Development of Thick-foil and Fine-pitch GEMs with a Laser Etching Technique

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Abstract

We have produced thick-foil and fine-pitch gas electron multipliers (GEMs) using a laser etching technique. To improve production yield we have employed a new material, Liquid Crystal Polymer, instead of polyimide as an insulator layer. The effective gain of the thick-foil GEM with a hole pitch of 140 µm, a hole diameter of 70 µm, and a thickness of 100 µm reached a value of $10^4$ at an applied voltage of 720 V. The measured effective gain of the thick-foil and fine-pitch GEM (80 µm pitch, 40 µm diameter, and 100 µm thick) was similar to that of the thick-foil GEM. The gain stability was measured for the thick-foil and fine-pitch GEM, showing no significant increase or decrease as a function of elapsed time from applying the high voltage. The gain stability over 3 h of operation was about 0.5%. Gain mapping across the GEM showed a good uniformity with a standard deviation of about 4%. The distribution of hole diameters across the GEM was homogeneous with a standard deviation of about 3%. There was no clear correlation between the gain and hole diameter maps.

Key words: Gas Electron Multiplier, GEM, X-ray Polarimeter
1 Introduction

Gas electron multipliers (GEMs) are one of the more recently developed micro-pattern gas detectors [1]. Dense through-holes are drilled in an insulator substrate sandwiched by thin copper foils. By applying high voltage to the copper electrodes in an appropriate gas, we are able to use the GEM as an electron multiplier in which each hole works as an individual proportional counter. This device is used for many applications such as time projection chambers [2], photon detectors [3], X-ray imagers [4], two phase xenon detectors for dark matter search [5], etc.

GEMs are generally produced by using a chemical etching technique [6]. As an alternative, we have successfully developed GEMs using a laser etching technique [7], which has many advantages. Cylindrical holes are easily formed with the laser method, while double-conical holes are formed with the chemical etching technique [6]. The capability to drill cylindrical holes helps to form finer pitch holes on a thicker substrate. With the laser etching technique we have achieved 50 $\mu$m pitch holes on a 50 $\mu$m thick foil [7].

The primary purpose of our GEM development is to construct a photoelectric X-ray polarimeter for space missions, particularly for astrophysics. Recently, several photoelectric polarimeters have been proposed [8,9,10]. For the polarimeters, the GEM is a key device to achieve the mission goals. The details of measuring the polarization of X-rays are described in Refs. [11,9]. The key to high sensitivity is to measure the track of the photoelectron in the gas (typically a few 100 $\mu$m) with sufficient accuracy. According to our simulations the GEM should have a good spatial resolution of 50–100 $\mu$m.

The most significant risk to operating a GEM in space are discharges. The electron multiplication factor (gain) of a “standard” GEM with a pitch of 140 $\mu$m, a hole diameter of 70 $\mu$m, and a thickness of 50 $\mu$m, is a few 1000 in a gas mixture of 70% argon and 30% carbon dioxide by volume (Ar-70/CO$_2$-30). Although a gain of 1000 is sufficient when a very low-noise readout ASIC is combined with the GEM, we require that the GEM works without any discharge up to a gain of around $10^4$ for safety in space. It is known that the gain of a double or triple GEM configuration can easily reach a value of $10^4$. The stack of GEMs, however, diffuses electrons in the transfer section.

Recently, the so-called “thick GEMs (THGEMs)”, in which through-holes are mechanically drilled on a glass epoxy substrate, have been fabricated to achieve robustness against electrical discharge [12]. THGEMs are already used for
some applications such as ultraviolet photon counting detectors. Mechanical drilling is a well-developed technique, and the glass epoxy substrate may be easier to treat than the flexible polymer used in ordinary GEMs. It is, however, impossible to mechanically drill fine-pitch through-holes, e.g. less than 100 µm pitch, on the glass epoxy substrate. Therefore, the THGEMs are not suitable for this application.

2 Production of Thick-foil and Fine-pitch GEMs

Table 1 presents the list of the GEMs that were used in this study. The production process was the same as those shown in our previous paper [7]. The active area of all GEMs that we tested was 30×30 mm², although Sci-Energy can provide up to 230×300 mm² GEMs. First, we fabricated the GEMs referred to as “RIKEN-140-PI” which had the same hole pitch (140 µm), diameter (70 µm), and thickness (50 µm) as the so-called “standard” CERN GEMs. The only difference between the RIKEN-140-PI and the CERN standard GEM was the method for drilling holes through the substrate. We have employed a carbon dioxide laser (λ =10.6 µm), whereas CERN uses a wet etching technique.

Second, we produced the GEMs by using a new material, Liquid Crystal Polymer (LCP), instead of using polyimide (PI) as the insulating layer. The first LCP GEM we produced, referred to as “RIKEN-140-LCP”, has the same hole pitch, diameter, and thickness as the RIKEN-140-PI. The mechanical, thermal, and hygroscopic properties of LCP are summarized in Table 2. LCP gives lower expansion rate in fabrication as it absorbs less water than PI. This is an advantage for etching micro-pattern foils with a good accuracy. The low moisture absorption rate also leads to less out-gassing in operations. Although the melting temperature of LCP is slightly lower than that of PI, this is not a disadvantage for normal operation.

Third, we fabricated GEMs which had 140 µm pitch, 70 µm diameter, and 100 µm thick LCP insulator, referred to as “RIKEN-140T-LCP”. According to a simulation to calculate the electric field inside the holes, we expected that a thicker foil would yield more gain than a 50 µm thick GEM at the same applied high voltage. This was the motivation for producing the thick-foil GEMs. When we employed the PI substrate, we produced very few of 100 µm thick GEMs. After we changed the substrate from PI to LCP, the production yield of the thick-foil GEMs was improved and reached almost

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1 GEM foils produced by SciEnergy Co., Ltd. (info@scienergy.jp)
2 The trade name of the LCP substrate we used is the ESPANEX® L-Series manufactured by Nippon Steel Chemical Co., Ltd.
100%. A cross-section of the GEM is shown in Figure 1a.

Finally, we fabricated fine-pitch holes on a 100 µm thick LCP substrate. The GEMs have 80 µm pitch and 40 µm diameter, referred to as “RIKEN-80T-LCP”. A cross-section of the GEM is shown in Figure 1b. The fine-pitch and thick-foil GEM was expected to give a high gain without any discharge while keeping the high spatial resolution.

3 Gain Measurements and Results

3.1 Test setup

Figure 2 shows a schematic view of the GEM test setup used in this study. The setup consisted of a drift plane, a GEM foil, and 3×3 readout pads each with an area of 9×9 mm². The spacing between two adjacent pads was 1 mm. Only the central pad was read out and the others were connected to ground. The drift plane was a 15 µm thick aluminum foil with an active area of 30×30 mm². The drift plane, GEMs, and readout pads were placed in a chamber which was then filled with gas. The vertical spacing of the target region, which was the spacing between the drift plane and GEM, was 5.5 mm, and the induction region between GEM and the readout pad was 1.0 mm. A high voltage was supplied via a chain of 10 MΩ resistors, and to minimize the risk of electric surges, a 2 MΩ protection resistor was added in series with each GEM electrode. The electric field in the drift region was \(E_d=2.5 \text{ kV cm}^{-1}\), and in the induction region, \(E_i=4-5 \text{ kV cm}^{-1}\).

During the test, Ar-70/CO₂-30 gas was made to flow through the system. 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 gas mixture. In this study, we did not add any additional gases to the mixture to prevent discharge, aging effects, etc. As shown in Figure 2 we equipped the chamber with a pressure gauge and a moisture meter as well as a thermometer. The experiments were carried out in an air-conditioned room at a temperature of around 20 °C. The moisture in the gas was kept at 50 ppm or less. The pressure and temperature of the gas were recorded automatically every 10 min or faster.

Charge signals from the readout pads were fed into an AmpTek A225, which consisted of a charge sensitive preamplifier and shaper module. The amplified and shaped voltage signals were fed into the custom-made main amplifier. This module had a discriminator and gate generator for data acquisition system control. The amplified signals were fed into a VME peak-hold ADC (Clear
Pulse 1113A) controlled by a PC. To make a calibration curve between the 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.

The effective gain \((G_{\text{eff}})\) is given by:

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

(1)

where \(S_{\text{mean}}\) is the ADC peak value of incident monochromatic X-rays, \(q_e\) is the electron charge \((1.602 \times 10^{-19} \text{ C})\), and \(n_e\) is the number of electron-ion pairs created by an X-ray photon. A typical value of \(n_e\) is 212 for a 5.9 keV X-ray photon from the radioactive \(^{55}\text{Fe}\) source in the Ar-70/CO\(_2\)-30 gas mixture \[13\]. Typical energy resolution was 18% (FWHM) at 5.9 keV. The relative systematic uncertainty of the measurement was about 1% of the gain value as far as we used the readout system described above. When we used other readout systems to estimate the absolute systematic uncertainty of the gain value, the maximum shift was 6%.

3.2 Gain curves

3.2.1 Polyimide and LCP GEMs

Figure 3 shows the gain curves of double RIKEN-140-PI and double RIKEN-140-LCP GEM stacks. Both gain curves show that an effective gain of around \(10^4\) was achieved at an applied high voltage of 430 V per GEM. No difference in gain was observed between the PI and LCP GEMs, indicating that the difference in the insulator materials is not essential for the multiplication mechanism of electrons in the holes. The gain curve of the CERN standard GEM was almost the same as the RIKEN-140-PI and RIKEN-140-LCP GEMs as shown in Figure 6 of our previous paper \[7\]. Since there was no significant difference between these three GEMs, we concluded that using a LCP substrate together with laser-drilled holes is an ideal method to produce GEMs, equivalent to other methods such as laser or wet etching with PI substrates.

3.2.2 Thick-foil GEMs

Figure 4 shows the gain curve of a single RIKEN-140T-LCP GEM. An effective gain of \(10^4\) was achieved at an applied voltage of 700 V per GEM. For comparison, a double RIKEN-140-LCP stack, in which the two GEMs were vertically spaced by 1 mm with an electric field between them of about 3.5 kV cm\(^{-1}\), is superposed on the same figure. The effective gain of the thick-foil
RIKEN-140T-LCP GEM was about 60 times higher than that of the double RIKEN-140-LCP GEM stack, when we operated the double GEM at the same combined voltage as the thick-foil GEM. Obtaining an appropriate gain at lower applied voltage decreases the risk of discharges. We can also avoid electron diffusion in the transfer region between two GEMs.

### 3.2.3 Thick-foil and fine-pitch GEMs

A gain curve of a single RIKEN-80T-LCP GEM is shown in Figure 4. The maximum gain obtained in Ar-70/CO$_2$-30 gas, without any micro-discharge was $3 \times 10^4$ at a high voltage of 725 V. Although the hole size of RIKEN-80T-LCP was smaller than that of RIKEN-140T-LCP, the gain curves were almost identical. This similarity was predicted from our previous study in which we demonstrated independence of the gain on the hole size, for 50 $\mu$m thick GEMs [7]. The RIKEN-80T-LCP GEM is the finest pitch GEM with a thickness of 100 $\mu$m, and has become our standard for future space missions. For the rest of this paper, we mainly focus on this GEM.

### 3.3 Gain instability

It has been shown that the gain of GEMs produced by a chemical etching technique increases with time following the application of high voltage. Simon et al. stated that the gain of CERN and industrially produced Tech Etch GEMs in a triple GEM configuration increased by 30–80% of the initial value over the 6 h following turning on of the high voltage [14]. A spacecraft in a low Earth orbit with an inclination angle of about 20–30°, which is the standard orbit for scientific satellites launched from Japan or the United States, passes through the inner Van Allen belt known as the South Atlantic Anomaly (SAA) every 90 minutes, where a significant flux of charged particles (mainly protons) exist and interact in the detector. To avoid breakdown caused by the charged particles, gas detectors onboard satellites are usually turned off during passage through the SAA. In the operational mode where the applied voltage is turned on and off frequently, the change in gain related to turning on the high voltage is critical. It has been reported that the gain decrease of a charged-up detector when the voltage is switched off is very slow, of the order of many 10 s of hours [15]. However, we want to avoid those gain variations to reduce the systematic uncertainty of measurement.

We have demonstrated that no significant gain increase is observed for the 50 $\mu$m thick laser etched GEMs under a very high rate of incident X-rays ($10^4$ counts mm$^{-2}$ sec$^{-1}$) [7]. Here we demonstrated the gain stability for the thick-foil and fine-pitch LCP GEMs under a lower incident rate. Since the
electron multiplication process in a gas detector is sensitive to the density of the gas, the measured gain has to be corrected by using the measured pressure and temperature. We have used the same correction function introduced in our previous study [16]. The corrected effective gain ($G_{\text{eff}}^{\text{corr}}$) normalized at a pressure of 760 Torr and a temperature of 300 K is given by;

$$G_{\text{eff}}^{\text{corr}} = \frac{G_{\text{eff}} \exp\left(C \times \left(\frac{1}{P/T} - \frac{1}{2.533}\right)\right)}{\exp\left(C \times \left(\frac{1}{P/T} - \frac{1}{2.533}\right)\right)}$$

where $G_{\text{eff}}$ is the measured effective gain introduced in §3.1, $C$ is a constant of 19.1 Torr K$^{-1}$ for the RIKEN-80T-LCP GEM in our setup, $P$ and $T$ are the pressure and temperature measured in Torr and K, respectively. During the experiment, the effective gain was around $10^3$ and the GEM was irradiated with 5.9 keV X-rays at a rate of about 100 counts cm$^{-2}$ sec$^{-1}$.

The corrected gain of a single RIKEN-80T-LCP GEM, normalized to 760 Torr and 300 K, as a function of the elapsed time after high voltage was applied, is shown in Figure 5. No time evolution was observed, and the standard deviation of the gain instability was 0.4%. For comparison, the time evolution of the gain of the standard CERN GEM, which was the same geometry as RIKEN-140-PI, is superposed on the figure. The gain measurement was carried out under the same condition as for RIKEN-80T-LCP.

As Benlloch et al. have pointed out [17], a cylindrical hole shape formed by laser drilling is likely to suppress the charging-up of the surface of the side wall in the hole. The extremely good gain stability makes the laser etched GEMs optimal for applications where the gain stability is critical, such as for space applications.

To demonstrate the gain stability of the PI GEMs, we have measured the time evolution of the gain for a single RIKEN-140-PI GEM, obtaining a standard deviation of 0.5%. The measured gain is plotted in Figure 5. The result implies that the good gain stability results not from employing the new insulator material LCP, but from the cylindrical hole shape formed by the laser.

3.4 Gain uniformity

We have measured gain uniformity across the RIKEN-80T-LCP GEM by using a finely collimated X-ray beam. A schematic view of the experimental setup is shown in Figure 6. The X-ray beam from an X-ray generator equipped with a copper target was connected to the experimental area with a 2 m long beam pipe. The beam size was controlled to a diameter of 200 $\mu$m by a pin-hole lead collimator attached to the beam pipe exit. Then, the beam was filtered
by nickel foils to obtain a quasi-monochromatic beam with an energy of 8 keV from Cu Kα. The GEM chamber, which was identical to the one shown in Figure 2, was mounted on an XZ-stage to move horizontally and vertically, perpendicular to the collimated X-ray beam.

We have measured the gain within the central readout pad (9×9 mm²) in 500 μm steps, i.e., we have measured the gain at 17×17 points within the pad. The gain was measured with an applied high voltage of 620 V between the electrodes of the GEM (gain~1000). A map of the measured gain is shown in Figure 7a. A fractionally higher gain was observed at the upper-left region, while a slightly lower gain was observed at the lower-right region of the GEM. The gain was gradually changed across the GEM with a scale of a few millimeters. A histogram of the measured gain is shown in Figure 7b with a standard deviation of 4.4%. To check the systematic error, we have measured the gain map after rotating the GEM by 90 degrees relative to the chamber, obtaining the exact same map as obtained above. The gain maps were measured for several GEMs, showing standard deviations of 4–5%.

4 Distribution of hole diameters

We have measured the distribution of hole diameters across the RIKEN-80T-LCP GEM, that was used for the gain uniformity measurement above, with an automatic laser confocal microscope at the High Energy Accelerator Research Organization (KEK) [18,19]. The microscope took images with a linear image sensor, and then the images were analyzed with a software that measured hole diameters by matching an ellipse to each hole.

Figure 8a shows a contour map of the hole diameter distribution for the same region of the GEM shown in Figure 7a. The hole diameter distribution seems almost random across the GEM. The randomness indicates that the variation of the hole diameters is probably induced by the production accuracy. From Figures 7a and 8a, there was no obvious correlation between the gain and hole diameter distributions.

The histogram of the distribution is shown in Figure 8b. The mean value was 47 μm and the standard deviation was 3%. Since we have measured the hole diameters on the surface of a copper electrode, the diameter was slightly larger than our design value (40 μm). The hole shape of the thin copper layer was conical with a surface diameter of 47 μm and a bottom (i.e., the boundary between the copper electrode and the LCP insulator) diameter of 38 μm.

A notable feature of the histogram is the second peak around 43 μm. This corresponds to small dark spots in Figure 8a, which are randomly distributed
all over the GEM. A close-up microscopic view of one of the regions is shown in Figure 9. Only the hole identified by an arrow has a smaller diameter than those of the other holes around it. We have measured the distribution of hole diameters for the other GEMs which had a nominal hole diameter of 70 µm, obtaining no such defects for those GEMs. We suspect that the defects came from an initial etching process which removed copper to form small diameter (40 µm) holes on the copper layers, and they will be improved in the next production.

5 Summary

(1) We have produced thick-foil GEMs by using a CO₂ laser etching technique. We employed an insulator layer of liquid crystal polymer (LCP) instead of polyimide. Production yield was significantly improved by employing LCP, and the gain properties remained unchanged. This implies that LCP is an ideal material for producing GEMs.

(2) We have produced 100 µm thick-foil GEMs with hole pitches of 140 µm and 80 µm. The achieved gain of the thick-foil GEMs was $10^4$ at an applied voltage of 700 V per GEM. The gain was 60 times higher than that of a double 50 µm thick GEM stack which was operated at the same combined voltage as the thick-foil GEMs.

(3) We have measured the gain stability of the thick-foil and fine-pitch GEM with 80 µm pitch, 40 µm hole, and 100 µm thick. No gain increase or decrease was observed after the high voltage was applied. This was a common feature of the laser etched GEMs, probably due to the cylindrical shape of the hole formed by the laser drilling.

(4) We have measured the gain uniformity across the thick-foil and fine-pitch GEM. The standard deviation of the gain distribution in a 9×9 mm² region was about 4%, and the gain gradually changed across the GEM on a scale of a few millimeters.

(5) We have measured the hole diameter distribution across the GEM. The standard deviation of the distribution was about 3%. The distribution of hole diameters across the GEM is homogeneous, with no clear correlation between the hole diameter and gain maps.

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Table 1
List of GEM foils examined in this study. All listed GEMs are produced by CO$_2$ laser etching.

| name              | hole pitch (µm) | hole dia. (µm) | thickness (µm) | insulator | thickness of Cu (µm) |
|-------------------|-----------------|----------------|----------------|-----------|----------------------|
| RIKEN-140-PI      | 140             | 70             | 50             | polyimide | 5                    |
| RIKEN-140-LCP     | 140             | 70             | 50             | LCP       | 9                    |
| RIKEN-140T-LCP    | 140             | 70             | 100            | LCP       | 9                    |
| RIKEN-80T-LCP     | 50              | 30             | 100            | LCP       | 9                    |
Table 2
Typical mechanical, thermal, and hygroscopic properties of LCP and polyimide provided by SciEnergy Co., Ltd.

| Property                        | LCP   | polyimide | note                                      |
|---------------------------------|-------|-----------|-------------------------------------------|
| Tensile Strength (MPa)          | 200   | 274       |                                           |
| Tensile Elongation (%)          | 40    | 57        |                                           |
| Tensile Modulus (MPa)           | 2900  | 4606      |                                           |
| CTE (ppm/K)                     | 20    | 20        |                                           |
| Thermal Conductivity (W/m·K)    | 0.5   | 0.2       |                                           |
| Water Absorption (%)            | 0.04  | 3.2       | 24 hrs in water                           |
| Moisture absorption (%)         | ≤0.04 | 1.5       | 24 hrs in 50%RH at 25 °C                  |
| CHE (ppm/%RH)                   | 1     | 28        |                                           |

CTE: Coefficient of Thermal Expansion
RH: relative humidity
CHE: Coefficient of Hydroscopic Expansion
Fig. 1. Cross-section of (a) RIKEN-140T-LCP and (b) RIKEN-80T-LCP obtained with a metallographic microscope.
Fig. 2. A schematic view of the GEM test setup.
Fig. 3. Effective gain of double RIKEN-140-LCPs and double RIKEN-140-PIs as a function of the applied voltage to each GEM.
Fig. 4. Effective gain of single RIKEN-140T-LCP, single RIKEN-80T-LCP, and double RIKEN-140-LCP GEMs.
Fig. 5. Relative gain as a function of elapsed time after turning on of high voltage for RIKEN-80T-LCP and RIKEN-140-PI GEMs. The gain was normalized to 1 at the first measurement. For easier visibility, the gain of RIKEN-140-PI was offset by a value of $-0.1$. A correction for temperature and pressure was applied. The gain evolution of a CERN GEM (which had the same geometry as RIKEN-140-PI), as measured with our test setup, is shown in the figure. The effective gain of the measurements was around $10^3$, and the count rate of irradiated 5.9 keV X-rays was about 100 counts cm$^{-2}$ sec$^{-1}$. 
Fig. 6. A schematic view of the experimental setup for the gain uniformity mapping. An enlarged view around the end of the beam pipe is shown in the box surrounded by a dashed line.
Fig. 7. (a) Map of the relative gain as a function of spatial location for a single
RIKEN-80T-LCP GEM. The 9×9 mm² region of the map is the same as shown
in Figure 8. (b) Distribution of the relative gain across the GEM. The standard
deviation of the distribution was 4.4%.
Fig. 8. (a) Spatial homogeneity of the hole diameter of RIKEN-80T-LCP. The color scale indicated on the right shows the hole diameter in units of µm. (b) The distribution of the hole diameters. The standard deviation was 3%.
Fig. 9. A defect of a hole. The diameter of the hole indicated by the arrow is 42 \( \mu \text{m} \), which is 5 \( \mu \text{m} \) smaller than average.