Development of gas electron multiplier foils with a laser etching technique

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Abstract

Fine-pitch gas electron multiplier (GEM) foils have been produced for cosmic X-ray polarimeters using a carbon dioxide laser etching technique. The finest hole pitch of the foil which can be produced repeatedly is 50\,\mu m and the smallest hole diameter is 30\,\mu m. The electron amplification factor was measured as a function of applied voltage. The behavior of the factor is almost the same as the 140\,\mu m-pitch standard foil fabricated by CERN. Our GEMs had no rate-dependent gain instability, which is expected of the GEMs having holes of good cylindrical geometry. The amplification factor of the 50\,\mu m foil in a mixture of 70\% argon and 30\% carbon dioxide reaches about 5000 without any micro-discharge at a voltage of 570\,V between foil electrodes.

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1. Introduction

The gas electron multiplier (GEM) foil has been developed at CERN since the pioneering work by Sauli in 1996\cite{1}. The basic structure of the GEM is quite simple. Small, densely packed holes are drilled through copper-plated polyimide which typically consists of a 50\,\mu m-thick polyimide sheet sandwiched by 5\,\mu m-thick copper layers. When a potential difference is applied between the two copper electrodes in a suitable gas, the foil works as an electron multiplier. Recently, GEM foils have been used in many applications, such as particle tracking\cite{2}, photon detectors\cite{3-5}, X-ray imagers\cite{6} and so on.

One of the interesting applications of the GEM is a cosmic X-ray polarimeter in which GEMs are combined with a fine pixel array detector\cite{7-9}. Based on the photoelectric effect, polarization of the incident X-ray is obtained by determining the emission angle of the photoelectron, which is correlated with the electric field vector of the X-ray.

X-ray polarimeters based on the photoelectric effect in gas have been developed with Micro Strip Gas Counter\cite{10} or with a capillary plate and Image Intensified CCD\cite{11}. Although they have measured X-ray polarization, larger analyzing power is needed for measuring polarization of cosmic X-rays with energies from a few to a few tens of...
keV, where the emission from many celestial sources, such as supernova remnants and active galactic nuclei, is relatively uncontaminated by thermal emission.

The key to increasing analyzing power is to accurately trace the photoelectron path, which is only about 1 mm even in neon at atmospheric pressure for 5 keV X-ray [12], though there is no sense in making pixels smaller than the lateral diffusion of drift electrons. If we carefully chose a gas and a depth of the drift region in order to extract the highest possible modulation, the pixel size is found to be 50–100 µm [8].

It is, however, difficult to produce a stable, high-gain GEM with a pitch less than 100 µm for 50 µm-thick foil using the standard chemical etching technique. Therefore, we have pursued another technique for the polyimide. We have produced GEMs by using plasma etching method since 2002 [13]. Although a new GEM was successfully produced with the method, we could not make the hole pitch smaller than 140 µm.

2. Production of GEMs with laser etching

Laser etching is the most promising method to produce fine-pitch GEMs. It was originally employed by Benlloch et al. [14] and some other efforts were reported [9,15,16]. Easily available wavelengths for laser etching are infrared (CO₂), optical (YAG), and ultraviolet (excimer). To minimize damage to the copper electrodes, we selected a CO₂ laser with wavelength of 10.6 µm for drilling the polyimide. We have produced GEMs by using plasma etching method since 2002 [13]. Although a new GEM was successfully produced with the method, we could not make the hole pitch smaller than 140 µm.

3. Properties of laser etching GEM

3.1. Experimental setup

A schematic view of the GEM test setup is shown in Fig. 4. The test setup consists of a drift plane, GEM foils, and 3 × 3 readout pads with each area of 10 × 10 mm². Only the central readout pad was read out in the study and the other pads were connected to ground. The drift plane is 15 µm-thick aluminum foil with active area of 30 × 30 mm². The drift plane, GEMs, and readout pads are placed in a gas filled chamber. The spacing between the drift plane and the upper GEM (i.e. the spacing of target region) is 5.5 mm, and that between the lower GEM and readout pad is 1.0 mm. The electric field in the drift region is $E_d = 2.5 \text{ kV/cm}$, and $E_i = 4–5 \text{kV/cm}$ for the induction region. A GEM is often used as a preamplifier to the other GEM to reduce discharge probability and ion feedback [18]. When we studied the GEMs in the multi layer configuration, the spacing among GEMs was 2.0 mm. The electric field of the GEM is supplied via a chain of 10 MΩ resistors, and a 2 MΩ protection resistor is added in series with each GEM electrode.

Charge signals from the readout pads are fed into a charge sensitive preamplifier and shaper module (AmpTek A225). The amplified and shaped voltage signals are fed into the custom-made main amplifier. This module has a discriminator and gate generator for data-acquisition.

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system control. The amplified signals are fed into CAMAC peak-hold ADC (LeCroy 2259B) controlled by a PC. To make a calibration curve between amount of input charge and ADC channel, a well-defined rectangular wave from a research pulser (ORTEC model 448) was fed into the preamplifier through a 2 pF capacitor.

During the test, we flowed a mixture of 70% argon and 30% CO$_2$ by volume through the chamber. The CO$_2$ sense as a quencher. The primary reason we selected this gas mixture was to easily compare our results to other experiments; many GEM studies have been done with this mixture.

![Fig. 1. A typical procedure of GEM production with the laser etching technique. Photographs in the left column are the SEM images of the foil, and those in the right column are the cross-section of the foil corresponding to each left image. Top images show the copper-removed polyimide foil, middle ones show laser-etched foil irradiated from a side, and bottom ones show laser-etched foil irradiated from both sides.](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Pitch (μm)</th>
<th>Hole dia. (μm)</th>
<th>Etching method</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN-140</td>
<td>140</td>
<td>70</td>
<td>Chemical</td>
</tr>
<tr>
<td>RIKEN-140</td>
<td>140</td>
<td>70</td>
<td>CO$_2$ laser</td>
</tr>
<tr>
<td>RIKEN-100</td>
<td>100</td>
<td>50</td>
<td>CO$_2$ laser</td>
</tr>
<tr>
<td>RIKEN-50</td>
<td>50</td>
<td>30</td>
<td>CO$_2$ laser</td>
</tr>
<tr>
<td>RIKEN-50ex</td>
<td>50</td>
<td>30</td>
<td>Excimer laser</td>
</tr>
</tbody>
</table>
gas mixture. We did not add any gases to prevent discharge, aging effects, etc. in this study. For a future polarimeter, we will probably use a neon-based gas to increase the path length of the emitted photoelectron and to minimize the energy transfer to the Auger electron [7].

3.2. Gain measurements

We have measured electron gain as a function of applied voltage between the two copper electrodes of a GEM. Since it is difficult to measure the real GEM gain in the amplification channel, we define effective gain ($G_{\text{eff}}$) as the ratio of detected charge to input one, and use this definition of gain throughout this paper. In this study, the effective gain is measured with 5.9 keV X-ray irradiation from a $^{55}$Fe radioactive source. Note that the effects of charge losses during the electron transfer in gas, GEMs and readout pads are merged into the $G_{\text{eff}}$ in this study.

Fig. 5 shows a typical $^{55}$Fe spectrum taken with our detector. The main peak in the spectrum corresponding to the 5.9 keV X-ray is fitted with a Gaussian to measure the central value ($S_{\text{mean}}$) of the peak. Energy resolution of our GEMs is 21–23% FWHM which includes about 1% of readout noise.

The effective gain is found as

$$G_{\text{eff}} = \text{Const} \times \frac{S_{\text{mean}}}{q_e n_e}$$

where $q_e$ is the electron charge and $n_e$ is the number of electron-ion pairs created by the absorption of 5.9 keV X-ray. Mean value of $n_e$ is 212 for a mixture of 70% argon and 30% CO$_2$ [19]. The constant value is found from the calibration curve between amount of input charge and ADC channel mentioned in Section 3.1.

The effective gain of single, double, and triple RIKEN-140 GEMs are shown in Fig. 6. The gain is well expressed with an exponential function; $G_{\text{eff}} \propto \exp(V_{\text{GEM}})$, where $V_{\text{GEM}}$ is the applied voltage between the two electrodes of a GEM. The effective gain of the double GEM is roughly the square of the gain of the single GEM, and that of triple GEM is roughly the cubic of the gain of the single GEM. The result of double layers of CERN-140 GEMs is also shown in the figure for comparison. The agreement between the gain curves of the CERN-140 and RIKEN-140 GEMs indicates that the gain is determined only by the geometry of the hole size and pitch. We therefore conclude that our production process is an effective procedure for making GEMs.

Fig. 7 shows gain properties of single layer of RIKEN-50 and RIKEN-50ex. The two GEMs have similar gain curves, indicating that their geometries are essentially identical. While we observed micro-discharge with RIKEN-50ex at $V_{\text{GEM}} = 530$ V, RIKEN-50 kept the voltage at 570 V without any micro-discharge. The effective gain of RIKEN-50 at 570 V reached almost 5000. The measure-
ment was carried out with new GEMs after one day aging at lower voltage. The voltage at which micro-discharge occurred was not changed after ramping up and down HV several times. The difference in the discharge voltages is probably due to roughness of the surface of the copper electrodes (see Fig. 3). The damage to the copper surface by an excimer laser was reported in producing micro-well detectors [20]. The tendency of excimer GEMs to discharge at lower voltages than CO$_2$ GEMs has been observed in another production of GEMs.

To study the effect of smaller hole diameter, we have measured the effective gain with single RIKEN-50, RIKEN-100, and RIKEN-140 GEMs. Fig. 8 shows the effective gain at $V_{\text{GEM}} = 400, 410, 420, 430, 440$ and 450 V as a function of hole diameter of the GEMs. RIKEN-100 has two times larger gain than that of RIKEN-140. In contrast, the gain of RIKEN-50 is smaller than that of RIKEN-100.

The gain should increase exponentially as the hole diameter decreases [21]. Other parameters, such as aspect ratio between hole diameter and pitch, are probably negligible in comparison with the decrease of the hole diameter. However, our results show that the gain difference among RIKEN-140, RIKEN-100 and RIKEN-50 is only a factor of two or less, though the hole diameter decreases. It is reported that the effective gain is saturated at diameters below 60–70 $\mu$m [22]. Since the spread of the
avalanche electrons in the amplification hole is almost comparable to the hole diameter, some of the secondary electrons are probably absorbed by the lower GEM electrode. Our results indicate that we have observed this region of the gain saturation. A GEM with this hole diameter should have fairly uniform gain in spite of some variation in hole diameter [22].

3.3. Rate-dependent gain instability

We have measured rate-dependent gain stability of our GEMs using 8 keV photons from an X-ray generator with intensity of $10^4$ counts/s/mm$^2$. Fig. 9 shows the results of gain dependence as a function of time measured from beam-on. RIKEN-140 did not show any gain variation during the experiment, while the gain of CERN-140 increased rapidly in the first five minutes and then remained stable for the rest of the experiment.

The short-term rate-dependent instability has been attributed to charging of the insulating material between the electrodes [14,22,23]. As expected, we have observed that GEMs with holes having cylindrical geometry (RIKEN-140) show no gain instability, as compared to the results obtained with foils having conical hole shape (CERN-140).

4. Summary

We have developed fine-pitch GEMs using carbon dioxide or excimer laser etching technique for cosmic X-ray polarimeters. The minimum dimension of the GEM we have fabricated is 50 μm-pitch and 30 μm-diameter. We have measured the effective gain for 140 μm-pitch and 70 μm-diameter GEMs, 100 μm-pitch and 50 μm-diameter GEMs, and 50 μm-pitch and 30 μm-diameter GEMs. The 140 μm-pitch GEM was compared to the same structure GEM fabricated by CERN, and we found that the gain property is nearly the same.

We have measured the effective gain for the 50 μm-pitch GEMs produced with CO2 and excimer lasers. The gain properties of the two types of GEMs were almost the same. However, the voltage where micro-discharge begins for the excimer GEM was 40 V lower than that of the CO2 GEM probably because the excimer laser roughens the surface of the electrodes. The effective gain of the CO2 GEM reaches about 5000 at 570 V without any micro-discharge. We therefore conclude that our production process is effective for making fine-pitch GEMs.

We have measured the effective gains for 140, 100, and 50 μm-pitch GEMs to study the effect of hole diameter. Since the gains at the same applied voltage differ by less than a factor of two, it is obvious that the gains of the GEMs are almost saturated at these hole diameters.

We have measured the rate dependence of gain for our 140 μm-pitch GEM and the same dimension GEM fabricated by CERN. Our GEMs shows no time dependence, due to the cylindrical shape of the RIKEN GEMs.

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References