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Two-dimensional Neutron Detector with GEM and its Applications

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Abstract

To improve material structure analysis using thermal (cold) neutrons at several pulsed neutron sources, we have developed a new gas detector for neutrons that employs a gas electron multiplier (GEM) as the detector. For neutron detection, both surfaces of a single GEM foil are coated with boron, and to increase efficiency, several GEM foils are stacked in a chamber. A prototype chamber was constructed with 10 cm × 10 cm GEM foils, and several beam tests were performed at a research reactor in Japan and at pulsed neutron sources (Hokkaido University and the Japan Proton Accelerator Research Complex). We achieved a detection efficiency of 30% for 0.22-nm thermal neutrons and a position resolution of ~0.5 mm. In addition, we demonstrate two applications.

Keywords: Gas electron multiplier (GEM); high-density electronics; high-speed data transfer; neutron beam monitor; energy-selective neutron radiography.

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1. Introduction

A gas electron multiplier (GEM) is a type of micro-pattern gas detector (MPGD), which was developed by F. Sauli about 10 years ago [1]. A GEM consists of a commercially available flexible printed-circuit foil with a 50-μm-thick polyimide having many small holes, as shown in Fig. 1. Copper layers of 5-μm thickness are coated on both sides. The diameter of each hole is 70 μm and many holes are distributed at 140-μm pitch. A high voltage is applied across the GEM foil to generate a large electric field in the holes. Gas multiplication occurs in the holes in a manner similar to that of the near sense wire of well-known gas wire chambers. Many small holes are distributed uniformly over the foil and each hole acts as a gas detector for radiation. Therefore, GEMs provide good counting capabilities and uniform two-dimensional performance. These features enable imaging capability, which is useful for various applications.

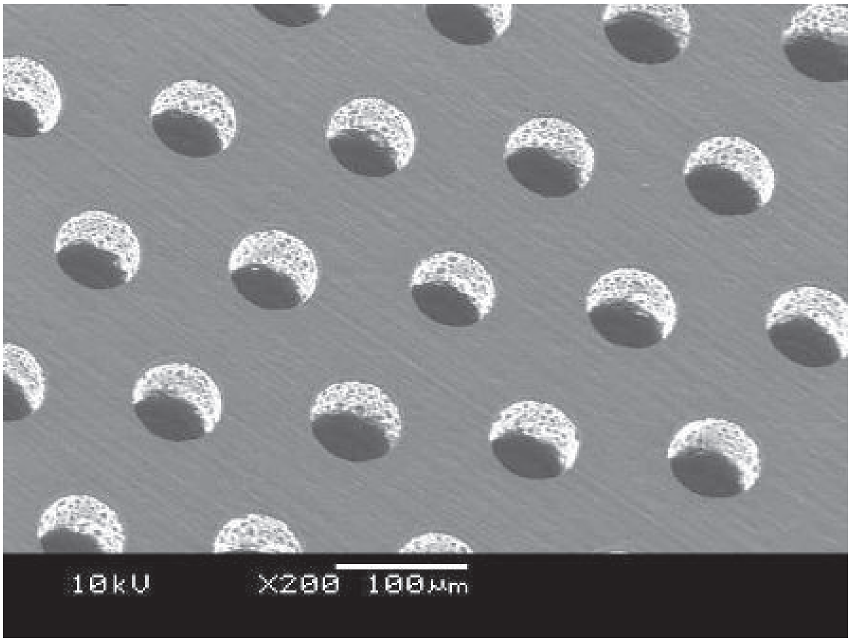

Fig. 1. Electron microscope image of a GEM foil.

A new gas detector for neutrons that employs GEM is being developed as a detector for material structure analysis using thermal (cold) neutrons from pulsed sources such as the Japan Proton Accelerator Research Complex (J-PARC). The two-dimensional position of the scattered neutrons must be measured to calculate the scattering angle. In addition, temporal information, which is essential in determining the neutron wavelength (i.e., energy), is determined by using a time-of-flight (ToF) method. To detect neutrons, a single GEM foil is coated on both sides with boron. Neutrons react within the boron layer and charged particles (an alpha particle and a lithium nucleus) are emitted, which can produce ionization electrons in the gas volume between the GEM foils, as shown in Fig. 2.

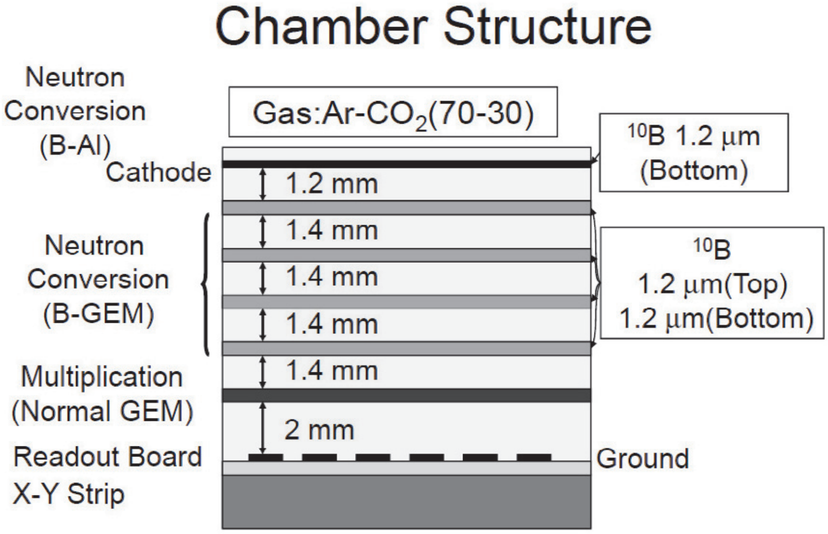

Fig. 2. Structure of prototype chamber.

The features of this detector are described below and are compared with a ^{3}He counter and a scintillation counter, which are commonly used at neutron facilities worldwide [1]. ^{3}He gas is not necessary for neutron detection, because neutrons react within the boron that is coated over the GEM foil [2]. Using this technique, it is easy to capture the two-dimensional readout pattern. The wire position (X) and the charge division method (Y) are used to obtain the two-dimensional position from the ^{3}He counter. In such cases, the X and Y coordinates are measured using different methods and resolutions that are not suitable for obtaining a uniform two-dimensional image [3]. Good position accuracy (1 mm) and high time resolution (10 ns) can be obtained using this detector. For example, a fine strip pitch (1 mm) can be obtained using the GEM chamber, which is much better than what is possible with the typical diameter of a ^{3}He counter (~1 cm). In addition, the typical time resolution of a ^{3}He counter is only 1 μs [4]. This detector is also insensitive to gamma rays; in contrast, scintillation counters that are normally used for neutron detection contain heavy materials, making them somewhat sensitive to gamma rays [5]. Finally, the GEM detector offers a high counting rate. The ^{3}He counter does not work in the high-counting regime of J-PARC.

Originally, this type of neutron detector was developed in Germany [2], but it has not yet been established for actual physics experiments. Therefore, we constructed a prototype chamber and performed several beam tests. In this paper, we describe the structure of the chamber and present the results of the beam tests.

2. Experiment

2.1. Prototype chamber

The prototype chamber (Fig. 2) was constructed to confirm the principles governing neutron detection. The chamber consists of one cathode plate, four boron-coated GEM foils, one normal GEM foil, and one readout board. The 10 cm × 10 cm GEM foils were produced by a Japanese company [3]. Two types of GEM foils with different thicknesses were selected: the thickness of the boron-coated GEM foils is 50 μm and that of a single non-boron-coated GEM foil is 100 μm. The 50-μm-thick GEM foils have 70-μm-diameter holes at 140-μm hole pitch, which is the same as that for the standard GEM produced at CERN [4].The 100-μm-thick GEM foil was recently produced; it uses a liquid crystal polymer (LCP) as insulator instead of the usual polyimide, which makes it easier to etch the holes. The hole diameter is slightly larger (90 μm) than that of the standard GEM, but the hole pitch is the same (140 μm) [5].

Both surfaces of each GEM foil were coated with boron. Enriched ^{10}B (purity > 99%) is used to obtain a high efficiency. In addition, boron is coated on one side of an aluminum cathode plate of thickness of basically 1.2 μm for each layer. Other thicknesses were also used for several basic tests.

The high voltage applied to the boron GEM foils was adjusted to give a unit gas gain to attain the same average pulse height for each conversion layer. It was performed as a pre-experiment with a special setting using X-rays of a ^{55}Fe radioactive source. The single 100-μm-thick GEM foil provides a gas gain of approximiately 200 in detecting a signal. A negative high voltage was supplied to the cathode and appropriate voltages were distributed to each GEM foil with a resistive chain. The readout board has two-dimensional strips with 0.8-mm pitch that measure X and Y coordinates simultaneously. In addition, 120 (X) and 120 (Y) strips cover a 100-cm^2 region. The chamber was filled with Ar-CO_2 (70/30) during the tests.

A new application specific integrated circuit (ASIC) chip was developed for application as front-end electronics for the MPGD. It contains a preamplifier, shaper, and discriminator [6]. A single chip contains 8 channels, and 8 chips are mounted on a single printed circuit board. Four boards are stacked to create a complete strip channel. One field programmable gate array (FPGA) board is also inserted to serve as a readout system, and it controls digital signals and correlates X and Y strips. In addition, it sends data to a PC directly through a single Ethernet cable using the TCP/IP protocol [7].

The electronics are attached just behind the detector, as shown in Fig. 3. The entire detector module is compact and more modules can easily be stacked to expand the detection area.

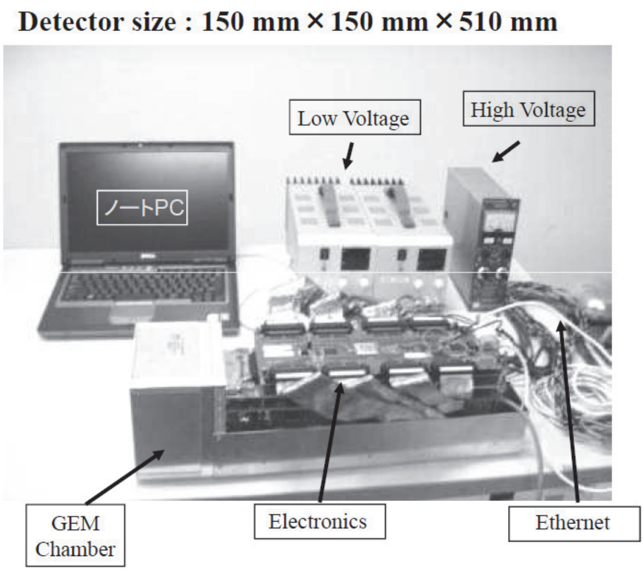

Fig. 3. Photograph of a detector with readout electronics.

2.2. Test with a radioactive source

First, the prototype chamber was tested with a ^{252}Cf radioactive source. The energy of neutrons from this source is quite high in comparison with that of thermal neutrons. Therefore, 5-cm-thick polyethylene blocks were inserted between the source and the chamber to reduce neutron energy. At the beginning of the experiment, a foil of the boron-coated GEM was installed in the chamber and the counting rate was measured for three different boron thicknesses. The data indicate that thicker boron layers provide higher efficiencies (Fig. 4). The flight range of alpha particles within the boron layer is very short, and hence, higher efficiencies cannot be obtained using thicker boron layers in a single GEM foil [8]. To obtain higher efficiency, more number of boron GEM foils should be stacked in the chamber. The optimal boron thickness in various conditions was estimated by simulation [8].

For two different boron-layer thicknesses, the counting rates as a function of the number of stacked GEM foils are shown in Fig. 5. The counting rates increase almost linearly up to 4 and 8 GEM foils for boron thicknesses of 1.2 μm and 0.6 μm, respectively. The counting rate for the 1.2-μm-thick boron-coated GEM foils can be obtained with half the number of the GEM foils by using 0.6-μm-thick boron-coated GEM foils. Clearly, a larger number of GEM foils is necessary to obtain higher efficiency for both cases.

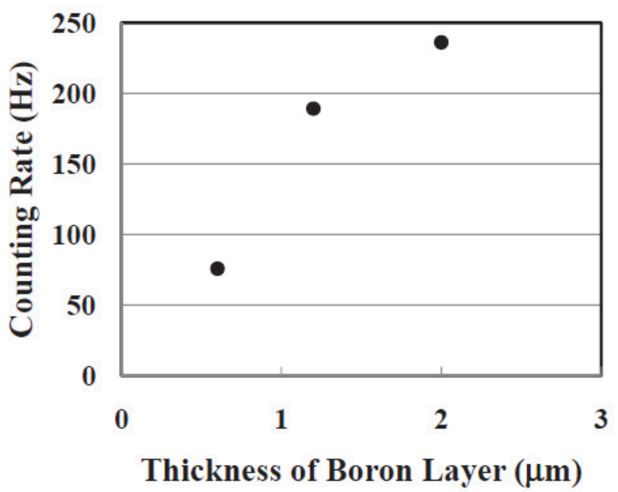

Fig. 4. Counting rate as a function of boron-layer thickness.

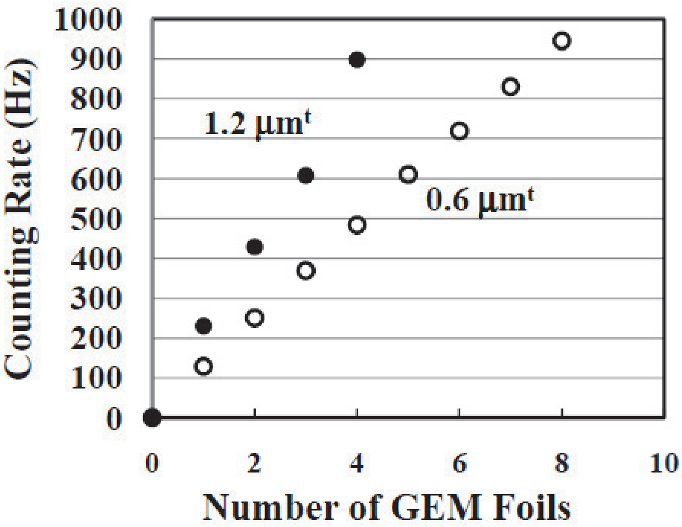

Fig. 5. Counting rates as a function of the number of stacked boron-coated GEM foils for two different boron-layer thicknesses

2.3. Beam test with a reactor neutron source

To characterize the performance of the prototype chamber, a beam test was performed with a thermal neutron beam at Guide hall of the Japan Research Reactor No. 3 (JRR3) at the Japan Atomic Energy Agency (JAEA). Fig. 6 shows the signal shape for thermal neutrons. Clear neutron signals can be observed using the prototype chamber, which indicates that this chamber is capable of achieving the high counting rates necessary for short pulse lengths. Fig. 7 shows the pulse-height distribution for thermal neutrons and gamma rays from a ^{60}Co radioactive source. Background gamma rays can be clearly rejected.

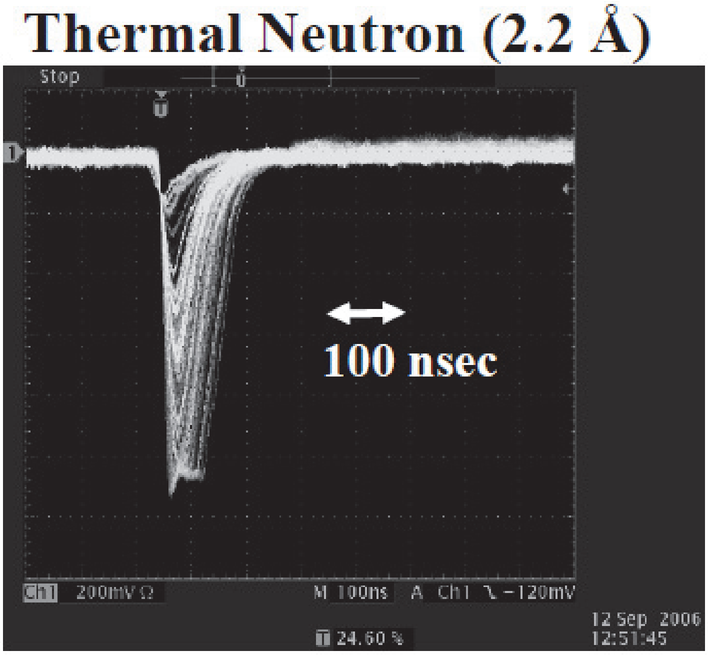

Fig. 6. Pulse shape for thermal neutrons.

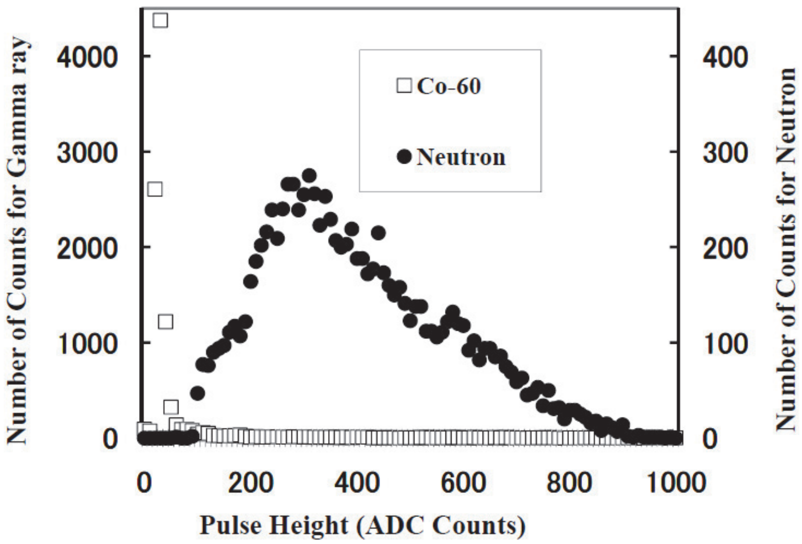

Fig. 7. Pulse-height distribution for thermal neutrons and gamma rays from a ^{60}Co radioactive source. A hardware threshold around 100 ADC counts was applied in the data taking for thermal neutrons to reduce the gamma rays.

In order to estimate detection efficiency, a cadmium plate with a 1.0-mm-diameter pinhole was set in front of the GEM detector or the ^{3}He counter with a 1-inch diameter and a pressure of 10 atm. The counting rates were measured simply for both detectors. The efficiency relative to the ^{3}He counter is about 30% for 0.22-nm neutrons with one boron-coated cathode and four boron-coated GEM foils. To estimate spatial resolution, a cadmium plate having a 0.5-mm-diameter pinhole was used. The incident neutron positions were almost restricted to a single strip, as shown in Fig. 8. By considering the leakage rates into neighboring strips, the resolution function is described by a Gaussian with sigma=0.5mm.

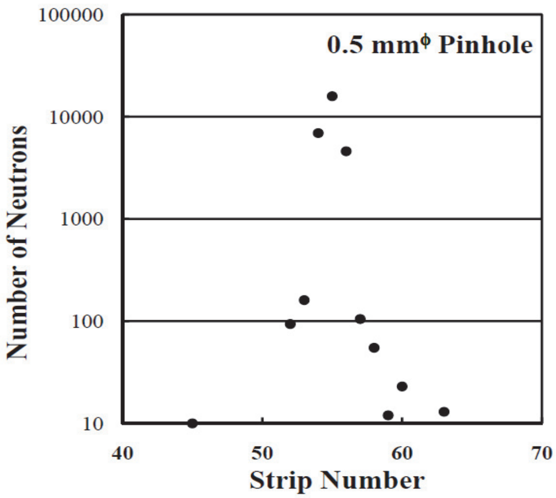

Fig. 8. Incident position of thermal neutrons using cadmium plate with 0.5-mm-diameter pinhole.

2.4. Test with pulsed neutron sources

One good application for this detector is as a neutron-beam monitor. To measure an absolute scattering cross section, the two-dimensional beam position and neutron wavelength at the sample should be monitored. In this case, high detection efficiency is not required; therefore, only a single boron-coated cathode was installed in the chamber with no boron-coated GEM foils. The detector was set up at beam line (BL) 21 at the Materials and Life Science Facility (MLF) of J-PARC. A two-dimensional beam profile was observed and the collimator shape could be clearly seen, as shown in Fig. 9(a). An energy spectrum for the neutron beam was also calculated based on a measurement of the time-of-flight of neutrons [Fig. 9(b)]. More detailed information is available elsewhere [9].

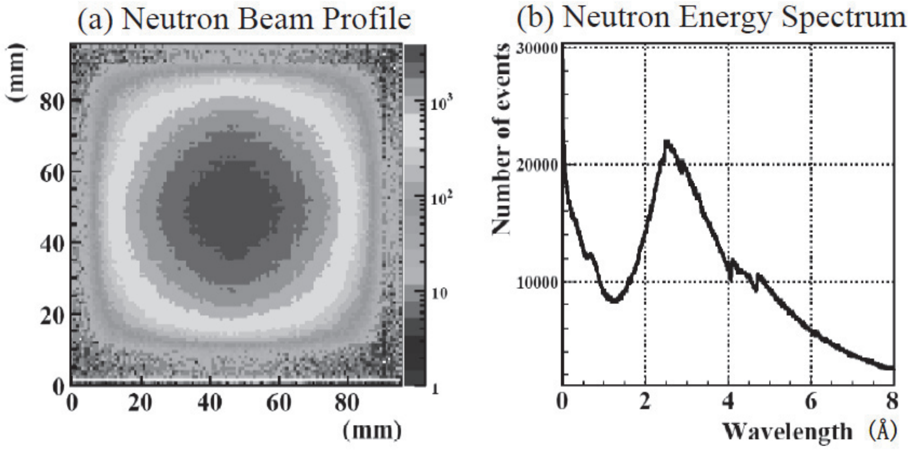

Fig. 9. Neutron beam profile (a) and neutron energy spectrum (b) obtained at BL21 of the J-PARC MLF.

Another useful application for the two-dimensional detector is radiography. Absorption cross sections for each material differ compared with X-ray absorption cross sections. Therefore, a different image can be obtained using neutrons. In addition, energy-selective radiography is much more attractive with pulsed neutron sources. The two-dimensional detector with its precise temporal measurement capability can visualize material microstructure. In this case, lower energy neutrons (so-called Bragg-edge region) are selected. The neutron scattering cross section changes steeply in the Bragg-edge region and the microstructure affects the energy-dependent shape of the cross section. Therefore, crystallite size, which is one of the microstructure parameters, can be calculated two dimensionally from a measurement of the neutron energy at each position [10].

At Hokkaido University, a demonstration beam test was performed at the pulsed neutron source with 1-kW beam power. The prototype chamber with five iron plates was set in front of the detector, which was 6.7-m downstream from a cold moderator. Each plate had different bending conditions, as shown in Fig. 10. The energy-selective absorption cross section was measured and the microstructure parameters were calculated bin-by-bin. Finally, a two-dimensional image of the crystallite size was obtained, as shown in Fig. 10. The bending regions clearly show small crystallite size. In particular, the re-flattening iron plate has smaller crystallites, although its shape is the same as the reference plate prior to bending. The method and different samples are described in more detail in Ref. [10].

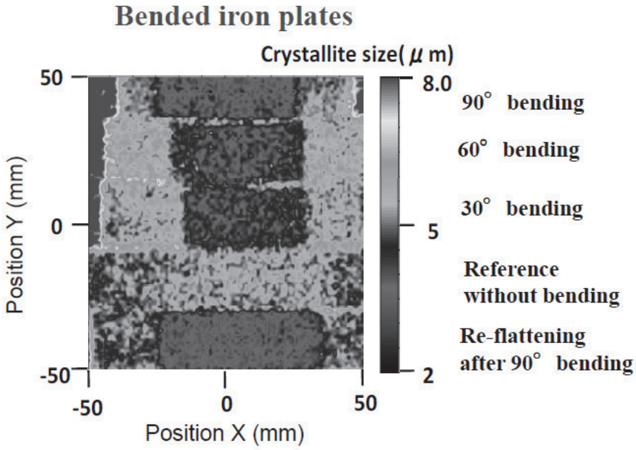

Fig. 10. Calculated crystallite size from fitting the energy-selective absorption cross section near the Bragg edge.

3. Summary

The neutron detector we developed can precisely measure time and two-dimensional position. It therefore permits a new field of energy-selective neutron radiography when used together with pulsed neutron sources.

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