Development and properties of 100 mm-square size LTCC-GEM

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Abstract. We developed a gas electron multiplier (GEM) that is highly reliable against discharge using a Low Temperature Co-fired Ceramic (LTCC) as an insulating layer (LTCC-GEM). Because LTCC is an inorganic anti-carbonized material, LTCC-GEM is expected to be strong against breakdown. The gain properties of a single layer of 100 μm-thick LTCC-GEM with an effective area of 100 × 100 mm² was evaluated in the gas mixture of 70% Ar and 30% CO₂ at 1 atm. The maximum gain was approximately 3,500 at an applied voltage of 730 V and the gain variation was less than 3% over 14 hours of operation. In addition, the LTCC-GEM remained unbroken during the experiment despite more than 20,000 discharges at a high applied voltage of 730 V. We confirm that the LTCC-GEM is discharge-tolerant and has the same performance as traditional GEMs.

1. Introduction

A Gas Electron Multiplier (GEM) has been under development as a charged-particle tracking device in nuclear and particle physics experiments at CERN since 1997 [1, 2]. The GEM is formed on a thin metal-clad polymer foil. An array of through-holes with a typical hole diameter of 70–100 μm are drilled into the foil. Since the GEM works as a planar electron multiplier where the electron avalanche is generated in the high electric field present inside each hole, GEM detectors can be used as two-dimensional radiation detectors. In high-gain operation, in the traditional GEM the risk of short-circuits between electrodes is present, since the polymer layers can be carbonized due to repeated discharges. To mitigate this risk, we have developed a GEM made with a ceramic, Low Temperature Co-fired Ceramic (LTCC).

2. Fabrication

2.1. Selection of insulator material

The selection of the GEM insulator material is essential to obtain discharge tolerance. The main reason of GEM breakdown by discharges is probably the occurrence of sufficient carbonization on the insulator surface due to arc-discharge. Since typical insulator materials for traditional GEMs namely, Polyimide (PI) and Liquid Crystal Polymer (LCP) are organic, carbonization is unavoidable. Thus, to search for new materials, we focused specifically on their arc-resistance parameter, standardized by ASTM D 495, for a time period during which a generated conduction path forms on the material surface [3]. Finally, we employed Polytetrafluoroethylene (PTFE)
Table 1. Material properties of GEM insulators.

| Materials       | PI   | LCP  | PTFE  | LTCC |
|-----------------|------|------|-------|------|
| Volume resistance [Ω cm] | $10^{17}$ | $6 \times 10^{16}$ | $> 10^{18}$ | $> 10^{14}$ |
| Arc resistance [sec]    | 135  | 186  | $> 300$ | $> 300$ |
| Melting point [°C]     | 800  | 450  | 327    | $> 800$ |
| Density [g cm$^{-3}$]  | 1.43 | 1.35 | 2.13–2.2 | $\sim 3$ |
| Dielectric constant, $\varepsilon/\varepsilon_0$ | $\sim 3.4$ | $\sim 3.5$ | 2.1 | $\sim 7.5$ |

and LTCC as insulator materials because of their higher arc-resistances than those of PI and LCP. Table 1 shows the material properties of PI, LCP, PTFE, and LTCC.

In our previous study, two types of GEM using PTFE and LTCC were fabricated: their specifications in ArCO$_2$ gas mixture, as well as those of LCP-GEM, are summarized in table 2. The PTFE- and LTCC-GEM showed excellent discharge tolerance and a maximum gain of more than 10,000, which significantly better than those of LCP-GEM. Although more than 10,000 discharges occurred, PTFE- and LTCC-GEM kept functioning without short-circuit. LTCC-GEM especially has clearer hole shape than PTFE-GEM, as shown in table 2. Thus, we chose LTCC as GEM material for prototypes with expanded effective area as large as $100 \times 100$ mm$^2$, a typical GEM size.

2.2. Fabrication process

We fabricated the LTCC-GEM using a technique which is widely used for fabricating electric circuit boards with ceramic. Our LTCC-GEM is fabricated by Hirai Seimitsu Kogyo, Co. (Japan). The process consists of 4 steps, as shown in figure 1. First, the green sheet of LTCC, which looks like clay, is cut to the required size. Second, a gold paste is applied on both surfaces

Table 2. Specifications and performance of LCP-, PTFE-, and LTCC-GEM.

| Insulator       | LCP-GEM[4, 5] | PTFE-GEM[6] | LTCC-GEM[7] |
|-----------------|---------------|-------------|-------------|
| Metal of electrodes | Cu            | Cu          | Au          |
| Effective area  | —             | 20×20 mm$^2$ | 10×10 mm$^2$ |
| GEM thickness   | 50 or 100 μm  | 50 μm       | 100 μm      |
| Drilling holes  | Laser etching | Laser       | Punch       |
| Hole diameter   | 70 μm         | 100 μm      | 100 μm      |
| Hole pitch      | 140 μm        | 200 μm      | 200 μm      |

Hole shape

The maximum gain  | $\sim 10^4$ | $> 10^4$ | $> 10^4$ |
Amount of discharges until the breakdown | few | (No breakdown) | (No breakdown) |
of the LTCC sheet to form the electrodes having a thickness of approximately 3 μm. Third, the through holes are punched out using a single dedicated punching needle. The needle size and hole pitch are selected such that the hole diameter and pitch become 100 μm and 200 μm, respectively, following the sintering process. This punching process can change fabrication size more easily than that of typical polymer GEMs using laser etching, as this process does not need etching nor a photo-resist mask process. Finally, the processed LTCC sheet is sintered below 1,000 °C. After this process, the sheet experiences a 10% shrinking and becomes rigid.

A picture of the whole detector, an image by microscope of the surface and the cross-section of a 100 × 100 mm² LTCC-GEM are shown in figure 2. We can confirm that the hole-shape is circular and the hole cross section is straight, i.e. the holes have cylindrical shapes. At the same time, some residues of the gold paste is present on the wall of the hole, presumably causing discharges. Table 3 lists the main parameters of this LTCC-GEM.

![Figure 1. Fabrication process of LTCC-GEM.](image)

**Figure 1.** Fabrication process of LTCC-GEM.

![Figure 2.](image)

**Figure 2.** (a) Photograph of 100 × 100 mm² LTCC-GEM. (b) Enlarged view of LTCC-GEM surface. (c) SEM image of the cross-section of LTCC-GEM.
Table 3. Parameters of the large-size LTCC-GEM.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Insulator LTCC                   |                        |
| Metal of electrodes              | Au                     |
| Electrode thickness              | $\sim 4 \mu$m          |
| Surface area                     | $124 \times 124 \, \text{mm}^2$ |
| Effective area                   | $100 \times 100 \, \text{mm}^2$ |
| GEM thickness                    | $100 \, \mu$m (design) |
| Hole drilling method             | punch                  |
| Hole diameter                    | $100 \, \mu$m (design) |
| Hole pitch                       | $200 \, \mu$m (design) |
| Resistance between electrodes    | $6 \, \text{G}\Omega \, @ \, 300 \, \text{V}$ |
| Cost                             | $\sim 1000 \, \text{Euro}$ |

2.3. Fabrication accuracy

The accuracy of the fabrication process has been studied by measurements of the hole diameter and hole pitch by optical methods and the insulator thickness measured mechanically. We scanned the hole diameter and hole pitch in the effective area by analyzing microscope images. The OpenCV library was used to fit the ellipses to the holes on micrographs, and then obtained the diameter and pitch. The thickness was measured using a Nikon Digimicro MFC-101 digital height gauge with a measurement attachment in an R1.2 shape. Figure 3 (a) and (b) show distribution maps of the hole diameter and hole pitch, respectively. The distribution map of the insulator thickness without electrodes is shown in figure 3 (c). The average values of the hole diameter, pitch, and thickness are $101.5 \pm 3.2 \, \mu$m, $198.6 \pm 5.1 \, \mu$m, and $112.6 \pm 2.2 \, \mu$m, respectively. Compared with the designed values shown in table 3, the hole diameter and pitch are within an error of 3%. Furthermore, the uniformity of insulator thickness can be controlled within an error of approximately 2%. The average value of thickness is not equal to the design value because the LTCC is decreased by approximately 10% during the sintering process. The gain uniformity and electron collection efficiency depend on these parameters[8]. The uniformity in the thickness clearly affects the gain variation. Because the gain is an exponential function of the electric field in the holes, a small variation in the thickness causes a large change in the

Figure 3. Distributions of (a) hole diameter, (b) hole pitch, and (c) insulator thickness without gold electrodes. The measured values in (a) and (b) are averaged over $10 \times 10 \, \text{mm}^2$ areas. The measurements reported in (c) are taken with 10 mm pitch.
gain at the same applied voltage between electrodes.

3. Experimental setup
Figure 4 shows a schematic view of the experimental setup for the LTCC-GEM evaluation test. The setup consists of a drift electrode, a $100 \times 100 \text{mm}^2$ LTCC-GEM, and a readout pad. The gap between the drift electrode and LTCC-GEM was 5.5 mm, and that between the LTCC-GEM and readout pad was 1.0 mm. A high voltage was applied to the drift plane and LTCC-GEM electrodes through a 10 MΩ resistor chain and a protection resistor of 2.2 MΩ. The applied electric field in the drift region ($E_d$) was 1.5 kV cm$^{-1}$, whereas that in the induction region ($E_i$) was 6–7.3 kV cm$^{-1}$. An Ar:CO$_2 = 70:30$ gas mixture was flushed through the chamber. The temperature, humidity, and pressure of the gas were monitored during the experiment. Uncollimated X-rays from a $^{55}$Fe source entered the chamber from the top through a thin mylar window. The signals from the readout pads were preamplified and shaped by an Amptek A225 module and, then, readout with a Multi Channel Analyzer (MCA) Kromek K102, PC controlled. A calibration of each MCA channel was obtained by injecting a square wave from an Agilent 33250A function generator into the A225 preamplifier through a 2 pF capacitor. The discharge events were identified if the signal height was significantly larger than that of an X-ray from $^{55}$Fe. The number of discharges was recorded using an ORTEC 996 counter.

4. Results
4.1. Gain curve
A typical ADC spectrum obtained using the readout pad with a 5.9 keV X-ray at $\Delta V_{GEM}$ of 680 V is shown in figure 5. The average count rate was 300 counts sec$^{-1}$. The induced charge ($Q_{\text{mean}}$) and the energy resolution were obtained by a Gaussian fit of the main peak. The energy resolution (FWHM) of the main peak was approximately 28%, although the ideal energy resolution is approximately 20%. We presume that the difference of energy resolution between
Figure 5. ADC spectrum of 5.9 keV X-rays from $^{55}$Fe source at $\Delta V_{\text{GEM}}$ of 680 V.

Our result and the ideal depends on the non-uniformity of the insulator thickness of LTCC-GEM according to figure 3 (c). The effective gain ($G_{\text{eff}}$) of LTCC-GEM is given by

$$G_{\text{eff}} = \frac{Q_{\text{mean}}}{e \cdot n_e}$$

where $e$ is the electron charge of $1.602 \times 10^{-19}$ C and $n_e$ is the total number of electron-ion pairs produced by an incident X-ray. The typical value of $n_e$ is 212 for 5.9 keV X-rays in the Ar and CO$_2$ (70%:30%) gas mixture [9]. Figure 6 shows the gain curve of a single layer of an LTCC-GEM and that of an LCP-GEM. The maximum gain of the LTCC-GEM, where the signals of $^{55}$Fe X-rays were not buried under the discharge signals, was 3,500 at $\Delta V_{\text{GEM}} = 730$ V. The result was one-fifth of the maximum gain of the 100-μm-thick LCP-GEM [5].

4.2. Discharge tolerance

In this study, a threshold voltage of 3 V was set to distinguish the discharge events from normal X-ray events from $^{55}$Fe which typically have a voltage of a few 100 mV. Figure 7 shows the effective gain of LTCC-GEM in Ar and CO$_2$ gas mixture at 1 atm as a function of $\Delta V_{\text{GEM}}$. 

![Figure 6. Effective gain of LTCC-GEM in Ar and CO$_2$ gas mixture at 1 atm as a function of $\Delta V_{\text{GEM}}$.](image-url)
discharge rate as a function of $\Delta V_{\text{GEM}}$. The discharge events were observed at above 600 V, and the rate drastically increased at above 700 V. At 730 V, the total number of discharges exceeded 20,000 events. Nevertheless, the LTCC-GEM is still properly working after this test. To reduce the dead time by discharges, some improvement is needed for the next production of the LTCC-GEM.

4.3. Gain stability for half day
Gain stability was evaluated at $dV_{\text{GEM}}=680$ V for 14 hours. Figure 8 shows the gain evolution by measurements repeated every 5 minutes. To compensate for gain variation due to changes in temperature and atmospheric pressure, the following equation was employed [5],

$$G_{\text{eff.}}^{\text{corr.}} = \frac{G_{\text{eff.}}}{\exp \left(C \times \left( \frac{T}{P} - \frac{300}{760} \right) \right)}, \tag{2}$$

Figure 7. Discharge rate as a function of $\Delta V_{\text{GEM}}$.

Figure 8. Gain stability for 14 hours at $\Delta V_{\text{GEM}}=680$ V. The data was corrected by measured values of $P$ and $T$. 
where $T$ and $P$ are the measured temperature and pressure, respectively. The constant $C$ is set at 43.5 Torr K$^{-1}$, a value obtained from the experimental data. The residual fluctuation of the effective gain was within 3%.

5. Summary
We have selected LTCC as GEM insulator material for a breakdown-free GEM. In this study, we have developed $100 \times 100 \text{ mm}^2$ LTCC-GEM and measured its gain properties. A prominent feature of the LTCC-GEM fabrication is the punching of a hole using a needle. This mechanical punching procedure is a simple and reliable method, achieving good accuracy in terms of hole diameter and pitch. The effective gain of the LTCC-GEM reached approximately 3,500 in Ar and CO$_2$ (70%:30%) gas mixture at 1 atm pressure at $\Delta V_{\text{GEM}}=730$ V between LTCC-GEM electrodes. Even at the highest operation voltage of 730 V, the LTCC-GEM avoided breakdown despite more than 20,000 discharges. We presume that the metallic residual in the holes caused by the punch process is probably a source of the discharges. The gain variation was also measured to be less than 3% during a 14-hours operation. Thus, we confirm experimentally the robustness of the LTCC-GEM against multiple discharges.

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