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High-tolerance nickel metalized glass gas electron multiplier: development and performance evaluation

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ABSTRACT: Micro-patterned gas detectors (MPGDs) are an important type of gaseous detector that can amplify and detect a small amount of electric charge generated by the interaction between radiation and gas. These detectors have high gain and high spatial resolution, making them useful in various applications ranging from high energy physics to medical instrumentation. However, one of the most widely used MPGDs, Gaseous Electron Multipliers (GEMs), may often experiences electrical discharges due to excessive electric field in the small space, which reduces their durability. To address this issue, we previously have developed a new type of GEM that uses glass as the insulator instead of conventional materials. Our glass GEM demonstrated excellent gas gain and energy resolution characteristics. In this work, we used nickel as the electrode, which has a higher melting point than copper and showed higher durability against arc discharges. Moreover, the nickel glass GEM performed comparably to conventional Cu-based glass GEMs in evaluation using radiation isotopes. Our findings suggest that our new glass GEM with nickel electrodes is a promising solution to the durability problem of conventional GEMs. This could lead to improvements in the performance and longevity of MPGDs, which could have significant implications for various applications in the fields of physics, engineering, and medicine.

KEYWORDS: Detector design and construction technologies and materials; Gaseous detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Electron multipliers (gas)

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Contents

1 Introduction

Micro-pattern gas detectors (MPGDs) are widely used in various applications such as high-energy physics experiments [1–3], neutron detectors [4, 5], space dosimetry [6], soft X-ray imaging [7–9], directional dark matter searches [10], observation of the Migdal effect in neutron scattering with application to direct dark matter searches [11], hadron therapy dosimetry [12, 13], and others [14], due to their good spatial resolution, suitability for measuring high-LET radiation, ability in particle tracking, relatively low cost for economically instrumenting large detection areas and low sensitivity to high-energy photons. MPGDs create a high electric field between a small gap of electrodes, which induces an electron avalanche and amplifies the signal. Various forms of MPGDs have been developed, including microstrip gas counter (MSGC) [15], Capillary Plate (CP) [16], Gas Electron Multiplier (GEM) [17], Micro Pixel Chamber (μ-pic) [18], and MICROMEGAS [19], which are operated at typical gas gain values of $10^2 \sim 10^5$, depending on the application. However, MPGDs are susceptible to discharges and instabilities which may occur spontaneously or may be triggered by cosmic rays or other factors [20]. Despite the various applications of MPGDs, their stability and robustness remain crucial performance indicators in all fields. In any application, MPGD should not be damaged by discharges.

To address this challenge, we have developed the glass GEM with high gas gain, a self-supporting structure, and good high-count-rate characteristics [21, 22]. However, while the glass substrate may be more robust against electrical discharges compared other materials like polyimide or FR4 used in GEMs or THGEMs, conventional glass GEMs were made of copper electrodes which could be damaged in severe discharges occurring within the hole (see figure 1). The heat generated by electrical discharges may melt and damage the electrodes while depositing Cu inside the holes thus causing conduction between the electrodes of glass GEMs.

In this study, we have addressed this issue by developing a glass GEM with nickel electrodes, which have a higher melting point than copper (Ni: 1,455°C, Cu: 1,085°C) [23]. We have evaluated the characteristics of this new glass GEM and demonstrated improved robustness against electrical discharges. Our findings suggest that using nickel electrodes in glass GEMs can significantly improve their performance in various applications.

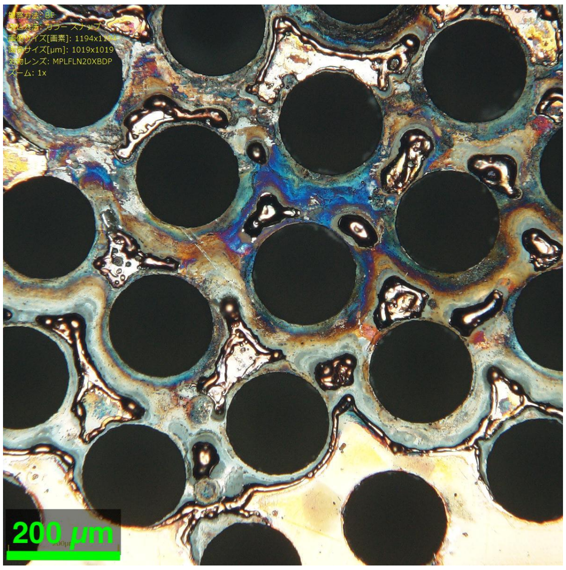

Figure 1. Micrograph of a glass GEM electrode after destructive discharges. The heat generated by the discharges caused melting and damage to the copper electrode, leading to conduction between the electrodes and decreased performance. This highlights the need for durable electrodes in MPGDs to ensure stable and reliable performance.

2 Fabrication of glass GEM with nickel electrodes

To ensure sufficient electrode thickness for optimal performance of the glass GEM, we conducted empirical studies and found that electrodes with a thickness of approximately 1 to 3 μm exhibit excellent characteristics. In addition to sputtering, we employed a plating method for depositing GEM electrodes. As we sought an electrode material with a high melting point to replace copper, we focused on metals that could be sputtered and plated. After careful consideration, we selected nickel as our electrode material. Nickel has a higher melting point than copper and is expected to withstand the localized heat generated by electrical discharges more effectively (Ni: 1,455°C, Cu: 1,085°C).

The fabrication process is illustrated in figure 2. While the basic fabrication process remains, the same, nickel is used instead of copper plating for electrode deposition [22]. Figure 3 shows the resulting glass GEM substrate, which features a sensitive area of 100 mm × 100 mm, holes with a diameter of 180 μm, a hole pitch of 280 μm, and a substrate thickness of 550 μm. Figure 4 provides a magnified view of the holes. Both the glass GEM with copper electrodes and the glass GEM with nickel electrodes succeeded in forming smooth electrodes with minimal irregularities.

3 Gas gain and energy resolution measurements

To compare the performance of the newly fabricated nickel electrode glass GEM with our previously developed Cu electrode glass GEM, we evaluated them using a ^{55}Fe X-ray source. Each glass GEM

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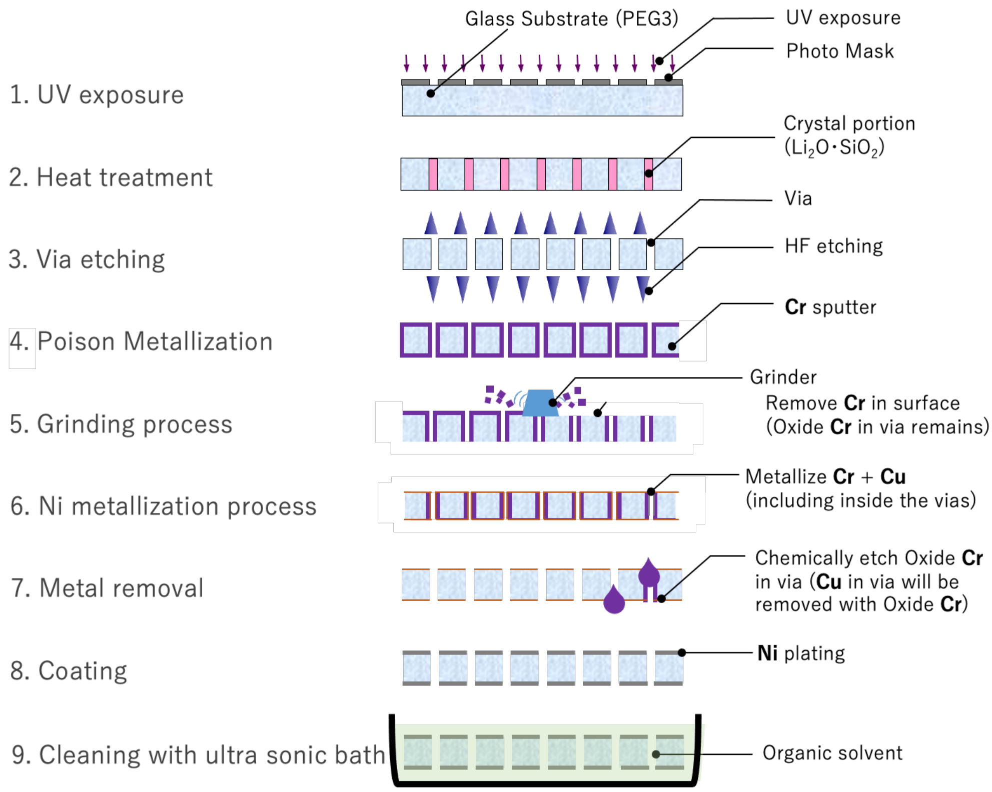

Figure 2. Multi-step process for fabricating durable and high-performance glass GEMs with nickel electrodes.

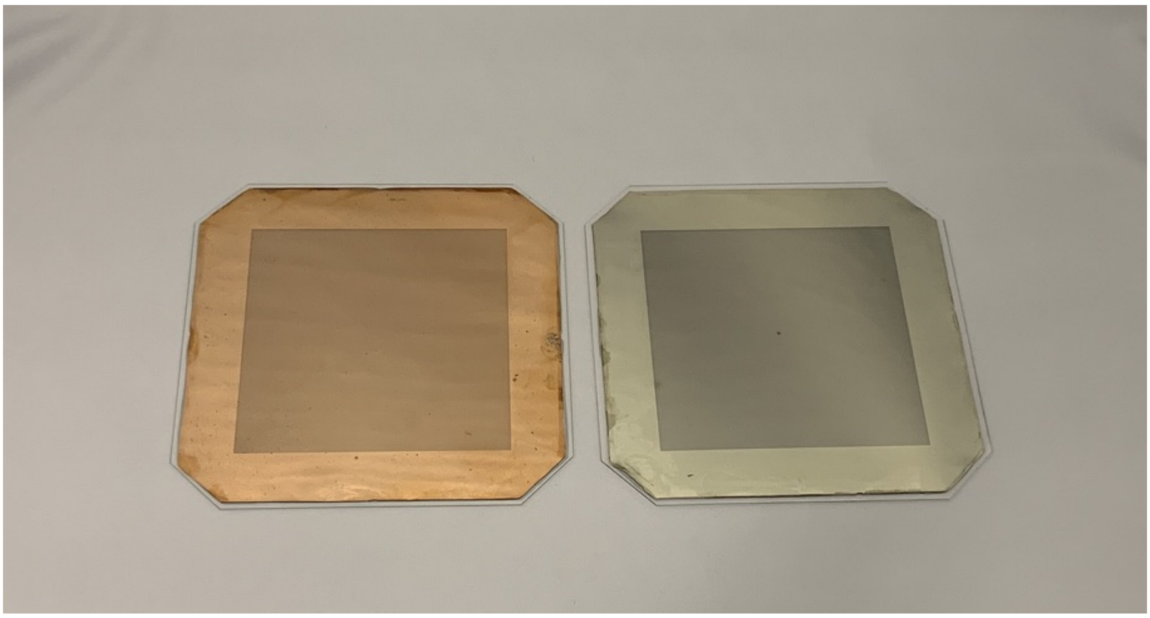

Figure 3. Glass GEM substrates with copper (left) and nickel (right) electrodes. The sensitive area of each substrate is 100 mm × 100 mm, with a hole diameter of 180 µm and a pitch of 280 µm. The thickness of the substrate is 550 µm. Smooth and uniform electrode surfaces are achieved for both electrode materials.

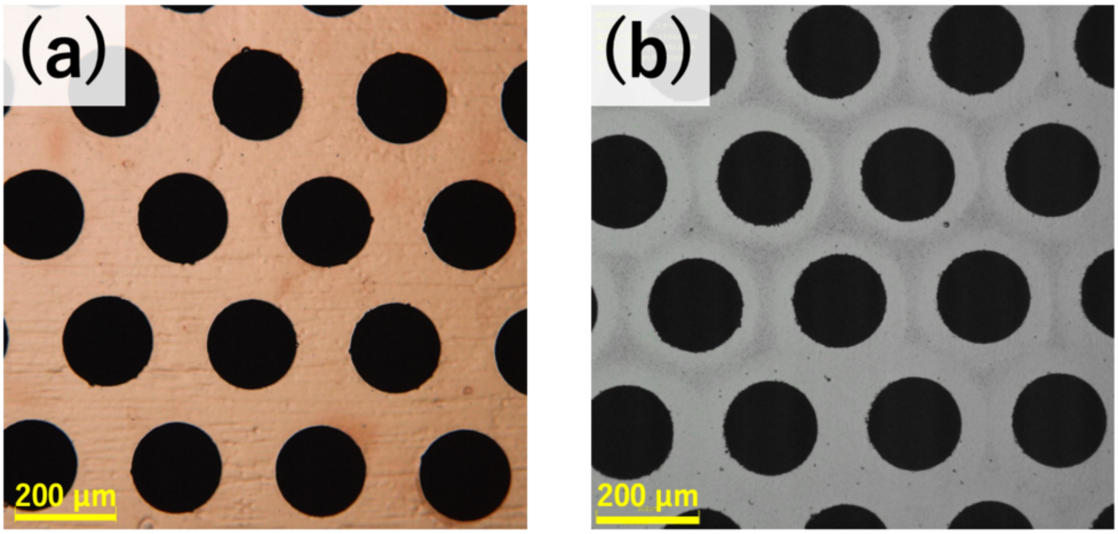

Figure 4. Micrographs of the sensitive area of glass GEM substrates with copper (a) and nickel (b) electrodes. The electrodes have a thickness of about 2 µm and were fabricated using the processes shown in figure 2. The magnified view of the holes (insets) shows the smooth and regular shape of the electrodes in both substrates, demonstrating the successful deposition of copper and nickel electrodes using our fabrication methods.

was mounted in an aluminum gas chamber and tested with gas flow [22]. A readout electrode was placed below the glass GEM in the gas chamber. We tested two types of gas mixtures (Ar/CH_4(90:10) and Ne/CF_4(90:10)) in this study. Pulses from the readout electrode were recorded using a charge-sensitive amplifier, shaping amplifier, and multi-channel analyser. The drift gap was 5.0 mm, and the gap between the glass GEM's bottom side and the readout electrode was 2.0 mm. The electric field in the drift region was 1.0 kV/cm, while it was 5.0 kV/cm and 2.0 kV/cm for the readout region of Ar/CH_4 and Ne/CF_4, respectively. We utilized an Ortec 556 and a REPIC RPH-034 (2 channels) power supply to independently administer high voltage to both the glass GEM sides and the readout electrode. Given that the resistivity of the glass substrate changes over time, we opted to apply the high voltage directly, bypassing the use of a voltage divider. Typically, a 10 cm square-sized glass GEM exhibits a resistance of a few 100s MΩ, which is comparatively lower than that of foil GEMs or FR4 THGEMs.

We measured effective gain using a 5.9 keV X-ray source (^{55}Fe). Figure 5 shows a typical ^{55}Fe energy spectrum measured using the nickel electrode glass GEM with Ar/CH_4 gas operated at a gas gain of approximately 10,000. The detected X-ray exhibited a count rate of 1.2 k counts/sec. The gain curves for both types of glass GEM with different operating gases are shown in figure 6. The highest effective-gain value, 6×10^4, was achieved using Ne/CF_4 gas. Although the Ni electrode glass GEM exhibited a slightly lower gas gain than the Cu electrode, no significant difference in energy resolution was observed between the two types of electrodes.

4 Electrical discharge evaluation

To assess the durability of the electrode materials, we conducted an electrical discharge evaluation using the setup depicted in figure 7. A continuous discharge was artificially generated in an air environment by applying a voltage of 2250 V to the tungsten needle, resulting in a current of 900 µA.

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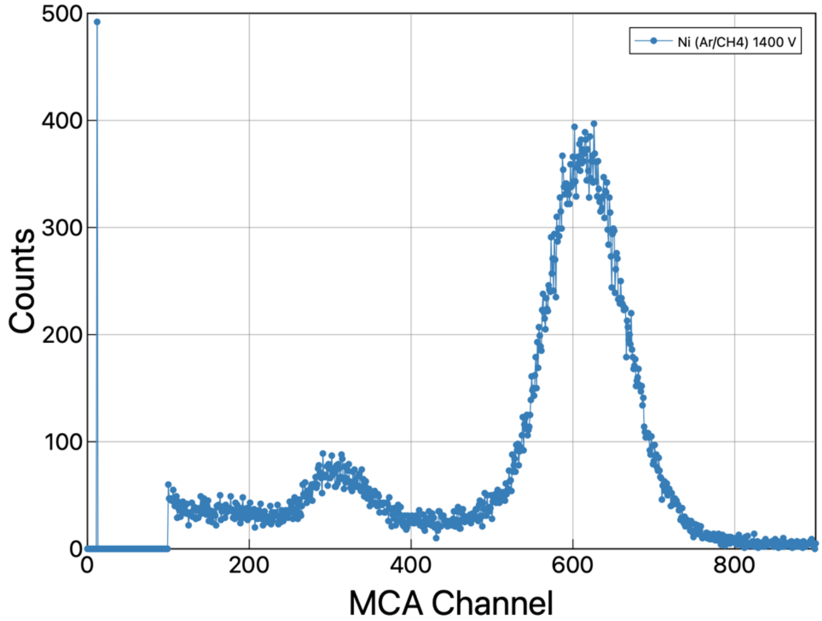

Figure 5. Energy spectrum recorded with nickel electrode glass GEM displaying an energy resolution of 16% (FWHM) for 5.9 keV X-rays.

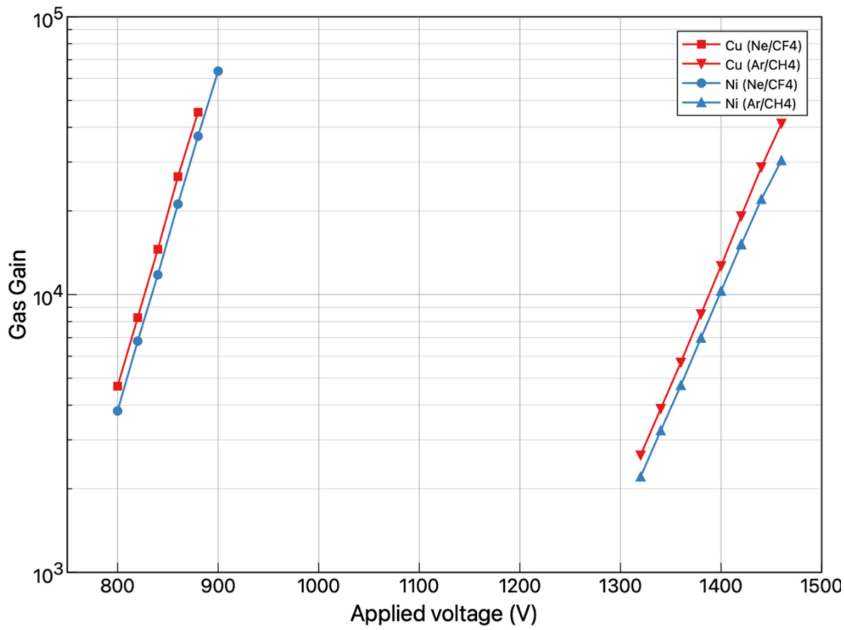

Figure 6. Gas gain curves of glass GEM measured with 5.9-keV X-rays using various gases. 1 bar Ar/CH_4(90:10) and 1 bar Ne/CF_4(90:10) are used in each measurement with a gas-flow mode. The maximum gain reached more than 6×10^4 with Ne/CF_4 gas.

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This discharge generated heat, which was used to evaluate the performance of the glass GEM electrodes. The electrodes were observed under a microscope after exposure to the discharge for varying durations, namely 10 seconds, 1 minute, 3 minutes, and 5 minutes. The surface of the electrode was observed under an optical microscope after the exposures, as shown in figure 8.

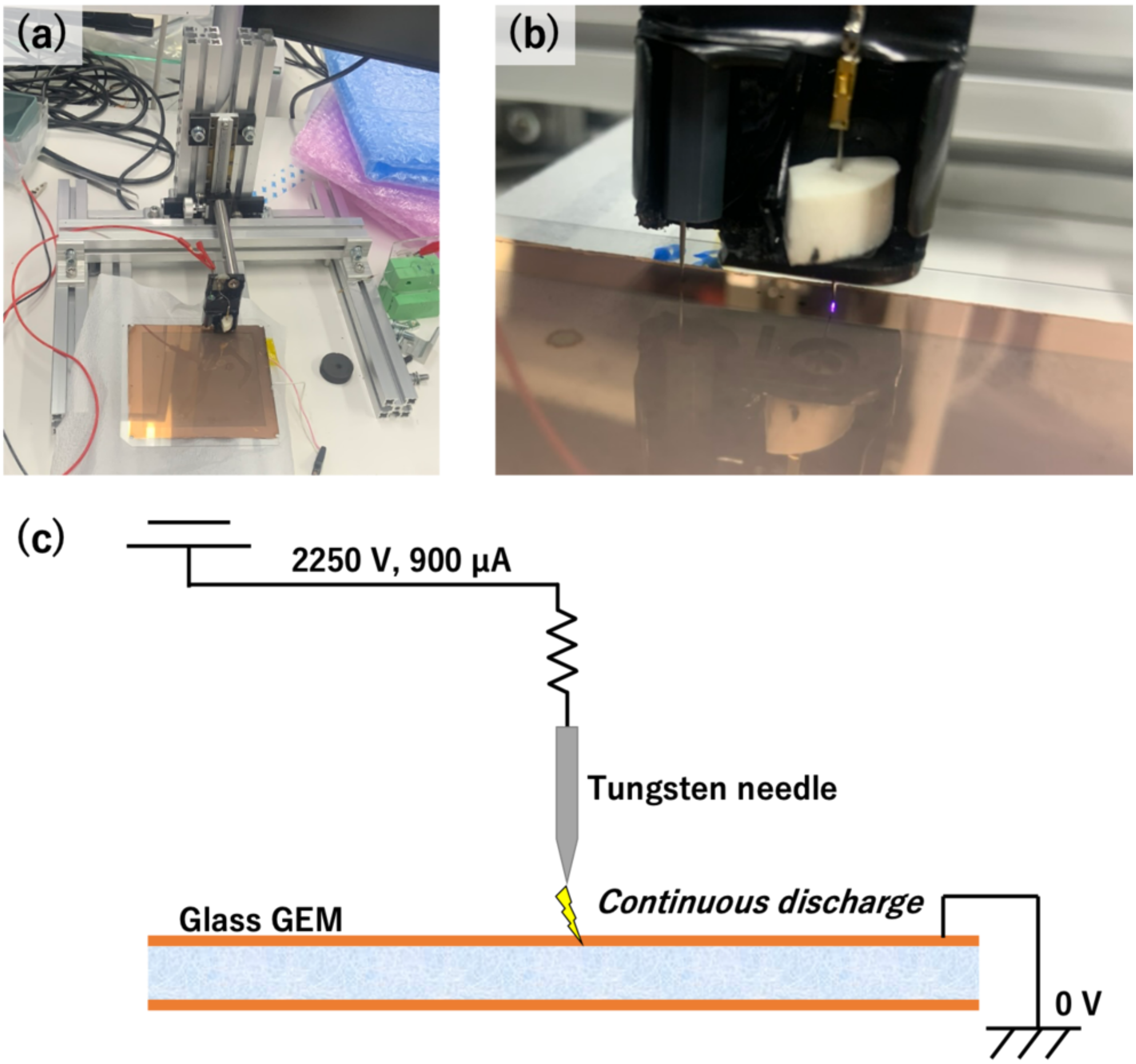

Figure 7. (a) Experimental setup for assessing the durability of the glass GEM electrodes under electrical discharges. A tungsten needle is positioned on the glass GEM substrate to generate a continuous discharge at 900 μA and 2250 V. (b) Close-up view of the electrical discharge generated by the tungsten needle. (c) The electrical discharge evaluation setup's schematic representation shows the components and their arrangement.

5 Discussion

One of the main challenges in using MPGDs is electrode damage caused by electrical discharge. In this study, we explored the use of nickel electrodes, which have a higher melting point than conventional copper electrodes, to address this issue. Our ^{55}Fe evaluation demonstrated that the nickel electrode

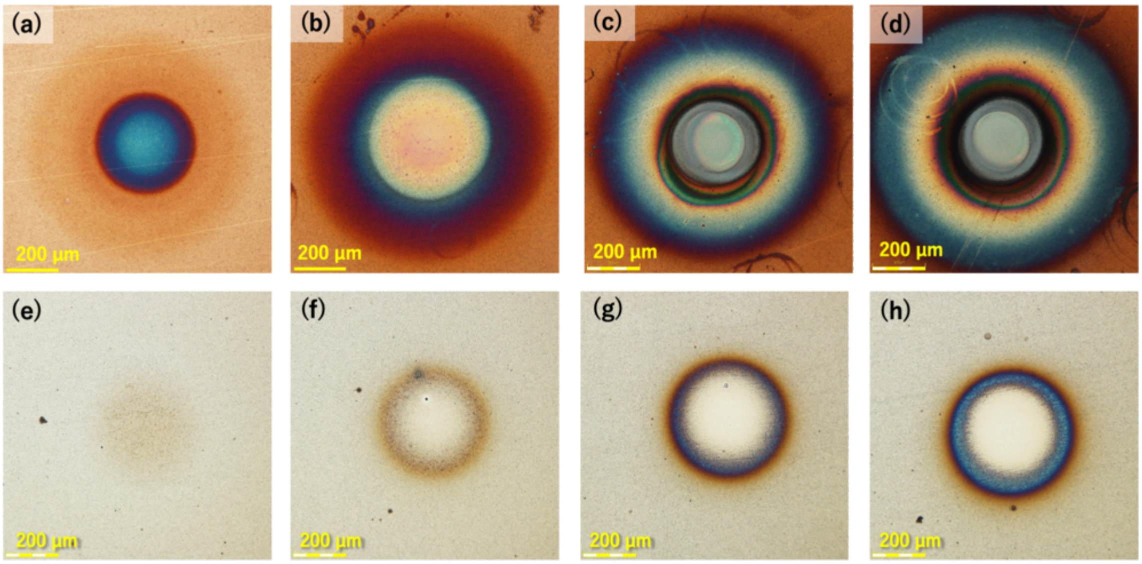

Figure 8. Micrographs of Cu and Ni glass GEM electrodes after exposure to electrical discharges generated by the setup are shown in figure 7. The electrodes were exposed to discharges for different lengths of time: (a) Cu electrode exposed for 10 seconds, (b) Cu electrode exposed for 1 minute, (c) Cu electrode exposed for 3 minutes, (f) Cu electrode exposed for 5 minutes, (e) Ni electrode exposed for 10 seconds, (f) Ni electrode exposed for 1 minute, (g) Ni electrode exposed for 3 minutes, (h) Ni electrode exposed for 5 minutes. Comparison of the Cu and Ni electrodes after exposure to electrical discharges. After 3 minutes, the Cu electrode lost its conductivity, while the Ni electrode remained conductive even after 5 minutes. This showcases the Ni electrode's superior tolerance to electrical discharges. Conductivity was measured using a direct multimeter probe on the electrodes. In the figure, damage to the central portion of the electrode reveals the underlying glass. On the reverse side, the electrode remains visible. As detailed in figure 2, the electrode comprises two layers: an underlying Cr layer and a top Cu layer. The gray region in the image (c, d) represents the Cr layer.

had sufficient uniformity and achieved an energy resolution of 16–18% (FWHM), comparable to copper electrodes. Additionally, the gas gain of the nickel electrode was almost equivalent to that of copper electrodes, indicating no significant difference in the basic performance of the glass GEM.

Our tests to evaluate the electrode's durability to electrical discharges by continuous discharges showed that the nickel electrode had improved durability compared to conventional copper electrodes, as expected. This ability to withstand electrical discharges without breaking is particularly advantageous in many fields, such as medical applications, neutron detectors, and high-energy physics experiments.

Overall, the results of this study suggest that the use of nickel electrodes in MPGDs has the potential to improve the durability and reliability of these devices. Furthermore, the use of glass GEMs with nickel electrodes can be further developed and improved to meet the specific needs of various applications, making them a promising candidate for future research and development in the field.

6 Conclusion

In conclusion, this study demonstrated that using nickel electrodes in MPGDs can improve their durability to electrical discharges while maintaining their basic performance as GEMs. Using nickel

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electrodes can be particularly advantageous in applications where experimental conditions require a high dynamic range operation with heavily ionising particles producing a large primary ionisation frequently leading to damaging discharges due to reaching the Reather limit [24]. In addition, in the areas such as medical imaging or high-energy physics experiments, GEM's durability is critical.

However, further studies are needed to fully understand these electrodes' long-term durability and performance in more complex detector systems. Overall, this study provides a foundation for the development and optimisation of MPGDs using nickel electrodes, which has the potential to expand the range of applications for this promising technology.

Acknowledgments

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References

[1] ALICE TPC collaboration, *The upgrade of the ALICE TPC with GEMs and continuous readout*, 2021 *JINST* **16** P03022 [arXiv:2012.09518].

[2] D. Abbaneo et al., *An overview of the design, construction and performance of large area triple-GEM prototypes for future upgrades of the CMS forward muon system*, 2012 *JINST* **7** C05008.

[3] F. Sauli, *The gas electron multiplier (GEM): Operating principles and applications*, *Nucl. Instrum. Meth. A* **805** (2016) 2.

[4] J.D. Parker et al., *Neutron imaging detector based on the muPIC micro-pixel chamber*, *Nucl. Instrum. Meth. A* **697** (2013) 23 [arXiv:1209.5856].

[5] T. Fujiwara, K. Kino, N. Oshima and M. Furusaka, *Development of a Bragg-edge Neutron Transmission Imaging Detector Combined with Micro-structured Boron Cathode and Glass Gas Electron Multiplier*, *Sensors Mater.* **35** (2023) 537.

[6] Y. Kishimoto et al., *Basic performance of a position-sensitive tissue-equivalent proportional chamber (PS-TEPC)*, *Nucl. Instrum. Meth. A* **732** (2013) 591.

[7] T. Fujiwara et al., *Gas scintillation glass GEM detector for high-resolution X-ray imaging and CT*, *Nucl. Instrum. Meth. A* **850** (2017) 7.

[8] F.M. Brunbauer et al., *Radiation imaging with glass Micromegas*, *Nucl. Instrum. Meth. A* **955** (2020) 163320.

[9] F.M. Brunbauer et al., *Radiation imaging with optically read out GEM-based detectors*, 2018 *JINST* **13** T02006.

[10] G. Mazzitelli et al., *MPGD Optical Read Out for Directional Dark Matter Search*, in the proceedings of the *2018 IEEE Nuclear Science Symposium and Medical Imaging Conference*, Sydney, NSW, Australia, 10–17 November 2018, p. 1–4 [DOI:10.1109/NSSMIC.2018.8824617] [arXiv:1901.04192].

[11] H.M. Araújo et al., *The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter*, *Astropart. Phys.* **151** (2023) 102853 [arXiv:2207.08284].

2023 JINST 18 P10025

[12] E. Seravalli, *A scintillating GEM detector for 2D dose imaging in hadron therapy*, Delft University Press (2008).

[13] T. Fujiwara et al., *Development and characterization of optical readout well-type glass gas electron multiplier for dose imaging in clinical carbon beams*, *Phys. Med.* **82** (2021) 72.

[14] M. Titov and L. Ropelewski, *Micro-pattern gaseous detector technologies and RD51 Collaboration*, *Mod. Phys. Lett. A* **28** (2013) 1340022.

[15] A. Oed, *Position Sensitive Detector with Microstrip Anode for electron Multiplication with Gases*, *Nucl. Instrum. Meth. A* **263** (1988) 351.

[16] H. Sakurai, T. Tamura, S. Gunji and M. Noma, *A new type of proportional counter using a capillary plate*, *Nucl. Instrum. Meth. A* **374** (1996) 341.

[17] F. Sauli, *GEM: A new concept for electron amplification in gas detectors*, *Nucl. Instrum. Meth. A* **386** (1997) 531.

[18] D. Banfi, M. Delmastro and M. Fanti, *Cell response equalisation of the ATLAS electromagnetic calorimeter without the direct knowledge of the ionisation signals*, 2006 *JINST* **1** P08001.

[19] G. Charpak, J. Derre, Y. Giomataris and P. Rebourgeard, *MICROMEGAS, a multipurpose gaseous detector*, *Nucl. Instrum. Meth. A* **478** (2002) 26.

[20] G. Croci et al., *Discharge probability measurement of a Triple GEM detector irradiated with neutrons*, *Nucl. Instrum. Meth. A* **712** (2013) 108.

[21] H. Takahashi, Y. Mitsuya, T. Fujiwara and T. Fushie, *Development of a glass GEM*, *Nucl. Instrum. Meth. A* **724** (2013) 1.

[22] T. Fujiwara et al., *The performance of Glass GEM*, 2014 *JINST* **9** P11007.

[23] B. Ulukutlu et al., *New (TH)GEM coating materials characterized using spectroscopy methods*, *Nucl. Instrum. Meth. A* **1019** (2021) 165829 [`arXiv:2104.12191`].

[24] H. Raether, *Electron avalanches and breakdown in gases*, Butterworths (1964).

2023 JINST 18 P10025