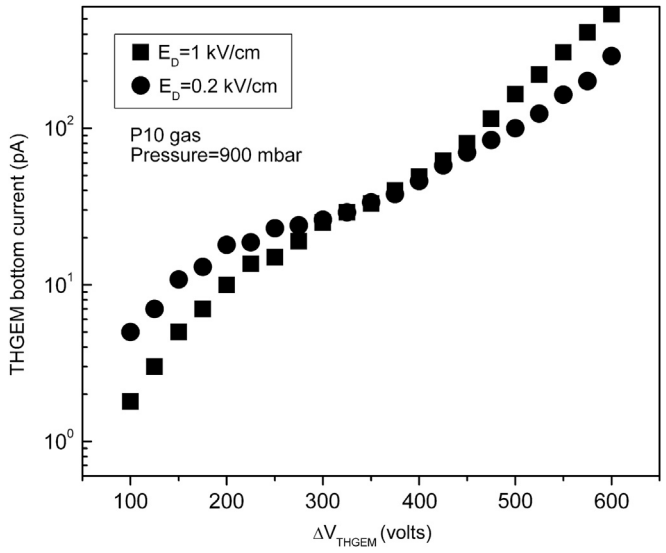

Fig. 6. Variation of THGEM bottom current with ΔV_{THGEM} applied between the THGEM electrodes.

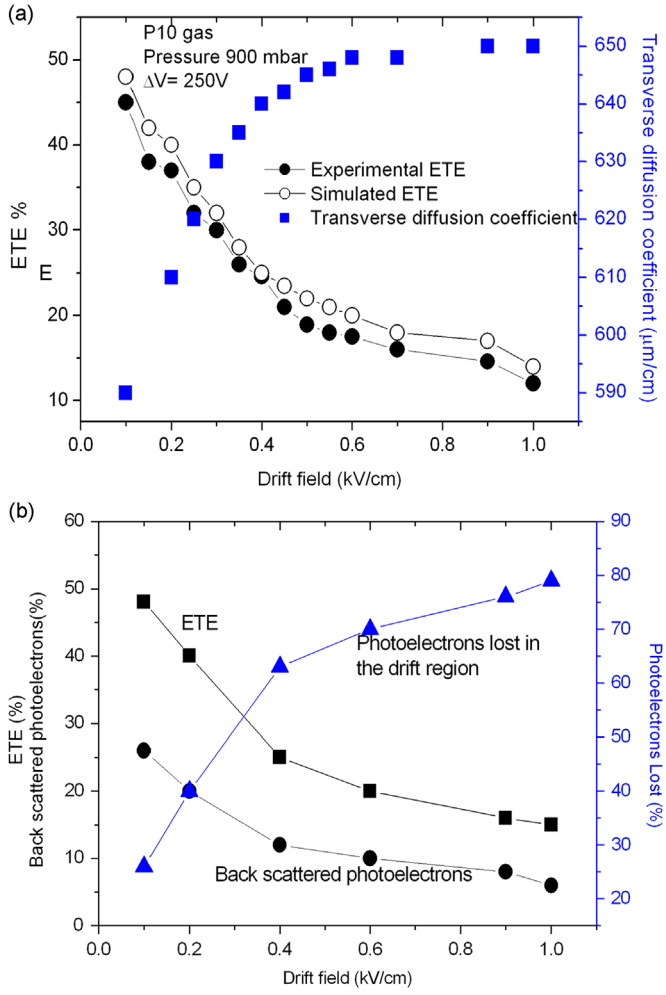

Fig. 7. (a) Effect of drift field on ETE, simulation and experimental validation. ΔV_{THGEM} was maintained at 250 V, P10 gas pressure at 900 mbar and drift gap was 5 mm. (b). Variation of the number of backscattered electrons as a function of drift field. ETE and percentage of photoelectrons lost in the drift region are also shown in the same plot. ΔV_{THGEM} was maintained at 250 V, P10 gas pressure at 900 mbar. Drift gap was 5 mm.

electrode) and their variation as a function of drift field. It was observed that backscattering was prominent at lower drift fields and reduced with the increase in drift field. This was reflected in the photocurrent measurement shown in Fig. 5, where the increase in photocurrent at higher drift fields is related to large photoelectron extraction due to reduced backscattering [4]. At low drift field of 0.1 kV/cm, 25% of the photoelectrons were lost due to backscattering, while at higher drift field (>0.6 kV/cm) it is less than 10%. It is important to note that the ETE reduces at higher drift field as shown in Fig. 7(a). Thus the photoelectron extraction from the photocathode and the ETE has opposite dependency on the drift field. In order to optimize the overall detection efficiency one has to find a compromise between photoelectron extraction efficiency (which increases with drift field) and ETE (which decreases with drift field). A plot of photocurrent (normalized to 100% at the plateau), ETE and the product of these two quantities (divided by 100) as a function of drift field is shown in Fig. 8(a). This can be used to find out the optimum value of drift field to attain maximum detection efficiency. As seen in Fig. 8(a), for ΔV_{THGEM} of 250 V, 0.3–0.4 kV/cm is the optimum drift field to achieve maximum detection efficiency.

However, for standard THGEM operation, ΔV_{THGEM} will be higher (above multiplication onset). At higher ΔV_{THGEM} (above multiplication

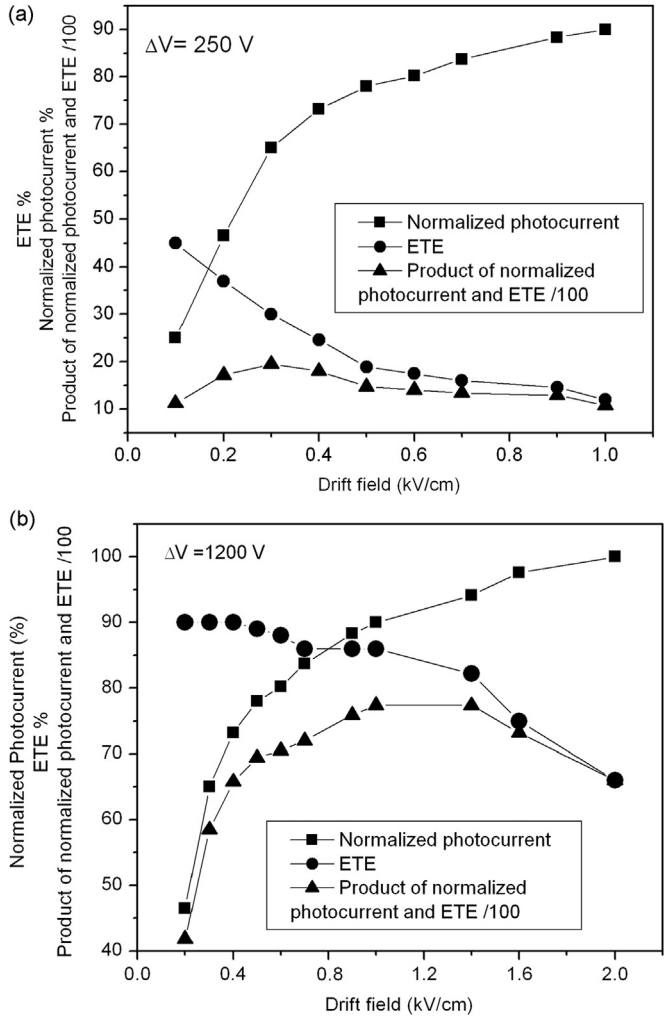

Fig. 8. (a) Plot of photocurrent (normalized to 100% at the plateau), ETE (for ΔV_{THGEM} of 250 V) and the product of these two quantities (divided by 100) as a function of drift field. P10 gas at 900 mbar was used for this study. Drift gap was maintained at 5 mm. (b). Plot of photocurrent (normalized to 100% at the plateau), ETE (at ΔV_{THGEM} of 1200 V) and the product of these two quantities (divided by 100) as a function of drift field. P10 gas at 900 mbar was used for this study. Drift gap was maintained at 5 mm.

field), the electric field line distribution changes leading to completely different electron focusing property. We have simulated the ETE variation as a function of drift field for ΔV_{THGEM} of 800 V and 1200 V. Higher effective gain can be obtained for these ΔV_{THGEM} values. It was observed that at 800 V, the optimum drift field for maximum detection efficiency lies between 0.6 kV/cm and 0.9 kV/cm, whereas at ΔV_{THGEM} of 1200 V, it is between 1 kV/cm and 1.4 kV/cm. The simulation result for ΔV_{THGEM} of 1200 V is shown in Fig. 8(b).

There are also other performance parameters that are affected by drift field. Ion back flow (IBF) to a ST photocathode, which is a performance limiting factor for GPMs, is 2–10% for a drift field of 0–1 kV/cm and 10–20% for a drift field of 1–2 kV/cm [5]. IBF does not have a significant dependence on the nature of the gas [17]. In addition, photon feedback due to secondary scintillations in the drift gap will also be less at lower drift field [4]. Thus the choice of drift field becomes important in maximizing detection efficiency.

While high ETE can be obtained at higher ΔV_{THGEM}, avalanche induced photon feedback is also high in this operating condition [5]. This problem can be reduced if the detector is operated in multi THGEM configuration, keeping the gain across the first THGEM element low (by maintaining a low multiplication voltage across the first THGEM). Due to low optical transparency of the THGEM (~22%), the photon feedback to the photocathode from the high gain second or third stage will be low in this configuration [12].

ΔV_{THGEM} was maintained at 200 and 250 V, i.e. well below the possible multiplication field, in the rest of our experimental studies on drift gap, gas mixture and pressure. This was done intentionally because it gives a clear understanding of the charge transfer and losses occurring in the drift region only [10], which is critical for ST photocathode used in GPMs. Also the method used for this work is current measurement mode which is valid only for the region below multiplication. However, simulations have been done for higher multiplication voltages which are the practical operating regime for these detectors.

5. Effect of drift gap on ETE

Drift gap is another parameter that can be varied in a ST type photocathode used in GPMs. In the present study, drift gap was varied from 5 mm to 13 mm. While the simulations were carried out for even smaller gaps lesser than 5 mm, the same was not possible in our experimental arrangement. Smaller gap resulted in higher ETE and experimental and simulation results agree well (Fig. 9). This is due to the fact that the diffusion width of the electron cloud increases according to the relation [18]

$$\sigma\alpha(d)^{1/2} \tag{2}$$

Where, d is the drift distance from the point of origin of the electron and σ is the diffusion width of the electron cloud.

Simulation results for drift gap less than 5 mm indicate that below 1 mm gap, the ETE worsens. Even though we could not verify experimentally, due to limitation in the setup we used, below 1 mm gap, the electrons generated at ST photocathode travel straight onto the THGEM top electrode before being captured into the THGEM hole by the dipole field. Simulation results obtained for higher ΔV_{THGEM} (1200 V) shown in the same Fig. 9 indicate similar type of variation of ETE with drift gap for which an optimum gap close to 1 mm was observed. Since drift gap in THGEM based UV photon detector is not relevant for detection efficiency as in X-ray detector, one can optimize the drift gap for maximizing ETE.

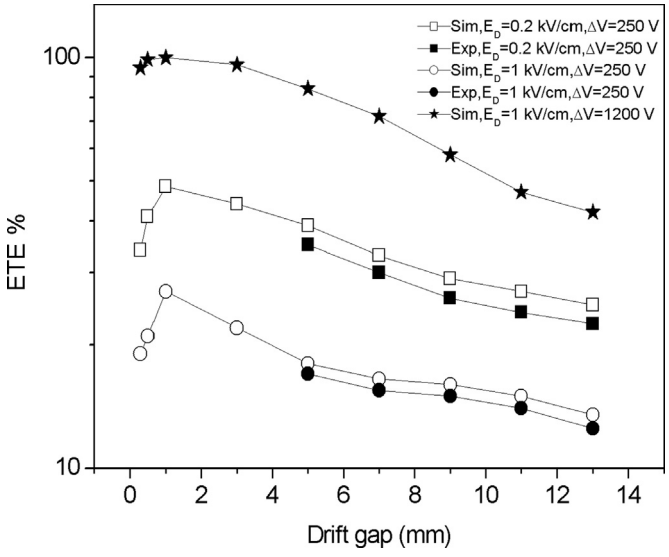

Fig. 9. Effect of drift gap on ETE. ΔV_{THGEM} and gas pressure were maintained at 250 V and 900 mbar respectively for this study. Simulation results for the same study at higher ΔV_{THGEM} of 1200 V are also included in the same plot.

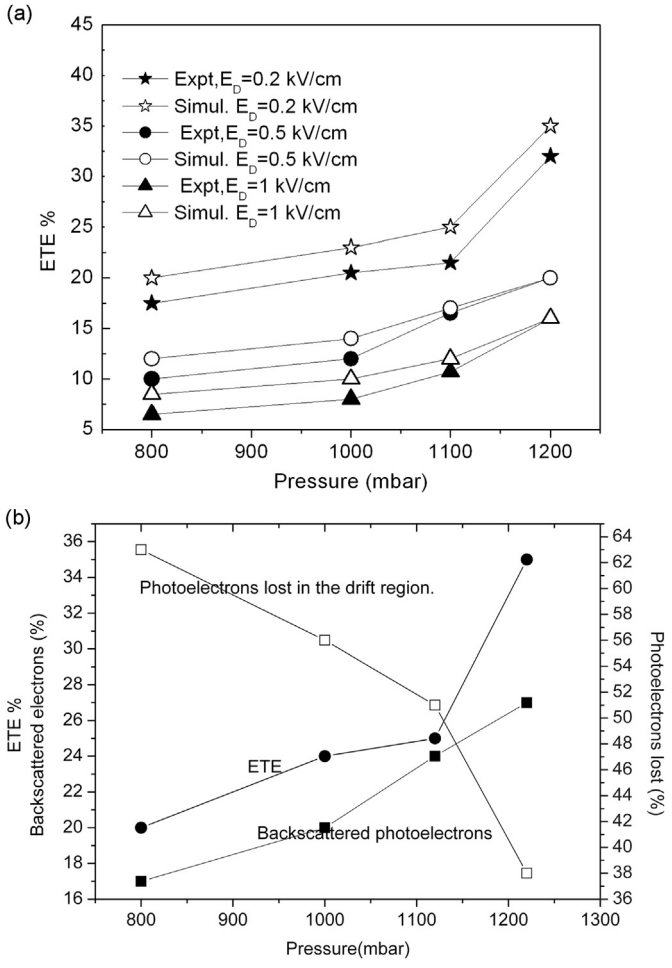

Fig. 10. (a). Effect of P10 gas pressure on ETE for semitransparent photocathode, validation of simulated results with experiments. ΔV_{THGEM} was maintained at 200 V and drift gap was maintained at 14 mm for this study. (b). Variation of the number of backscattered electrons as a function of pressure. ETE and percentage of photoelectrons lost in the drift region are also shown in the same plot. The simulation was carried out for a drift field of 0.2 kV/cm and ΔV_{THGEM} of 200 V. Drift gap was kept 14 mm for this study.

6. ETE dependence on gas pressure and gas mixture.

In order to study the dependence of ETE on gas pressure, P10 gas pressure was varied from 800 mbar to 1200 mbar. ΔV_{THGEM} was maintained at 200 V. Experimental and simulation results are shown in Fig. 10(a) for different drift field values. Both the experimental and GARFIELD simulation results show an increase in ETE with the increase in pressure and there is a good agreement. This is attributed to reduction in transverse diffusion coefficient with increase of pressure as calculated by MAGBOLTZ. It is evident from simulations that, with the increase of gas pressure, the transverse diffusion coefficient decreased. This reduced the diffusion of electrons in the gas medium, which enhanced the ETE. Change in gas pressure also affects the backscattering. Simulation results in Fig. 10(b) show the percentage loss of photoelectrons due to backscattering as a function of pressure. It can be observed that ETE is increased by higher percentage (~75%) than backscattering (~58%). This implies that transverse diffusion has larger impact than backscattering on ETE. Hence higher pressure, where transverse diffusion is reduced is advantageous for achieving improved detection efficiency.

Gas mixtures used for UV photon detectors are chosen to give lower backscattering of photoelectrons. Backscattering effect results in a noticeable decrease of photoelectron extraction efficiency in any gas compared to that of vacuum [12–14]. Commonly used gas mixture in THGEM based UV photon detector applications are Ne:CF_4 (90:10) or Ne:C_4H_{10} (90:10). Neon based gas mixtures are used over argon due to its higher Townsend coefficient and hence lower operating voltage [4]. Considering the good agreement between simulation and experimental results for P10 gas, our simulation study was extended to other gas mixtures.

We have done simulation studies for Ne:C_4H_{10} (90:10) and Ar:CO_2 (70:30), which have been used in many studies [19]. ETE simulation results for these mixtures at different pressures are plotted in Fig. 11(a) along with the results for P10 gas. A plot of transverse diffusion coefficient in the same Fig. 11(a) at these pressures suggests that ETE mainly depends on the diffusion coefficient, with lower diffusion resulting in higher ETE. Simulation results shown in Fig. 11(b), for the multiplication regime (ΔV_{THGEM} of 1200 V) also show increase in ETE with pressure. For higher ΔV_{THGEM}, the electric field distribution changes very close to the THGEM hole. This implies that the drift field (E_d), which is responsible for change in transverse diffusion, is not altered significantly. However, electron focusing due to higher ΔV_{THGEM} enhances the overall ETE as observed in simulation. Thus even at higher ΔV_{THGEM} there will not be any change in the optimization of operating pressure and the choice of gas mixture with respect to ETE. Our studies indicate that Ar:CO_2 (70:30) mixture could be a better choice in terms of ETE.

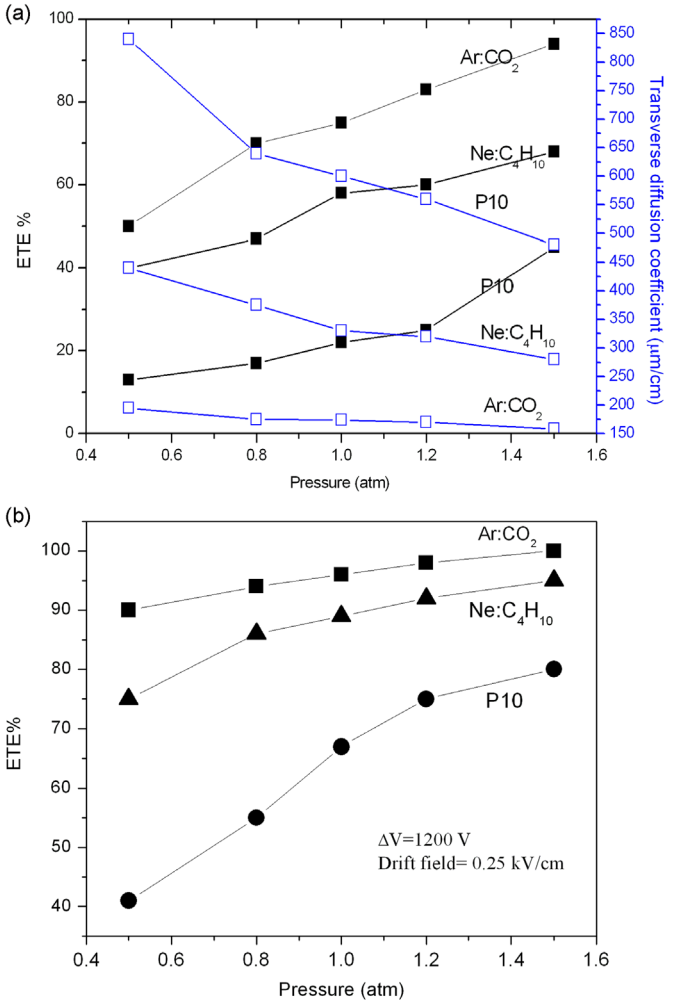

Fig. 11. (a). Effect of gas mixture and pressure on ETE. (Closed symbols show ETE while open symbols show transverse diffusion coefficient). The drift field was fixed at 0.25 kV/cm. Drift gap was maintained at 14 mm. (b). Simulated results on the effect of gas mixture and pressure on ETE at higher ΔV_{THGEM} of 1200 V. The drift field was fixed at 0.25 kV/cm.

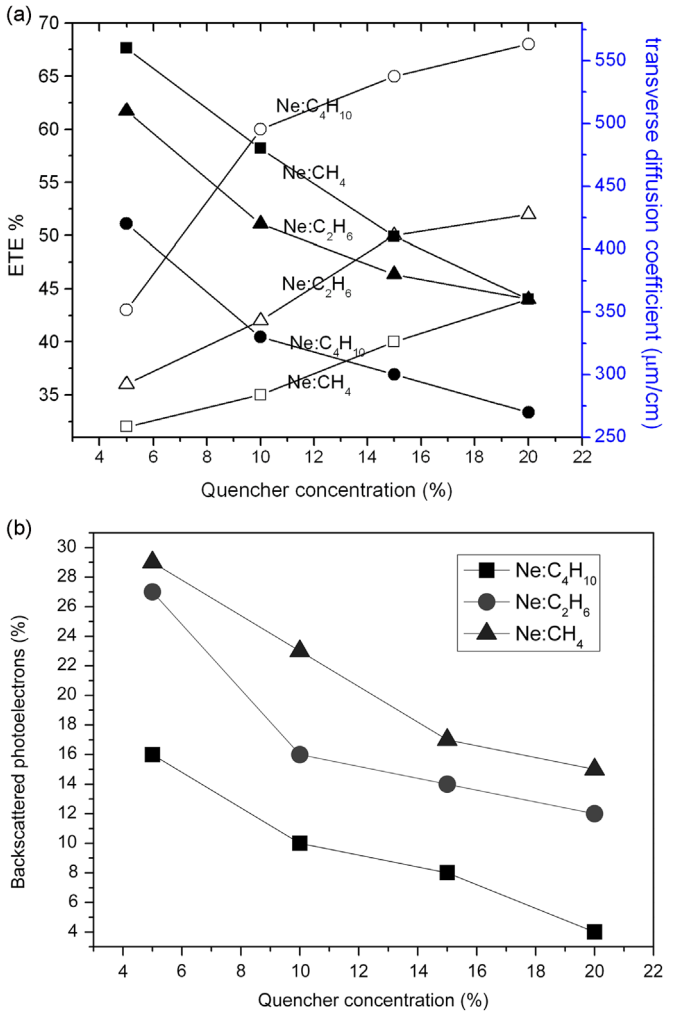

Fig. 12. Effect of quencher gas concentration on ETE. (Open symbols show ETE while close symbols show transverse diffusion coefficient variation for different gas mixtures). The drift field was maintained at 0.25 kV/cm and ΔV_{THGEM} was 250 V.

We have carried out simulations on various quenching gases added with Ne at different mixture ratio for ETE estimation. Molecular gases like CH_4, C_2H_6 and iC_4H_{10}, which have reduced photoelectron backscattering were chosen for this study. From Fig. 12(a) we can see that ETE is higher for Ne:C_4H_{10} and it increases with quencher percentage for all gases. We observed from our simulations that the percentage of photoelectrons backscattered to the photocathode also reduces with the increase in quencher percentage as shown in Fig. 12(b). Quencher percentage above 20% was not attempted here as higher quencher concentration necessitates higher operating voltages enhancing the discharge probability [4].

7. Conclusion

The single photon detection efficiency in THGEM based GPMs with ST photocathode depends on the ETE in the first stage, in addition to other parameters like photoelectron yield from the photocathode surface, multiplication in the THGEM hole and transfer of charge towards next amplification stage. Higher ETE along with higher photoelectron extraction efficiency should be considered for optimizing the operating parameters for high detection efficiency in a THGEM based UV photon detector.

We have carried out both experimental and simulation studies on the dependence of ETE on drift parameters for ST photocathode based THGEM GPMs with P10 gas. Detailed simulation study was carried out for other gas mixtures and conditions. Our studies confirm that drift parameters such as drift field, gas mixture, pressure and drift gap play important role in determining ETE and hence the detection efficiency.

Considering opposite dependency of photoelectron extraction and ETE on the drift field, optimization of the drift field becomes important for maximizing the detection efficiency. The optimum drift field range depends on ΔV_{THGEM}. At higher ΔV_{THGEM}, higher ETE can be obtained due to better focusing of the electrons near the THGEM hole. In addition, higher ETE can also be obtained for higher gas pressures, gas mixtures with lower transverse diffusion coefficient and smaller drift gap. Simulation studies revealed that transverse diffusion coefficient has major impact on deciding ETE and the ultimate detection efficiency. Because of avalanche induced photon feedback at higher ΔV_{THGEM}, a multistage THGEM detector with a low multiplication in the first stage is preferred. This can give good efficiency with optimized drift parameters and also low photon feedback due to low multiplication field in the first stage.

GARFIELD simulation can be used as an effective tool for optimizing the drift parameters.

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