Current progress of study on gas electron multiplier

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Abstract Recent progress of study on gas electron multiplier (GEM) has been described. Due to its fast time response and excellent position sensitivity, the GEM will find wide applications in particle physics, medicine and astrophysics. These potential applications have been briefly introduced.

Key words Gas electron multiplier, High rate radiation detector, Particle tracking, Fast triggering

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1 Introduction

Over the past two decades, a variety of micro-pattern gas detectors (MPGD) have been developed.[1,2] By providing good detection efficiency and localization accuracy with high rate, the MPGDs are potentially powerful for uses in high energy physics experiments and other applied fields. However experience has shown that most MPGDs have tendency to discharge when exposed to high rate or highly ionizing particles, while on the other hand, gas electron multiplier (GEM) offers a way to improve on this crucial point.[3,4]

GEM, which was invented by F. Sauli at CERN, is a two-side copper-clad (5 μm) Kapton (50 μm) foil, with a high density of holes, typically 50—100/mm^2. Etched by photolithographic process, these holes have diameters of 70 μm (external) or 50 μm (internal), with a pitch of usually 140 μm (standard geometry), as shown in Fig.1.[5] By applying suitable voltage difference between the two sides of the GEM, an electric field with an intensity as high as 100 kV/(cm·atm) will be produced inside the holes (Fig.2 displays the distribution of electric field in a hole of GEM foils, simulated by MAXWELL[6]) and therefore proportional gains in the holes can reach to 10^3 in a wide range of operating gases and conditions. A unique feature of GEM is that the multiplication element—each hole which acts as an independent proportional counter, is separated from the readout plane, so we have wide freedom on selecting readout patterns. Another feature of GEM is that by cascading several GEM foils, sustainable large gains can be obtained easily. For example a nominal gain of triple GEM is around 10^4, making it comfortable to detect minimum ionizing particles (MIPs), while the discharge probability is barely measurable.[7] Just for these features, many workshops have made lot of researches on GEM, and this report is a review of current progress of study on GEM.

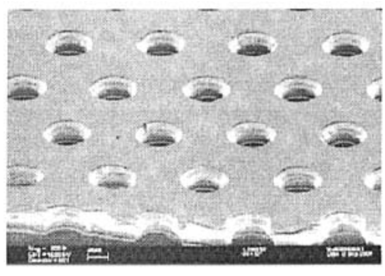

Fig.1 Electron microscope view of a GEM foil. The hole diameter and pitch are 70 and 140μm, respectively.

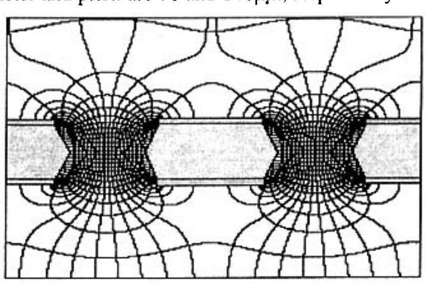

Fig.2 Electric field lines in a GEM foil. The dotted ring indicates the region with the highest charge density.

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2 Current situation of study on GEM

Since GEM appeared in 1997, there have been more than 130 literatures on GEM published on the journal of Nucl. Instr. Meth., and most of them are focused on the study of performances and potential applications of GEM.

2.1 Methods for fabricating GEM foils

Up to now, there are three candidate methods for fabricating GEM foils: chemical etching invented by CERN, plasma etching[8] developed by a group of Center for Nuclear Study, Japan and laser micro-machining realized by a workshop at the University of Louisville.[9]

In general, the sensitive area of a standard GEM at CERN is 10 cm×10 cm. After making holes on copper layers by conventional photolithography, the foil is immersed in a specific solvent, which dissolves the Kapton layer. As a result, a GEM at CERN can be produced, as shown in the upper photograph of Fig.3. Based on chemical etching, a group at Chicago University has also developed a way for mass production of GEM by using 3M's fully automated roll-to-roll flexible circuit production line.[10]

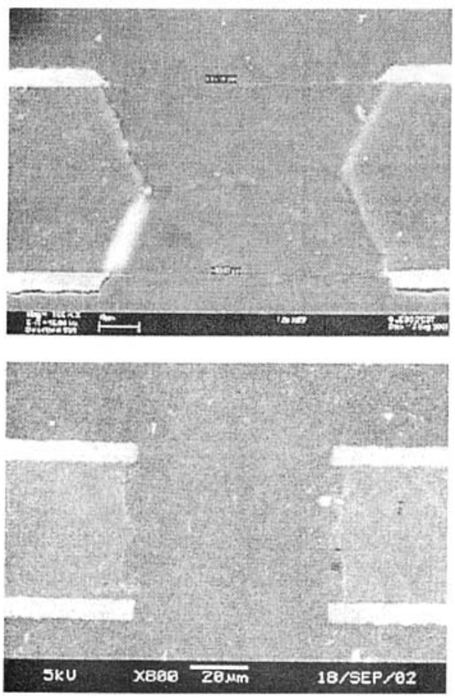

Fig.3 The upper photograph shows a hole of GEM produced at CERN. The lower photograph shows the one produced by using the plasma etching method.

The first step of plasma etching method for fabricating GEM is similar to the chemical etching method. Holes on the copper layers are made by photolithography, but the second step for making holes on Kapton layer by plasma etching method is reactive ion etching (RIE). Holes on GEM produced by plasma etching has a sharper edge at the copper edge (shown in the lower photograph of Fig.3) than that by chemical etching, so GEM based on plasma technology can hardly hold up high voltage more than 530V.

Laser micromachining is a combination of micromachining techniques developed and applied in microelectronics and micro-electromechanical systems (MEMS). Indeed this new technology can allow a general and flexible control of the GEM holes' geometry, but the cost of the fabrication is much higher than the former two methods.

2.2 Studies on GEM performance

Many groups have done a lot of experiments on the performance of GEM involving its working condition, gain, energy resolution, efficiency, discharge, aging, time resolution, etc.

According to many experiments,[11-13] it has been proved that almost any working gases filled in proportional counters or MPGDs can also be utilized in GEM. For example: when high voltage powered on both sides of GEM foil is in a range of about 350V to 530V, noble gases such as Ar, Kr, and Xe mixed with a little organic gases as DME, TEA, CF_4, CH_4 or CO_2 by appropriate proportion can make GEM work in stable condition. Fig.4[7] shows, for gas detectors based on single, double and triple GEM foils, the total gain and the discharge probability for exposure to 6 MeV α-particles emitted by ^{220}Rn carried with the gas. It has demonstrated that one can get higher gain in multi-GEM than in a single one, and at the same time, the discharge probability can hardly be measured. This result has motivated the adoption of multi-GEM devices by several experiments operated in harsh radiation environments.

Based on some groups' experiments, it has been affirmed that for a gas detector based on a single GEM foil, as MICROMEGEM[14] (its cross-section is shown in Fig.5 and the readout width is 80 μm with a pitch of 200 μm), when exposed to 5.9 keV X-rays, its energy resolution can reach about 20%. A pulse charge spectrum of MICROMEGEM obtained with ^{55}Fe is shown in Fig.6. The gas mixture filled in MICROMEGEM is Ar/CO_2 (70%/30%), and the energy resolution of the iron peak is 22%. But for multi- GEM, the resolution will be worse, because electrons produced by primary ionization in different gaps of multi-GEM will be multiplied by various gains, which will deteriorate the energy resolution.

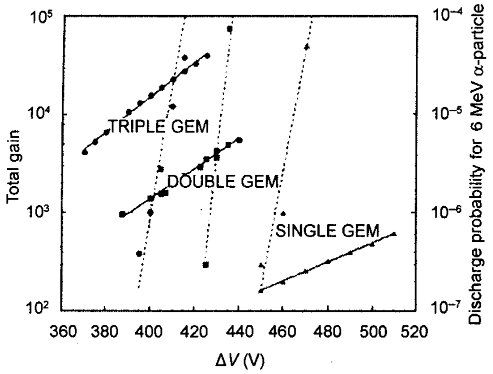

Fig.4 Total gain (full lines, left scale) and discharge probability of GEM detectors with different numbers of GEM mounting for exposure to α particles.

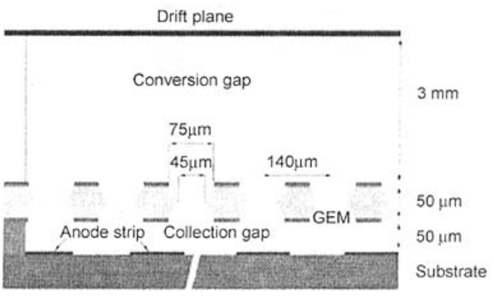

Fig.5 The cross-section of a MICROMEGEM detector.

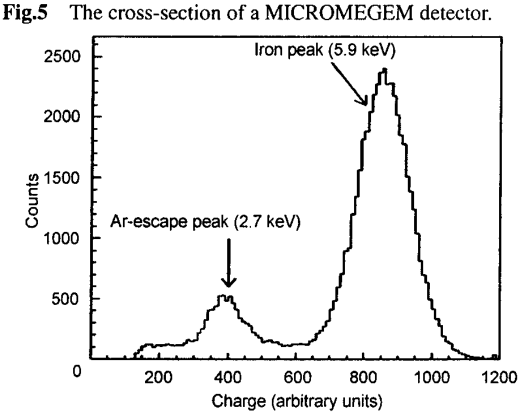

Fig.6 Charge spectrum in Ar/CO_2 (70%/30%) at an effective gain of 4000 with V_{LOW}=−300V and ΔV_{GEM}=340V. The iron peak and the escape peak of argon are seen clearly.

The efficiency of GEM and its electron & ions transfer efficiency have also been measured by several groups with several working gases and over a broad range of electric-field configurations. By summarizing the experiments on efficiency of GEM and other related experiments, it can be concluded that for MIPs, under proper working condition, and with enough thickness of drifting or ionizing field, the detection efficiency of a prototype GEM-TPC[15] can be more than 95% in two working gases, as shown in Fig.7. The electron transfer efficiency is strongly affected by the transverse diffusion of the electron and transferring field,[16] which means gas mixture and configuration of GEM detector influences the electron transparency strongly. Fig.8[17] shows the ion transparency as a function of potential difference across the GEM in pure argon and in Ar/DME (70%/30%). The drift field is 150 V/cm; and the transfer field is 1.5 kV/cm. There is little difference in ion transfer efficiency with different gas mixtures and transfer field, so we can ignore the effect of transverse diffusion on ion transfer efficiency.

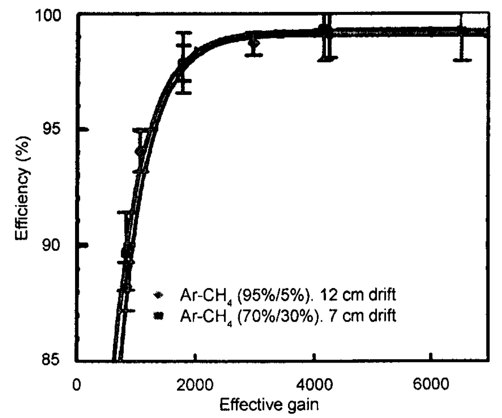

Fig.7 The efficiency of detection for MIPs, measured with a small prototype GEM-TPC device.

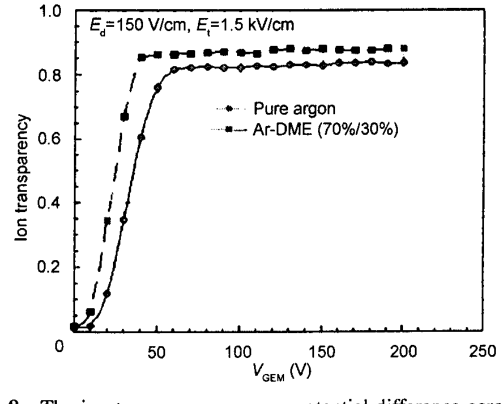

Fig.8 The ion transparency versus potential difference across the GEM in pure argon and in Ar/DME (70%/30%).

There are two main factors that may lead to discharge of GEM detectors: electrode edge effect and Raether limit. For a single GEM, the discharge is mainly caused by electrode edge effect, but for multi-GEM, when lots of positive ions reaching cathode, excessive gain leading to second avalanche may be the most important reason for the discharge.

The latest experiments on triple-GEM for COMPASS (its configuration is shown in Fig.9) has confirmed that filled with Ar/CO_2 (70%/30%), and exposed to 8.9keV X-ray beam, after accumulating 7mC/mm^2 or so, corresponding to seven years of nominal operation in COMPASS, neither loss of gain nor degradation of energy resolution has been observed in GEM detectors.[18]

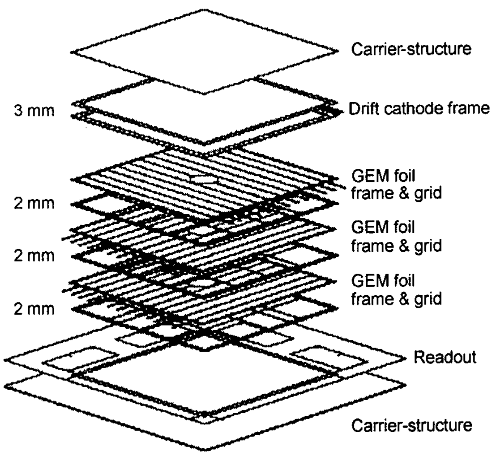

Fig.9 View of the triple-GEM detector for COMPASS.

Time resolution is another important performance of GEM when it is used as TPC for particle physics experiment. Fig.10[19] shows time distribution of triple-GEM detectors filled with (a) Ar/CO_2 (70%/30%) gas mixture and (b) Ar/CO_2/CF_4 (60%/20%/20%). Time resolution of triple-GEM filled with Ar/CO_2/CF_4 (60%/20%/20%) can be RMS of 6ns, less than the one (10 ns) filled with Ar/CO_2 (70%/30%). This result is from the fact that in the same electric field, the drift velocity of electrons in Ar/CO_2 (70%/30%) gas mixture is faster than the one in Ar/CO_2/CF_4 (60%/20%/20%).

As for position resolution of GEM, it is dominated by the pattern of readout plane.Fig.11 shows the position resolution of triple GEM for COMPASS. By method of centre gravity, the position resolution is around 70 μm RMS for MIPs, when the pitch of readout strips is 400 μm.

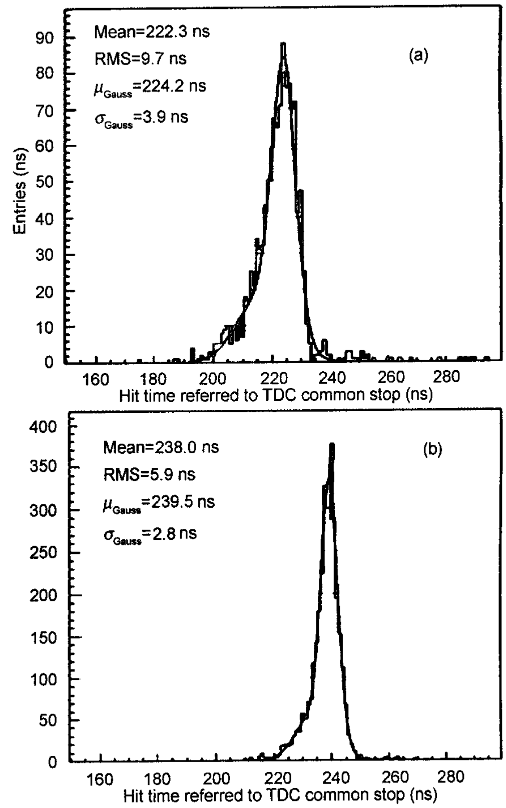

Fig.10 Time distribution of triple-GEM detectors filled with (a) Ar/CO_2 (70%/30%) and (b) Ar/CO_2/CF_4 (60%/20%/20%).

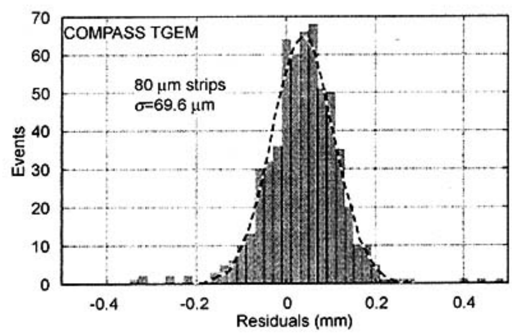

Fig.11 Position resolution of triple-GEM for MIPs.

3 Potential applications of GEM

Besides application of GEM detectors as particle tracking detectors or TPCs in particle physics, the excellent performance and robustness of various types of GEM detectors, have already encouraged many researchers to exploit their use in other applied fields such as medical imaging,[20] radiation therapy monitoring, micro-dosimetry,[21] astrophysics,[22] etc.

Meanwhile, by making use of the feature of amplifying charge and photons in GEM holes with proper gas mixtures, some authors are also trying to use GEM as a gaseous photon-multiplier device or a device coupled to a low-noise CCD camera for recording various types of events, from X-ray absorption radiography to neutron conversions.

Fig.12 shows a multi-GEM detector with a two dimensional readout plane. The structure of the readout plane consists of two layers of micro-strips, each at a pitch of 200 μm, and separated by 25 μm Kapton . The strip width is 80 μm in the upper ,and 150 μm in the lower layer. Exposed to an X-ray tube providing a beam of 8 keV photons, the detector can generate X-ray absorption radiography of a bat, shown in Fig.13. The position resolution of this photo is about 100 μm, which is comparable to the one acquired on film.

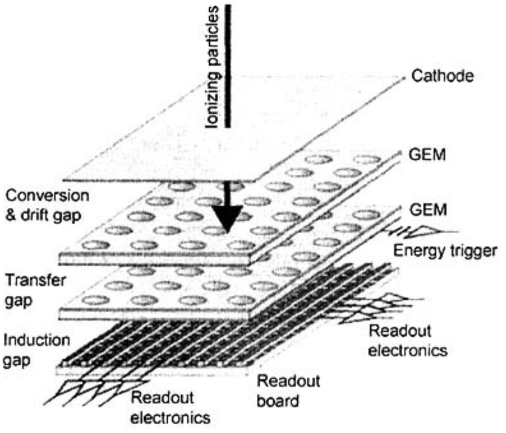

Fig.12 Schematic view of a multi-GEM detector.

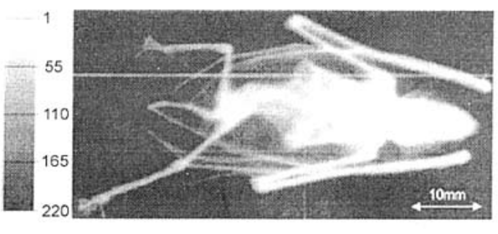

Fig.13 The absorption image of a small mammal when exposed to 8keV X-rays.

Fig.14 shows proton and triton tracks knocked off by neutrons in ^{3}He. This picture is acquired by a CCD camera coupled to a scintillating GEM detector.[23]

Indeed experimental results of GEM detector applications in particle physics and other fields have assumed a promising future. However experiments found that with the increase of gas pressure, the maximum attainable gain in most working gases decreases rapidly. As high-pressure operation of GEM detectors is necessary in some applications to get high conversion efficiency for neutral radiation such as hard X-ray or neutrons, future work in this respect is needed.

Fig.14 Tracks generated from proton-triton produced by neutrons in ^{3}He.

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