Ion Feedback Effect in the Multi GEM Structure

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The feedback of positive ions in a gas electron multiplier (GEM) has to be suppressed to reduce the photocathode degradation in GEM photomultipliers and to prevent the field distortion in a time projection chamber (TPC). The ion feedback dependency on the drift electric field, the transfer field, the asymmetry in the voltages across the GEM, and the effective gain was carefully measured in various gases. The ion feedback is sensitive to the drift field and the effective gain. A model prediction of the ion feedback in a double GEM structure was compared with the measurement. Our systematic study of the ion feedback effect can lead to progress in gas detectors with GEMs.

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I. INTRODUCTION

A new concept for a gas avalanche detector was introduced by Sauli [1] with a gas electron multiplier (GEM). The considerable progress that has been made is motivated by the growing interest in the applications of the GEM. The GEM is superior to other gas detectors because of its high counting rate, excellent spatial resolution, good imaging capability, operability in a magnetic field, large sensitive area, flexible geometry, and low cost [2]. In Korea, GEMs are coupled with multi wire proportional chambers (MWPC) and microstrip gas chambers (MSGC), and the charge sharing and electron transfer process were examined [3,4].

GEM end-cap detectors for the time projection chamber (TPC) were investigated by several groups such as the TESLA collaboration [5]. One of the important features in such an application is the strong suppression of feedback of positive ions, which are generated from the avalanche. Ion feedback in the TPC can cause serious problems in high-rate and high-multiplicity devices. Another interesting application of a GEM is the GEM-based photo-multipliers. The broader use of gas photon detectors, especially in commercial systems, has been hindered by the necessity for permanent gas flushing. Sealed gas detectors usually age very fast with standard gas mixtures, but operation with a noble gas can prevent the problem. However, the gain for a noble-gas-filled detector is usually very low due to photon- and ion-mediated secondary processes [6]. Since the electron avalanche in a GEM is confined to holes, a GEM can be operated with a high gain in a pure noble gas [7]. The GEM photomultiplier is being intensively investigated at present [2]; however, the ion feedback must be reduced if photocathode degradation from ion impact is to be prevented.

The ion feedback was measured previously in single and multiple GEM structures [8,9]. One of the interesting features in the previous studies was that the ion feedback ratio (the ratio of the cathode-to-anode currents) was independent of the gas and the pressure for a given gain even though the applied voltages across the GEM under various gas conditions were not the same. That means the charged particle diffusion, which is a function of the pressure, the gas, and the electric field, does not affect the ion feedback. However, only a few kinds of gas mixtures were used in the previous experiment [8], so it is necessary to confirm the effect of the gas on the ion feedback. Also, it would be helpful for the development of a gas detector with GEM to study the ion feedback effect systematically.

In our experiment, the ion-feedback effect in a multi-GEM structure was studied extensively for various gas conditions. We studied it in a simplified condition, where a double GEM structure was employed and the anode signal was recorded directly through the bottom of the second GEM. This helps in understanding the ion-feedback phenomenon with only a small number of parameters. An ion-feedback model was made for our GEM structure. The effects of the drift field, the asymmetry of the voltage applied across the GEM, and the gain on the ion feedback can be explained with the charge transfer parameters of a single GEM.

II. EXPERIMENTAL PROCEDURES

The experimental setup was similar to that used in Ref. 3 and 4. Two GEM foils(50-µm-thick Kapton, 60-
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μm hole diameter on the metal side, and 100-μm hole pitch), with a 10 × 10 cm² active area each were mounted in a cascade inside a stainless-steel chamber. The GEM foils were fabricated at CERN. The experimental setup is shown in Fig. 1. The drift plate, which was made of aluminized mylor foil, was placed above GEM1. The drift gap between the drift plate and GEM1 and the transfer gap between GEM1 and GEM2 were 3 mm and 2 mm, respectively. X-rays (5.9 keV) from ⁵⁵Fe were beamed through a 0.5-mm-thick Be window, and the anode signal was measured directly through the bottom electrode of GEM2. The anode and the cathode signals were measured in a current mode. Each electrode (V_{G1T}, V_{G1B}, V_{G2T}, or V_{Drift}) was connected to an individual channel of the power supply, allowing a flexible setting of the electric fields in the two gaps and of the voltages across the GEM surfaces.

Highly pure Ar and CO₂ or N₂ (99.999 %) flowed through the chamber, and the gas mixing ratio was changed to determine the influence of the gas on the ion feedback. The effective gain of the detector was defined as the anode current divided by the primary ionization current, which was measured when the drift gap was operated in an ionization mode. The ion-feedback ratio was defined as the cathode current divided by the anode current.

Figure 2 shows the voltage-effective gain characteristics for various gas mixtures, where the lines are exponential functions of the voltage across the GEM (∆V_{GEM}). The drift and the transfer electric fields (E_D, and E_T) were fixed at 2 kV/cm, and 3 kV/cm, respectively. We biased the same ∆V_{GEM} on GEM1 and GEM2. The effective gains follow an exponential behavior up to high values of ∆V_{GEM}.

The effects of the effective gain and the gas mixing ratio of various gases on the ion-feedback ratio are shown in Fig. 3. The ion-feedback ratio decreased with the effective gain and was almost independent of the gas mixing ratio, which was consistent with previous results [8]. This means the diffusion of charged particles does not affect the ion feedback.

Figure 4 shows the effect of E_D on the ion feedback. The same voltages were biased across GEM1 and GEM2. E_T and ∆V_{GEMS} were kept constant. E_T = 3 kV/cm, and ∆V_{GEM} in each gas mixture was set to make the effective gain 10³. The ion-feedback ratio increased almost linearly with E_D. The effective gain was not sensitive to E_D.

Figure 5 shows the effect of E_T for various gas mixture. The voltage across GEM1 was also equal to the voltage across GEM2. The data were obtained with a fixed E_D (2 kV/cm) and ∆V_{GEM}. The effective gain increased with E_T, and the ion-feedback ratio decreased slowly with E_T in the high-E_T region.

The effect of the asymmetry of ∆V_{GEM} on the ion-feedback ratio was also measured and is shown in Fig. 6. Only the voltages across GEM1 and GEM2 were changed. We increased ∆V_{GEM} on GEM1 and decreased ∆V_{GEM} on GEM2 to keep the same effective gain of 10³. As the voltage across GEM1 became higher, the ion-feedback ratio increased.
III. ION FEEDBACK MODEL FOR THE DOUBLE GEM STRUCTURE

The physics of a multi-GEM structure can be described with a few parameters [8], which are from the charge-transfer mechanism in single-GEM foil. In a single-GEM foil, the collection efficiency, gain, and extraction efficiency will determine the charge transfer. The collection efficiency is the probability of a charged particle in the drift region being transferred into a GEM hole. The gain is the factor by which the number of electrons is multiplied by the gas avalanche inside the GEM hole. The extraction efficiency is the fraction of charged particles extracted from the GEM holes into the transfer volume.

Previous measurements and numerical simulations of the charge transfer in a single GEM were performed to understand the charge-transfer parameters [10]. The gain is determined by the mean electric field inside the GEM hole, $E_{\text{hole}}$. That is, $E_{\text{hole}}$ of GEM1 in Fig. 1 is a linear combination of $E_D$, $E_T$, and $\Delta V_{\text{GEM}}$:

$$E_{\text{hole}} = a\Delta V_{\text{GEM}} + b(E_D + E_T),$$  \hspace{1cm} (1)

where $a$ and $b$ depend on the GEM geometry. The collection efficiency is a function of the field ratio $E_D/E_{\text{hole}}$. The collection efficiency decreases in a high drift field due to the defocusing of field lines above the GEM. The collection efficiency of electrons and ions shows a sharp decrease when $E_D/E_{\text{hole}}$ approaches zero due to the recombination of charge pairs at very low drift velocities. The extraction efficiency is a function of $E_T/E_{\text{hole}}$. The extraction efficiency increases with $E_T/E_{\text{hole}}$ because more charged particle can be extracted from the lower side of the GEM foil at larger $E_T/E_{\text{hole}}$.

Our measurement of the ion-feedback effect in the multi GEM can be explained using the charge-transfer parameters for a single GEM. Let us say that the electron collection efficiency into the GEM hole is $c_i$, the real gain of a GEM is $g_i$, the electron extraction efficiency from the GEM hole is $e_i$, the ion extraction efficiency from GEM hole is $f_i$, and the ion collection efficiency into GEM hole is $i_i$. Then the effective gain, $G$, in our double-GEM structure is

$$G = c_1 g_1 c_2 g_2.$$  \hspace{1cm} (2)

The ion-feedback current to the cathode, $I_D$, is

$$I_D = c_1 g_1 f_1 + c_1 g_1 c_2 g_2 f_2 i_1 f_1.$$  \hspace{1cm} (3)

The first term is from the ions generated in GEM1, and the second term is from the ions generated in GEM2. Then, the ion-feedback ratio ($I_D/G$) can be expressed as

$$I_D/G = f_1 (i_1 f_2 + \frac{1}{c_1 c_2 g_2}) = f_1 (i_1 f_2 + \frac{c_1 g_1}{G}).$$  \hspace{1cm} (4)

Since $G$ is almost independent of $E_D$ in our measurement, we assumed that $b$ of Eq. (1) was negligible. Then, $E_D$ and $E_T$ do not affect $g_i$. The effect of $E_D$ on the ion-feedback ratio can be understood from Eq. (4). $E_D$ cause $f_1$ and $f_2$ increase with $E_D$ [10], which is consistent with Fig. 4.
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Fig. 7. Phenomenological formula for the dependency of the effective gain on the ion feedback was fitted to the measurement. The lines are the fitting results, and the circles are the data.

The effect of the asymmetry in $\Delta V_{GEM}$ on the ion-feedback ratio follows from the model. Equation 4 predicts that if the effective gain ($G$) remains the same, the ion-feedback ratio will increase with $g_1$, which is consistent with Fig. 6. The discrepancies in the ion-feedback ratio with respect to the gas mixture in Fig. 6 come from the fact that the values of $g_1$ are different in various gas mixtures even if the same $\Delta V_{GEM1}$ is applied, which is shown in Fig. 2.

The dependency of the effective gain on the ion-feedback ratio is also from Eq. (4). $\Delta V_{GEM}$ can affect all the parameters in Eq. (4). However, the effect of $\Delta V_{GEM}$ on $g_1$ is much larger than the effect on the other parameters. Therefore, one can take all parameters to be constant, except $g_1$, if only $\Delta V_{GEM}$ is varied. Since $g_1$ is equal to $g_2$ in our measurement, we get

$$I_D/G = a + \frac{b}{\sqrt{G}},$$

(5)

where $a$ is $f_1 i_1 f_2$ and $b$ is $f_1 \sqrt{e_{1G} e_{2G}}$. We can make a two-parameter fit to the measurement, which is shown in Fig. 7. The lines are from a least-squares fitting, and the circles are from the measurements. The model can explain the effective gain dependency of the ion-feedback ratio, except in the higher gain region. That is, the measured data are smaller than the model prediction. As pointed out by Bondar [8], that could be related to the avalanche extension effect in the GEM. Since positive ions are produced outside the GEM hole at higher gain, they have more chance of drifting to the bottom of the GEM rather than entering the hole.

**IV. CONCLUSION**

We studied the ion-feedback effect in a multi-GEM structure. The dependencies of the ion-feedback ratio on $E_D$, $E_T$, the effective gain, the gas mixture, and the asymmetry of $\Delta V_{GEM}$ were measured extensively. The ion feedback is very sensitive to $E_D$ and to the effective gain; the ion-feedback ratio increases linearly with $E_D$, and decreases with the effective gain. $E_T$ has a minor effect on the ion feedback, which decreases in the higher-$E_T$ region. When $\Delta V_{GEM1}$ becomes higher than $\Delta V_{GEM2}$ for the same $G$, the ion feedback ratio becomes smaller. We made a model prediction for our measurement, and the ion-feedback ratio could be explained by the collection efficiency, the gain, and the extraction efficiency in a single GEM. The effective gain dependency was well reproduced by the model prediction, except at higher gains, and could be understood by using an avalanche extension. Also, the model could explain the effect of the asymmetry of $\Delta V_{GEM}$ on the ion feedback. With our study, we could predict the ion-feedback effect in a multi-GEM structure from the charge-transfer parameters in a single GEM, which could be helpful for further research on GEM photomultipliers and the TPC.

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