Study of LTCC-GEM gain properties

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Abstract. Low Temperature Co-fired Ceramic (LTCC) is an insulator and has been used for electronic circuit boards. The features of LTCC are good electric discharge resistance and high rigidity. A GEM foil using LTCC is expected not to be broken by an electric discharge. The manufactured LTCC-GEM has a hole area of $100 \times 100 \text{ mm}^2$, the hole diameter is $100 \mu \text{m}$, and the hole pitch is $200 \mu \text{m}$. We have measured the performance with respect to the gain properties of $200 \mu \text{m}$ thick LTCC-GEM with $^{55}\text{Fe}$ X-ray. In the measurement, the gain achieved was about 2000 for three gases, $\text{ArCO}_2$ ($\text{Ar}:\text{CO}_2 = 70:30$), $\text{P10}$ ($\text{Ar}:\text{CH}_4 = 90:10$) and T2K ($\text{Ar}:\text{CF}_4:i\text{C}_4\text{H}_{10} = 95:3:2$), and the long-term (100 hours) fluctuation was within 6%. And when the $100 \times 100 \text{ mm}^2$ LTCC-GEM hole area was divided into $10 \times 10 \text{ mm}^2$, the gain uniformity of the entire region was estimated to be 12%.

1. Introduction
The Gas Electron Multiplier (GEM) has been developed by F.Sauli[1] and is recently used for many applications. The particle detectors using GEM have a good position resolution in two-dimensional plane. But GEM operation has a risk of electric discharge. The discharge happens between an upper and a lower electrode of the GEM and it sometimes breaks the GEM. Since an insulator of “Standard GEM” includes carbon, the discharge carbonizes the polymer on its way, establishing a conductive path which shorts the two sides. To avoid this problem, finding material without carbon is important. One of the candidates is a ceramic and it is the fired sintering body made by an inorganic matter. Low Temperature Co-fired Ceramic (LTCC) are a ceramic substrate co-fired with a conductor at low temperatures below 900 degrees. LTCC is an insulator and has been used for electronic circuit boards. The features of LTCC are good electric discharge resistance and high rigidity.

K.Komiya and Hirai Seimitsu Kogyo Corporation have developed LTCC-GEM which used LTCC as an insulator[2]. In Ref.[2], the geometry of LTCC-GEM they made is a size of $10 \times 10 \text{ mm}^2$, a hole diameter of $100 \mu \text{m}$, a hole pitch of $200 \mu \text{m}$, and a thickness of $100 \mu \text{m}$. The material of the electrode on both sides of the GEM is Au with $6 \mu \text{m}$. The gain obtained by a gas detector using single layer LTCC-GEM was achieved over $20000$ in the $\text{Ar-CO}_2$ gas ($\text{Ar}-70\%, \text{CO}_2-30\%$) environment. And it was also reported that LTCC-GEM continues to operate without breakdown even if discharge occurred more than 10000 times. Figure 1 shows the production process of LTCC-GEM. In this figure, “green sheet” is a sheet of raw ceramic. Since the holes are punched with a needle one by one, a wide selection of hole diameter and pitch is available. To remove any Au left in the holes, an etching process is applied after heat sintering. As an optional process, Au plating is applied to recover the possible decrease in Au-thickness by the etching.
Figure 1. LTCC-GEM production process. Au plating is an optional process.

The geometry of LTCC-GEM used in this measurement is a size of 127×127 mm$^2$, a hole diameter of 100 µm, a hole pitch of 200 µm, and a thickness of 200 µm. Figure 2 shows the picture of the LTCC-GEM used in this measurement. Since LTCC-GEM of 100 µm thickness is easily cracked by a locally applied force, the thickness has been changed to 200 µm to prevent cracking. The difference between 100 µm and 200 µm thickness is only the thickness of the insulator (LTCC). And there is no difference in the production process. The measurement used two kinds of the hole area, 60×60 mm$^2$ and 100×100 mm$^2$. To avoid cracking, the edge on both sides of the LTCC-GEM sheet has been attached to a G10 frame with thickness of 500 µm.

Figure 2. Left: Picture of LTCC-GEM. Right: A photomicrograph of the LTCC-GEM.

2. The experimental setup
The experimental setup in this measurement is the same as the setup for our “Standard GEM”¹, because the LTCC-GEM size and positions of holes have been designed as our “Standard GEM” in our study. Figure 3 shows the setup of this measurement. The signal readout pad was an unsegmented 100×100 mm$^2$ Cu foil (size of an entire Cu foil substrate was 127×127 mm$^2$). As a cathode was used a 125 µm thick transparent conductive film to see the discharge occurred in the GEM. The HV power supply used was CAEN A1470. The power supply and the GEM were connected in a daisy chain, and the resistance to apply HV to the GEM was determined so that the current in the daisy chain were 20 µA. The high voltage line, the GEM and the cathode were connected through the protection resistor. There was the drift region with a length of 10 mm or 5 mm and an induction region with a length of 2 mm. Only one readout channel is connected to the signal readout pad. The charge signal from the signal readout pad was converted to a voltage signal by a preamplifier (ORTEC 142IH) and a spectroscopy amplifier (ORTEC 672), and the MCA (AMPTEK MCA800A) measured its pulse height. A 5.9 keV X-ray from $^{55}$Fe placed

¹ This refers to the GEM with polyimide or liquid-crystal polymer as an insulator.
on the chamber passed through the Mylar sheet to reach the drift region. This measurement used three gases, ArCO\textsubscript{2} (Ar:CO\textsubscript{2} = 70:30), P10 (Ar:CH\textsubscript{4} = 90:10) and T2K (Ar:CF\textsubscript{4}:iC\textsubscript{4}H\textsubscript{10} = 95:3:2). All gases were premixed. Table 1 shows the electric field setting for the three gases. These values were not special to LTCC-GEM and were also used with our “Standard GEM” (for example, values of the T2K gas was used in Ref.[3]).

### Table 1. Electric fields setting for the three gases

| Gas       | ArCO\textsubscript{2} (Ar:CO\textsubscript{2} = 70:30) | P10 (Ar:CH\textsubscript{4} = 90:10) | T2K (Ar:CF\textsubscript{4}:iC\textsubscript{4}H\textsubscript{10} = 95:3:2) |
|-----------|------------------------------------------------|----------------------------------|----------------------------------|
| Drift region (E\textsubscript{D}) | 1.5 kV/cm | 0.75 kV/cm | 0.23 kV/cm |
| Induction region (E\textsubscript{I}) | 6.0 kV/cm | 3.0 kV/cm | 2.7 kV/cm |

3. Results

3.1. Gain and Energy resolution

Gain and Energy resolution measurements were taken at two different times (60\times60 mm\textsuperscript{2} - 2018 winter, 100\times100 mm\textsuperscript{2} - 2019 winter). Figure 4 shows the \textsuperscript{55}Fe X-rays spectrum obtained with the 60\times60 mm\textsuperscript{2} LTCC-GEM in ArCO\textsubscript{2} gas. This figure shows the distribution with the applied voltage difference (V\textsubscript{GEM}) of 860V on both sides of LTCC-GEM. The two peaks are a main peak (5.9 keV) and the Ar escape peak (2.94 keV) of \textsuperscript{55}Fe X-rays. The total number of electrons obtained as a signal can be determined by the calibration curve calculated from the proportional relation between the input charge and MCA counts. Since the numbers of ionized electrons by \textsuperscript{55}Fe X-rays in this measurement are known, the gain was calculated from the total charge obtained by the measurement. The main peak distribution was fitted with a Gaussian distribution, and the central value was taken as the total charge. The measurements were performed while changing the V\textsubscript{GEM} values until the main peak distribution was no longer observed because of a discharge. Figure 5 shows the gain of a single layer LTCC-GEM for various V\textsubscript{GEM}. The gain was found to exceed 1000 for all gases. There is no difference of gain between the 60\times60 mm\textsuperscript{2} and the 100\times100 mm\textsuperscript{2} LTCC-GEM, even on different measurement dates. Although it was about 1/10 of the gain obtained in Ref.[2], it is expected that a gain of
Figure 4. $^{55}$Fe X-rays spectrum obtained with the 60×60 mm$^2$ LTCC-GEM in ArCO$_2$ gas ($V_{\text{GEM}} = 860$V)

Figure 5. Gain of 200 µm LTCC-GEM

Figure 6. Energy resolution of 200 µm LTCC-GEM

over 5000 can be obtained by finding some methods for suppressing the discharge. The ceramic is considered to have no effect on the gas, as the trend of gain curve for all gases are similar.

Figure 6 shows the energy resolution of a single layer LTCC-GEM for various $V_{\text{GEM}}$. For any gas, it can be seen that the energy resolution in the 100 to 800 gain range is about 22%. The energy resolution became worse as the gain decreased, because the signal level at the low gain region was about the same as the noise level of the detector or the readout circuit. And it also became worse at the high gain region because the number of discharges increased as the gain increased.

3.2. Long-term gain stability and discharge rate

Long-term measurements of the 60×60 mm$^2$ were performed for 82 hours in the winter of 2018, and the measurements of 100×100 mm$^2$ were performed for 105 hours in the winter of 2019. Both measurements used the T2K gas. $^{55}$Fe was placed on the detector at the same time of
applying HV to the detector, and the pulse height distribution of $^{55}$Fe X-rays was measured every 30 minutes. As for the measurement of 100×100 mm$^2$ (60×60 mm$^2$), data were taken every 10 minutes (15 minutes) until 1 hour passes from a start. $^{55}$Fe remained placed on the detector during the measurement. The detector and the gas bottles were placed in the same room, and the room temperature was made as constant as possible using an air conditioner. The temperature was measured by a thermocouple attached to the outside of the detector and the absolute pressure of the gas flowing in the detector was measured. Using these values, the obtained gain has been corrected to the gains at 25 degrees and 760 Torr. When discharge occurs, the current of the daisy chain connecting the HV and the GEM increases. Since the daisy chain was designed to have a current of 20 µA, the time when the current value exceeded 15 nA from the set value (20 µA) was defined as the time when the discharge was occurred. Figure 7 a) shows the fluctuation of gain, energy resolution and discharge rate on 100×100 mm$^2$ LTCC-GEM. And Figure 7 b) shows the comparison between 100×100 mm$^2$ and 60×60 mm$^2$. In Figure 7a), the gain decreased gradually after the start of the measurement and became nearly constant (730) after 10 hours. The energy resolution also gradually got worse after the measurement was started and became nearly constant (29%) after 10 hours. The fluctuation of the discharge rate did not depend on time. However, the data after 20 hours from the start of measurement have a lower gain, a worse energy resolution and a higher discharge rate, so it is assumed that this fluctuation was affected by the discharge. The average value and FWHM obtained by fitting each distribution to a Gaussian curve were, 731 ± 24 for the gain, 0.283 ± 0.017 for the energy resolution, and $(3.201 ± 0.092) \times 10^{-3}$Hz for the discharge rate. In Figure 7b), it is difficult to determine whether the gain of the 60×60 mm$^2$ has the same tendency as the 100×100 mm$^2$ because there was some lack of data on the 60×60 mm$^2$ measurement. The discharge rate of 60×60 mm$^2$ was about 1/3 smaller than that of 100×100 mm$^2$ ($(1.272±0.066) \times 10^{-3}$Hz). This is considered to be due to the fact that the gain at 60×60 mm$^2$ was 68% lower than 100×100 mm$^2$ and the area with holes is small. However, these results mean that the discharge occurred 4 to 12 times per hour, so further discharge prevention methods are needed.

3.3. Position dependence

The GEM was divided into 10×10 mm$^2$ areas, and the gain and energy resolution of each area were measured by placing $^{55}$Fe source at the center of the area. A collimator was used to
collimate $^{55}$Fe X-rays into a circle of about 1.4 cm in diameter on top of the GEM. The gas used was the T2K gas. Figure 8 shows distributions of the gain and energy resolution in 100×100 mm$^2$ GEM, and Figure 9 shows distributions of the gain and energy resolution in 60×60 mm$^2$ GEM.

The uniformity of gain and energy resolution was as follows. For 100×100 mm$^2$ GEM, the gain was $449 \pm 51.6$ (FWHM) and the energy resolution was $0.246 \pm 0.051$ (FWHM). For 60×60 mm$^2$ GEM, the gain was $419.2 \pm 24.3$ (FWHM) and the energy resolution was $0.279 \pm 0.033$ (FWHM). In the gain distribution (Figure 8a), there is one region about 10% higher than the average value, which deteriorates the uniformity. On the other hand, in the energy resolution distribution (Figure 8b), places where the resolution was higher than the average value and places where the resolution was lower are scattered, and it can be seen that distributions of the gain and the energy resolution have no correlation. In Figure 9, the gain distribution (Figure 9a) seemed to have a gradual increase from top to bottom. In the energy distribution (Figure 9b), the bad part was in the center and the good part was in the lower left, but there is no systematic change.
and no correlation with the gain distribution. Although it is difficult to identify the cause of the bad uniformity from these distributions, it is necessary to measure the distribution with more LTCC-GEM, and to identify and solve the cause of it.

4. Summary

LTCC is an insulator material with high discharge resistance and high rigidity, and can be a good candidate as a GEM insulator. We have fabricated a GEM using LTCC (LTCC-GEM) and measured some characteristics related to gain using a $^{55}$Fe X-ray source. The LTCC-GEM, which was used at this measurement, had an insulator with thickness of 200 $\mu$m for safer handling. In the gain measurement using three kinds of gas, gains of about 2000 times were obtained until discharge, and the energy resolution was 22% within the range where the influence of the discharge was small. In 100 hours of measurement, the fluctuations of both gain and energy resolution were within 6% (FWHM), and the discharge rate was $3 \times 10^{-3}$ Hz. Since the discharge rate was still high, more measures against discharge are needed. The gain uniformity of the $100 \times 100 \text{mm}^2$ LTCC-GEM has been about 12% (FWHM), and it is necessary to identify and improve the cause of the uniformity deterioration. Based on the results obtained, LTCC-GEM is not inferior in performance to “Standard GEM”, and there are many advantages such as the discharge resistance, so it is considered that it can be used in actual experiments. However, there are many problems that must be solved for actual use, so we will solve them one by one.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP17K05473. The author thanks K. Komiya and Y. Takeuchi for their suggestions.

References

[1] F. Sauli, 1997 Nucl. Inst. and Meth. A 386 531
[2] K. Komiya, et al, “Development of Gas Electron Multiplier by Applying Technique of Low Temperature Co-Fired Ceramics” (written in Japanese), 2018 Journal of the Japan Society for Precision Engineering Vol.84 No.11 936
[3] M. Kobayashi, et al, 2019 Nucl. Inst. and Meth. A 918 41