Performance study of the PTFE-THGEM at room and low temperature

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Abstract: GPM based on THGEM has shown its competitive strength compared to the conventional PMT, especially in the low background research such as dark matter detection. A kind of THGEM made from PTFE, named PTFE-THGEM, is developed for the GPM to be used in CDEX. The PTFE has a lot of advantages especially its low level radioactivity. The PTFE-THGEM was tested at room and cryogenic temperature. It has a high gain in different gases and shows good stability at room temperature. The gain of a single PTFE-THGEM reached 112 at 117 K. The penning effect is also discussed in this paper to explain the "abnormal" phenomena of the gain in different gases.

Key words: THGEM, PTFE, cryogenic temperature, GPM, penning effect

PACS: 29.40.Cs **DOI:** 10.1088/1674-1137/37/11/116001

1 Introduction

CDEX, China Dark matter EXperiments, is proposed to detect the dark matter WIMP particle in low mass region. In this project the background count level must be very low, so a liquid argon detector is designed as a veto detector to separate the background events from the real signals, and in the meantime to provide the low temperature surrounding for the HPGe detector.

Figure 1 is the scheme design of the cryostat of the CDEX [1]. In this design, the high pure germanium is used as the working material of the detector, and the PMT is used in cryogenic temperature to readout the 128 nm scintillation light from the liquid Ar. However, conventional PMTs are not the best option because of their high manufacturing cost, limited area, unmatched spectral response and obvious radioactivity. In recent years the GPM (Gas PhotoMultiplier) based on the micro pattern gas detector has been studied widely as a substitute for PMT to overcome the disadvantages mentioned above.

The THGEM has became a strong candidate to make GPM since it was first introduced by R.Chechik et al. [2]. Usually the standard PCB materials, FR4 or G10, are selected to produce the THGEM. But those materials contain lots of radioactive substances, such as fiber glass. So a kind of low background material is needed for the GPM designed for the CDEX. PTFE (Polytetrafluoroethylene) is known for its stability in various environments. This kind of polymer almost has no radioactivity and could work well in cryogenic conditions. The THGEM made from the PTFE, named PTFE-THGEM is studied in this paper.

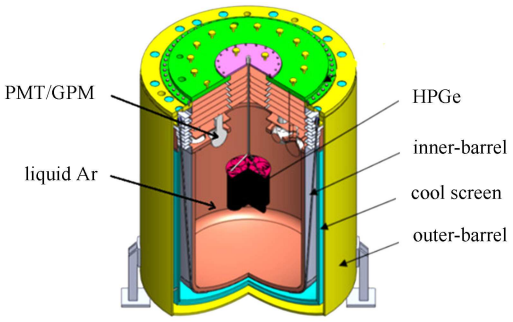

Fig. 1. Scheme design of the cryostat in CDEX.

2 Experimental setup

The PTFE-THGEM, with an effective area of 5 cm×5 cm, was produced with standard industrial PCB technology. Then the global etching was used to make the rim of 15–50 μm.

Figure 2 is a photograph of the PTFE-THGEM and its several holes observed under the microscope. It can be seen that the rim has a smooth edge and is coaxial with the hole. The final parameters of the PTFE-THGEM studied are as follows: thickness of 0.38 mm, hole diameter of 0.3 mm, hole pitch of 0.7 mm and rim of 30 μm. The right panel of Fig. 3 shows the experimental

Received 30 January 2013
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setup of the detector, in which a single PTFE-THGEM is assembled in a stainless steel chamber working in gas flowing mode. A titanium window is selected because of its toughness, which meets the need of experiments at low temperature. The 8.09 keV characteristic X ray photon of Cu, generated by striking the Cu slide with X rays from the Mini-X, AmpTek, is used as the radiation source. The readout pad has the same area with the PTHFE-THGEM and its capacitance is measured as 16.3 pF. The signals are recorded through an ORTEC 142AH preamplifier followed by an ORTEC 572 amplifier and an ORTEC EASY-MCA-8K.

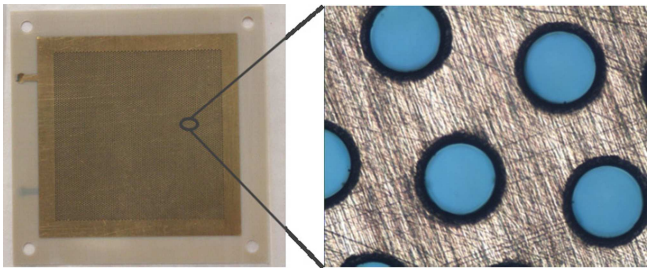

Fig. 2. A photograph of the PTFE-THGEM; the enlarged part (right) shows the holes and the rims surrounding them.

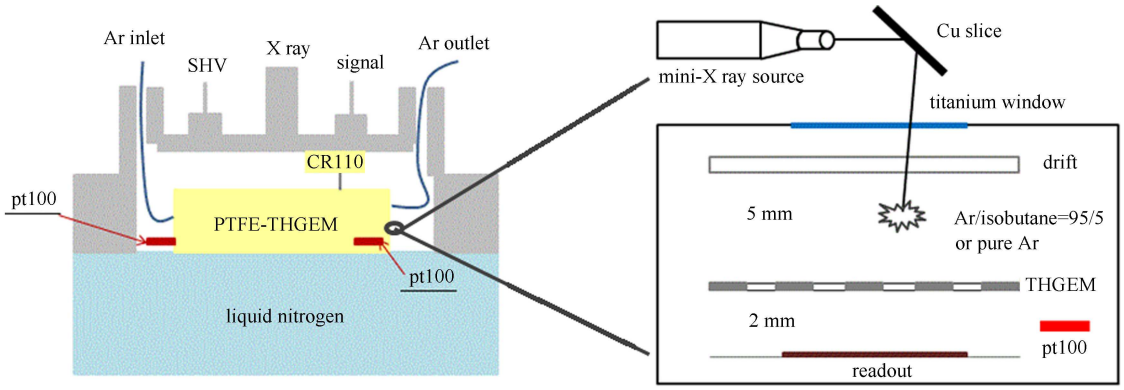

Fig. 3. Schematic diagram of the experimental setup. On the left is the test of the PTFE-THGEM at cryogenic temperature; and on the right is the internal structure of the PTFE-THGEM used.

3 Performance of the PTFE-THGEM

3.1 Optimization of the field

The electric fields, including the drift region field ($E_{\rm drift}$) and the induction region field ($E_{\rm ind}$), have effects on the performance of the detector. The voltages on the PTFE-THGEM are set to 770 V in the Ar/iso (95/5) and 1170 V in the pure Ar at room temperature. Both the voltages are selected according to the previous experiments and are moderated to the PTFE-THGEM.

Figure 4 shows the influence of the fields on the gain. In the upper panel of Fig. 4, a maximum gain exists because many primary electrons are attached or recombined in a smaller $E_{\rm drift}$ and parts of the primary electrons terminate on the Cu surface of the PTFE-THGEM rather than be pulled into the holes of the THGEM when the $E_{\rm drift}$ is too large [3]. The lower panel of Fig. 4 shows that the collection efficiency of the avalanche electrons increases along with the increase of the $E_{\rm ind}$. But too large $E_{\rm ind}$ may lead to secondary amplification of the avalanche electrons, resulting in a sudden rise in the curve. So the $E_{\rm drift}$ of 1 kV/cm and the $E_{\rm ind}$ of 4.5 kV/cm are chosen as the optimal values.

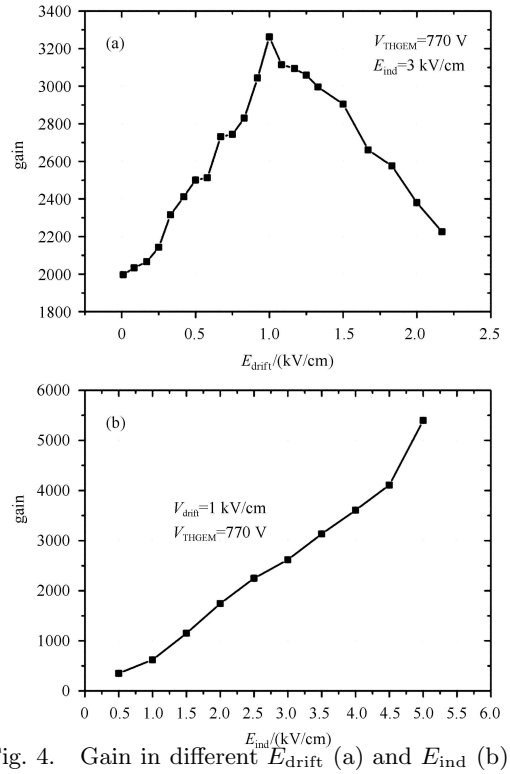

Fig. 4. Gain in different $E_{\rm drift}$ (a) and $E_{\rm ind}$ (b) in the Ar/iso (95/5).

3.2 Research of the stability

The stability of the THGEM is a key issue in the R&D of THGEM. Many factors are related to the stability, such as the material of the THGEM, size of the rim, the surface quality of the Cu edge and so on [4]. Generally speaking, a small rim and smooth Cu edge lead to good time stability. The PTFE-THGEM shows good stability after a series of treatment, during which the critical step is training at cryogenic temperature with high voltage.

Figure 5 shows the stability comparison in 90 min before and after the cryogenic treatment. It can be seen that the cryogenic treatment plays an important role in the stability improvement of the PTFE-THGEM. It is an encouraging result but further study needs to be done to discover the reason. Then a long time test was carried out and the result is shown in Fig. 6 in which the PTFE-THGEM shows good stability within dozens of hours.

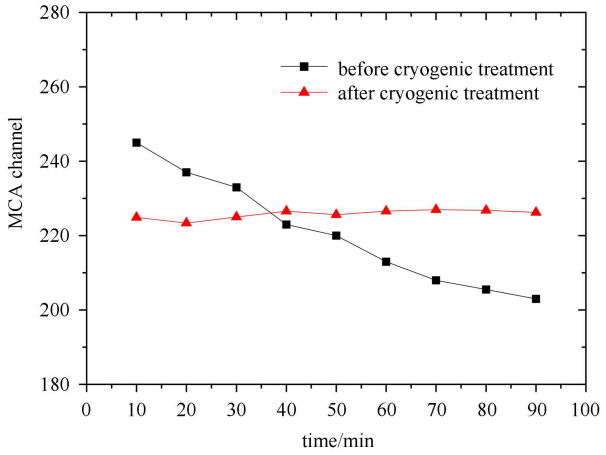

Fig. 5. The stability comparison before and after the cryogenic treatment in pure argon.

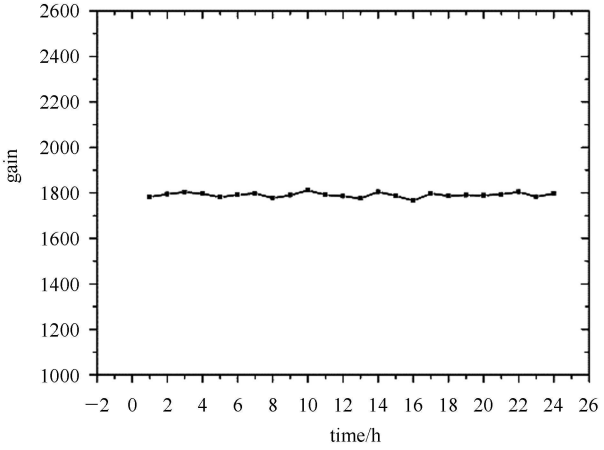

Fig. 6. The stability tests of PTFE-THGEM in pure Ar for 24 h, with the gain around 1800.

3.3 Gain in different gases at room temperature

Gains above 3000 were measured in different gases in a single PTFE-THGEM with 8.09 keV X ray in atmospheric pressure and room temperature, shown in Fig. 7.

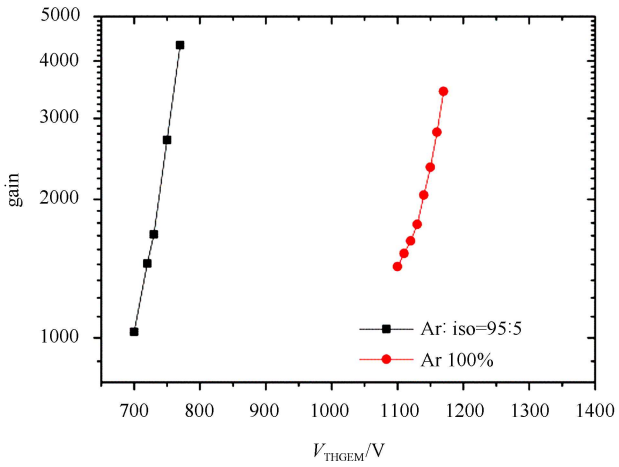

Fig. 7. Gain of the single PTFE-THGEM in different gases.

It can be seen that the THGEM in the mixture of argon and isobutane needs lower voltage when obtaining the same gain. This phenomenon will be discussed in the last part of the paper.

3.4 Gain at low temperature

The PTFE-THGEM will work in the gas phase of the cryogenic two-phase argon in the CDEX. So its working performance at low temperature is tested using the setup shown in the left panel of Fig. 3. The liquid nitrogen in the cryostat provides a low temperature environment. The detector chamber is lowered into different positions in the cryostat for different temperatures until reaching the interface of the two phase nitrogen. The preamplifier CR110 which can work in −40 ℃ at most is installed on the bottom of the end cover of the cryostat, about 30 cm above the detector. Two pt100 sensors, a kind of platinum resistance thermometer, are adopted to monitor the temperature in and out of the detector stainless steel chamber. The pure argon flows through the detector at a very low rate, about 2 ml/min while the volume of the chamber is 404 ml.

The results of the experiment are shown in Fig. 8 and Fig. 9. It can be seen that the PTFE-THGEM could work normally under the cryogenic conditions. The onset voltage of the PTFE-THGEM increases along with the drop of the temperature, and this may increase the probability of the spark in the pure argon. Meanwhile the gain of the single PTFE-THGEM goes down obviously as the temperature decreases, 112 at 117 K.

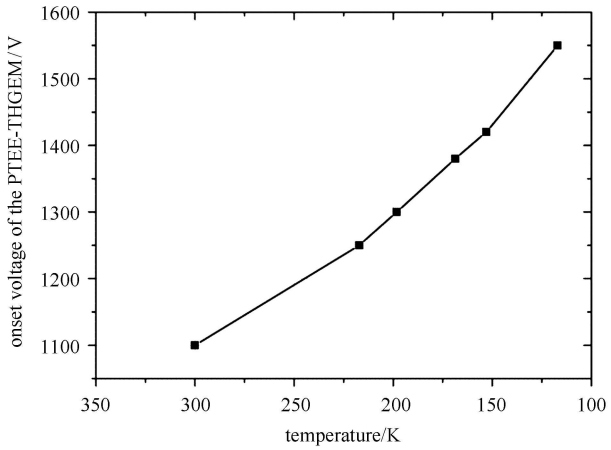

Fig. 8. Change of the onset voltage of the PTFE-THGEM along with the change of temperature.

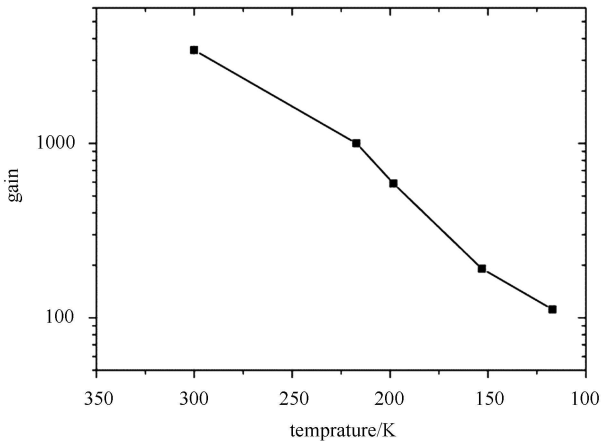

Fig. 9. Gain of the single PTFE-THGEM in pure argon at different temperatures.

4 Discussion on the gas ionization process

The quenching gas, like CO_2 and hydrocarbon, is often used as impurity mixed into the noble gas to quench the avalanche. At this point, to obtain the same gain, the detector with mixture of argon and isobutane should need higher voltage than that in the pure argon; however the experiment gives the opposite result. Another group also found the same problem [5]. So there must be some mechanisms making the discharge potential of the mixture gas drop down. Penning effect is a factor with high probability.

Penning effect was first brought forward by Frans Michel Penning at 1930 s [6, 7], which is also the origin of the name of this kind of gain enhancement. The main process of the Penning transfer mechanism is the collision of a metastable excited atom A^*(here argon) with an admixture molecule B (here isobutane). If the excitation energy level of A^* is energetically higher than the ionization energy of B, the collision will result in the ionization of B:

$$A^*+B\rightarrow A+B^++e. \quad (1)$$

The main metastable states of argon are 11.55 eV(S-level), 13.0 eV (P-level) and 14.0 eV (D-level) [8] while the ionization energy of the isobutane is 10.67 eV. So the Penning transfer occurs in different possibilities with different metastable states of argon.

In the Townsend ionization theory the gain of detector is expressed with the first Townsend coefficient as follows:

$$G=\exp\left\{\int_0^d \alpha(E(x))\mathrm{d}x\right\}. \quad (2)$$

Where d is the distance between the drift electrode and the anode in the detector and α is the first Townsend coefficient changing with the applied electric field $E(x)$ and the nature of the gas: component, pressure and the temperature. Considering the Penning effect, the Eq. (2) should be adjusted into:

$$G=\exp\left\{\int_0^d \mathrm{d}x\alpha(E(x))\frac{\Sigma f_i^{\mathrm{ion}}E(x)+\Sigma P_i f_i^{\mathrm{exc}}E(x)}{\Sigma f_i^{\mathrm{ion}}E(x)}\right\}. \quad (3)$$

Here $\Sigma f_i^{\mathrm{ion}}E(x)$ is the sum of all ionization without Penning transfer and P_i stands for the Penning transfer possibility. Based on the Eq. (2) and the Eq. (3), the Townsend coefficient was calculated by the Magboltz program [9]. The Monte Carlo simulation results are shown in Fig. 10.

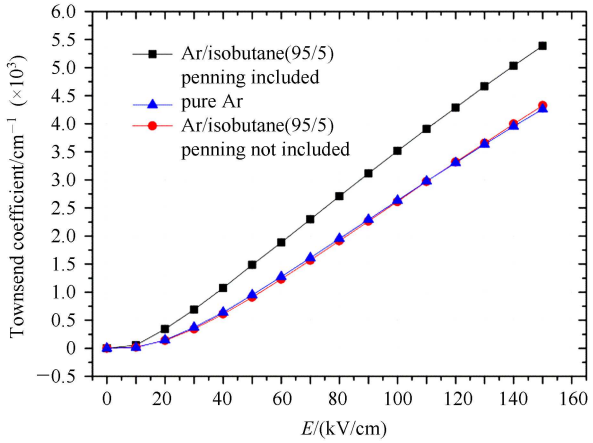

Fig. 10. Townsend coefficient contrasts of pure Ar and the mixture Ar/isobutane (95/5).

It can be seen in Fig. 10 that the gain in pure argon G_{Ar} is about the same as that in the mixture G_{mix} when the Penning effect is ignored, but G_{mix} is much higher when the Penning effect is included. We made a comparison between the simulation and the experiment in Ar/isobutane (90/10) and the results are shown in

Table 1. It can be seen that the simulation fits with the experiment when the Penning effect is taken into account.

Table 1. The comparison between the simulation and the experiment with the same voltage.

experiment	simulation	
$G_{\rm mix}/G_{\rm Ar}$	$G^{1)}_{\rm mix\_np}$ / $G_{\rm Ar}$	$G^{2)}_{\rm mix\_p}/G_{\rm Ar}$
2	0.4	3

1) $G_{\rm mix}$ of Penning effect not included;
2) $G_{\rm mix}$ of Penning effect included.

During the Penning transfer process there are also other transfer mechanisms like the collision of the "excimer", a combination of an excited noble gas atom and one in the ground state [10], and the admixture molecules and energy transfer between them in the Eq. (4) and Eq. (5).

$$A^*+2A\rightarrow A_2^*+A, \tag{4}$$

$$A_2^*+B\rightarrow 2A+B^++e. \tag{5}$$

The isobutane has a metastable state 17.0 eV which is higher than the ionization level of argon 15.7 eV, so the Penning transfer between the excited isobutane molecule and the argon atom will happen, even though the possibility is small. These problems need further research.

5 Conclusion and discussion

The performance of the PTFE-THGEM developed for the CDEX was studied in this paper. After optimizing the electric field, the detector consisting of a single PTFE-THGEM shows a high gain above 3000 in pure argon and its mixtures at room temperature, and more than 100 at 117 K.

It has been found that the PTFE-THGEM has a good stability within 24 hours though the 30 μm rim is relatively large. The GPM based on the PTFE-THGEM is under study and further testing will be done at cryogenic temperature.

The Penning effect was introduced to explain the "abnormal" phenomena in the experiment. The simulation results show that the Penning transfer is a very important reason for the gain enhancement. The gain of the Penning gas mixtures is notoriously hard to calculate with the Townsend coefficient and the simulations here need to be improved further.

We would like to express thanks to professor Xie Yi-Gang for and Liu Qian from the UCAS the useful advice on THGEM and also Steve Biagi for help on the use of Magboltz.

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