Imaging Gaseous Detector based on Micro Processing Technology

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Abstract

The development of gaseous detectors has been exciting again since the appearance of a MicroStrip Gas Chamber (MSGC) in 1988, which is made using a microelectronics technology. These days lots of variations of the advanced gaseous detectors are being intensively studied in the world.

We have developed the two-dimensional MSGC having a 10 cm square detection area and the ultra fast readout system for a real time X-ray imaging. The MSGC was made using Multi-Chip Module (MCM) technology, and has a very thin substrate of 17 µm, lots of thin anodes and back strips both with 200 µm pitches. This enables us to get fast digital X-ray images with recording both the timing and an energy of each X-ray photon. In addition, an intermediate gas multiplier has been realized using a capillary plate having a conductive surface of a capillary. The MSGC combined with the conductive capillary plate can be steadily operated with a high gain under intense irradiation. Here we also report new approaches of X-ray crystal structure analyses using timing information obtained by the MSGC.

Key words: MicroStrip Gas Chamber (MSGC), Area detector, Time-resolved

1 Introduction

The MicroStrip Gas Chamber (MSGC) was proposed in 1988 by Oed [4]. This new detector has been expected to provide stable operation under intense irradiation and radiation hardness, which are required for an X-ray photo-counting detector operated in high intensity radiation environments. MSGCs also have a good position resolution of ~ a few tens µm. Therefore a two-dimensional MSGC would enable to realize an ideal X-ray imaging detector also having a photo-counting ability.

A MSGC is usually produced using micro-electronics technology: sequences of alternating thin anodes and cathodes are formed with a few hundred micron
pitch on an insulating substrate. The closeness of the electrodes provides the
above features of a MSGC. While most MSGCs have been realized on glass
or quartz substrates so far, we have been developing another type of MSGC
having a ~20µm thin polyimide substrate since 1991 (Nagae et al.[2], Tanimori
et al.[8]). Our MSGC is made using Multi-Chip Module (MCM) technology,
which allows a high density assembly of bare silicon LSI chips on a silicon or
a ceramic board.

A very thin substrate of the MSGC enables us to control the flow of positive
ions from anodes to cathodes by optimizing the potential on the back plane.
Also due to the thin substrate, a fast signal is induced on a backplane, which
enables two-dimensional readout from one MSGC (Nagae et al.[2], Tanimori et
al.[7]). In 1993, the 5cm square 2D-MSGC with 200 µm anode and backstrip
pitches were made, and clear two-dimensional X-ray images were successfully
obtained. The performances obtained from this MSGC were described in detail
in Tanimori et al. [8], in which position resolution, stability, durability, and
operation in high counting rate were investigated.

Based on that study, the new 2D-MSGC having a large area of a 10cm square
has been developed since 1997. In addition, we have developed a new type of
the readout system in which the data are synchronously managed in digital
electronics to handle the huge quantity of data from the MSGC for real-time
image processing. Using this new system, we successfully got real-time movies
from the MSGC, and examine the new X-ray crystal analysis methods using
the photo-counting ability of the MSGC (Tanimori et al. [9]).

Here, after summarizing both the MSGC imaging device and the readout
system, we mainly report the new approach to overcome the destruction of
electrodes due to discharges, which is the most crucial problem for MSGCs,
and the further development of the application of the MSGC imager to the
X-ray crystal analysis.

2 Structure of the MSGC

Figure 1 shows a schematic structure of our two-dimensional MSGC, which
is formed on the 20 µm thin polyimide substrate. On the polyimide layer,
10 µm wide anodes and 100 µm wide cathodes are formed alternately by
photo-lithography technology. Between the ceramic base and the polyimide
substrate, there are back strips with a 200 µm pitch in orthogonal to the an-
ode, which provide information in the second dimension. All electrodes are
made of gold with a thickness of 1 µm (recently chromium are used as men-
tioned in section 5). In order to reduce the effect of parallax broadening of
the position distributions, a drift plane is placed 3 mm above the substrate.
Every 32 cathode strips are aggregated to one group at one end in the a 10cm square MSGC. There are 16 cathode groups, to which high voltages are independently supplied. The signal from groups of cathodes can be used as an energy measurement of an X-ray. The edge of the cathode is coated by polyimide with a width of \( \sim 7 \mu m \) for suppressing discharges between anodes and cathodes (Tanimori et al. [8]). The back strips are connected to the preamplifiers. A gas mixture of Argon (80%) and \( \text{C}_2\text{H}_6 \) (20%) was used in atmospheric pressure. The absorption efficiency of this condition (3mm gap and the use of the above gas) is \( \sim 8\% \) for 8.9 keV X-rays. The resistivity of the substrate is considered to be a key factor to keep stable operation of a MSGC under high counting rate. A very thin organic-titanium is coated on the surface, by which a surface resistivity of \( \sim 10^{15} \Omega/\text{square} \) was obtained. We found an optimum operating point by adjusting both the thickness of the substrate and the potential of both anodes and cathodes. The details of the features about gas amplification and its stability of the MSGC are reported in Tanimori et al. [8].

### 3 Read-out Electronics System

The new 10 cm square MSGC was directly mounted on the 30 cm square mother board by a bonding technique. In order to handle more than a thousand-signal lines in a 30 cm square size, the structure of 8 layers and the micro resistor arrays were adopted. Figure 2 shows the mother board and the gas vessel in which the 10 cm square MSGC is mounted. The preamplifier cards are inserted vertically to the connector on the rear side of the motherboard, which has 64 fast amplifiers (MQS104 developed by LeCroy) and discriminators. All discriminated signals from the anodes and the cathodes (ECL level) are fed to the position encoded system mentioned hereafter.

As pointed out in the Tanimori et al. [8][9], the fast and narrow pulses from both anodes and back strips provide very tight timing coincidence between anodes and back strips within \( \sim 10\text{ns} \). This means that the two coordinates of an incident point are able to be synchronously encoded with a few ten ns clock cycle by requiring the coincidence between the timings of both anodes and back strips. This procedure enables us to encode more than \( 10^7 \) events per second. Since almost all events generates about three hit strips on both anodes and back strips, a simple method of getting the hit position as a center gravity of the hit electrodes can provide a position resolution of less than 100 \( \mu \text{m} \). This resolution reaches the limit due to the diffusion of drift electrons. Therefore, we need to record only the positions of the hit anodes and back strips instead of the pulse heights of those electrodes.

To realize the above idea for handling more than million events per second,
the synchronous encoding system has been developed, of which block diagram is shown in Fig. 3. The readout system consists of 9-U VME modules of two types. One is the position encoding module (PEM) which has 128 inputs and trees of Programmable Logic Devices (PLD). The PEM encodes hit strips to X or Y coordinates. The other is the control and memory module (CMM) which has a large buffer memory of $\sim 200$ Mbyte for keeping the image data during $\sim 10$ seconds at the counting rate of $10^7$ events/s, and generates the synchronous clock. The new system can handle more than 3 million events per second, which is more than $3 \times 10^3$ times the ability of the CAMAC system. This enables us to take $\sim 30$ frames/seconds of images with enough quality. Figures 4 show the several sequent frame images in the movie taken a metal pendant rotating at the front of the MSGC by an X-ray irradiation, where 25 images per second were taken.

The details of the readout method and those VME modules are described in Tanimori et al. [9] and Ochi et al. [3], respectively.

4 New approach for crystal analysis

In general, a two-dimensional image of a diffraction pattern is not sufficient to obtain the three dimensional information of the objective crystal. When using a monochromatic X-ray beam, several diffraction patterns are taken varying the angle between one axis of the crystal and the X-ray beam over an acceptable angle range (a few degrees). The MSGC can record the arriving time of each X-ray photon with a few ten ns resolution. The timing just gives us the information on the angle of the rotation of the crystal with a very fine angular resolution. Figures 5(a) shows the three-dimensional images obtained from MSGC which consists of two positional and one rotating angle coordinates. You note that this fine angular resolution of $\leq 0.1$ degree is obtained for each diffraction spot, which enable to remove the noises spreaded uniformly in this space from real spots made by an X-ray diffraction from a target crystal. Using this method, the sensitivity for a faint diffraction spot can be improved more than 10 times as shown in Fig.5(b). For crystals having the little constituent atoms, the MSGC allows us to get all the information needed for crystal analysis from only a few minutes measurement with one continuous rotation of a crystal. Fig.6 shows a reciprocal lattice image calculated from the data obtained by the MSGC. Thus the MSGC would dramatically improve an X-ray crystallography.

The most intriguing approach for an X-ray crystallography using an ultimate time resolved image is a direct observation of the dynamical change of a crystal structure for periodic variations or reactions. The imaging device based on the photo counting method such as MWPC or MSGC has an essential upper limit
of $\leq 10^7$ events/s for handling the data, which restricts the number of picture frames to less than hundreds per second. However, a fast process within $\leq \mu s$ can be observed as continuous images if periodic measurements are done for this process. Since the MSGC records the timings both of each detected X-ray and of each periodic process, all X-rays obtained by the MSGC can be folded into one phase of the periodic process. When a process with variation times of 100 $\mu s$ is measured periodically by the MSGC at the event rate of a few MHz during 10s, hundred images with $\sim 1 \mu s$ timing bin could be obtained in one process. Each image made of about $10^6$ X-rays gives a high quality picture. We already applied this method, and succeeded to catch the dynamical change of the crystal structure of $[\text{Bu}_4\text{N}]_4[\text{Pt}_2(\text{pop})_4]$ between a photon excited state and a stable state first in the world.

Details of the X-ray crystallography application and another potentialities of MSGC are described in Ochi [11].

5 Diagnosis of discharges: Capillary intermediate multiplier

Although the technology of a MSGC seems to be established due to the recent intensive studies in the world, there still remains one crucial problem to prevent a MSGC from the stable operation: discharges damage the electrodes of a MSGC. The process of the discharge in MSGCs are studied in detail by Peskov, Ramsey & Fonte [5]. Although we do not know the complete diagnosis of discharges in a MSGC yet, the tolerance can be increased by several improvements. About 5$\sim$8% of electrodes were damaged by discharges during one years operation in our experience, testing lots of 5 cm square MSGC. Since damage due to discharges usually concentrated in warming up at the first use, dust and parts of bad quality of electrodes might be the reasons for discharges. For the 10cm square MSGC, the surface are now looked into by a microscope before the operation to remove dusts. Also chromium has been used as the material of the electrode in the latest MSGCs due to its higher melting point. These efforts have distinctly suppressed the occurrences of broken strips by a discharge.

Another solution is the insertion of an intermediate gas-multiplier such as Gas Electron Multiplier (GEM) proposed by Bouclier et al. [1]. An intermediate gas-multiplier was at first realized in a multi-step avalanche chamber using fine mesh planes, which were intensively studied around 1980. Originally an intermediate gas-multiplier was used to attain a very high gain by combined with a MWPC, for detecting one ultraviolet photon of Cherenkov light. We are now investigating a capillary plate as an intermediate gas-multiplier, which consists of a bundle of fine glass capillaries with uniform length, the ends of which forms flat planes and was coated by Inconel metal. The gas multiplication of
a capillary plate in gases has already been confirmed by Sakurai et al. [6]. In this paper, high voltages were fed to both end planes of a capillary plate with the diameter of 2cm, and the high-electric field in a capillary induced a gas multiplication. Its gain was reported to reach up to more thousands. The detail is mentioned in this reference.

Figure 7 shows the side view of our system combined with the 10cm square capillary and the 10 cm square MSGC, where capillary are set 4mm above the MSGC. The large capillary plate used here is made by Hamamatsu Photonics, and the diameter and the length of its capillary are 100 µm and 1mm respectively. A thickness of a capillary plate of ~1mm, which is more ten times thicker than that of GEM, and the very high surface resistivity of a capillary easily let us infer the unstable operation of its gas multiplication under a high intense radiation due to a space-charge effect in a capillary. Actually, non-uniformity and instability of a gain were observed every measurement for this 10 cm square capillary even under a relative low irradiation of ~100 Hz/mm². Under a medium radiation, most bright parts in an image obtained by this system were observed to diminish soon. By such instability, we could not evaluate the performance of it quantitatively.

In order to absorb ions in a capillary, a little conductivity was added to the surface of the capillary, by which the resistivity of 40 MΩ appeared between both sides of the 10cm square capillary. This conductive capillary has dramatically improved the performance of this system. Figure 8 shows the energy spectrum of Cu characteristic X-rays obtained by this improved system, where the peak generated by a single MSGC and that by combined MSGC and capillary plates are obviously distinguished. From this figure the gain of the capillary itself can be estimated, and the rate capability was measured. As shown in Fig.9, the capillary was observed to be operated steadily up to more than a 10⁵Hz/mm². The gain of a conductive capillary reached more than ~3000, and non-uniformity of the gain more than 10% was not observed. Figures 10(a) and (b) show the comparison of the image performance between this system and Imaging Plate using the powder diffraction of sugar for same exposure times; the very good performance of this system are distinctly noted. Here this system was operated with the total gain of 1000 (Cu characteristic X-rays were used), and the gain of the MSGC itself was only a few tens. By adopting this intermediate multiplier, the total gain was increased about ten times, and the operation voltage of the MSGC between anodes and cathodes could be reduced by ~100 V. This condition ensures the stable operation free from both discharges and electrical noises even under an intense irradiation. The detail of the study on the conductive capillary plate will be described in Nishi et al. [10].

Summary
We have developed a two-dimensional MSGC and the fast readout system, both of which are essential developments to realize a new time resolved X-ray imaging detector. In addition, the new type of an intermediate electron multiplier has been proposed: the capillary plate of which capillary has a conductive surface was made and set above the MSGC. This combined system was found to be operated very stably with an enough gain, which has never been attained by a simple MSGC. Furthermore, supplied voltages for anodes and cathodes of the MSGC can be kept within the quite safety range against discharges, and we have been free from the risk of the destruction of electrodes due to discharges. Such an desirable operation of the MSGC provides an ideal image having very high qualities such as good position resolution, no distortion, very wide-dynamic range, and steady and flat uniformity of the efficiency; the new application of this device for the X-ray imaging analyses has been able to be discussed with reality as described in above section.

We also stress that this detector system is a complete electric system controlled by the computer, where electric system means not only that the data are electrically transferred to computers, but also that all the components of this system are made from IC technology. The MSGC itself is made using high density printed board technology for the direct mounting of a bare LSI. All electrical elements of the MSGC readout system are made of commercially available LSI chips. In this system, IC chips with single function such as fast amplifiers, comparators, and the ECL-TTL transfers are the main elements of the components, whereas PLDs, the core parts of the readout system, occupies less than 10% of the system. Then we have begun to redesign the readout system using commercially manufactured IC chips having 32 channels amplifiers or discriminators in one chip which will be mounted directly on the MSGC mother board. PLDs for the position encoding also will be set in the the MSGC box, and no ECL-TTL transfer chip is needed. This improvement will realize a handy MSGC imager similar to a liquid crystal display in very near future.

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Figure Captions

Figure 1. Schematic structure of the two-dimensional MSGC which were formed on a 17 $\mu$m thin polyimide substrate. On the polyimide layer, 7 $\mu$m wide anodes and 63 $\mu$m wide cathodes were formed with a 200 $\mu$m pitch (the width of the cathodes was changed to 100 $\mu$m in the imaging measurement as mentioned in section 4). Between the ceramic base and the polyimide substrate, there are set back strips with a 200 $\mu$m pitch orthogonal to the anodes. All electrodes are made of gold with a thickness of 1 $\mu$m (recently chromium are used as mentioned in section 5). To define the drift field, the drift plane was placed at 10 mm above the substrate.

Figure 2. Top view of the new 10 cm square MSGC mother board. The MSGC is mounted in the gas vessel seen in the lower right of the mother board.

Figure 3. Block diagram of the new synchronous readout system.

Figure 4. Several sequent frame images in the movie taken a metal pendant rotating at the front of the MSGC by an X-ray irradiation, where 25 images per second were taken.

Figure 5. (a) Three dimensional image (X, Y and rotating angle coordinates) of X-ray diffraction spots of the Phenothiazine-Benzilic acid complex, in which the sample crystal at 10 cm front of the MSGC was rotated continuously along the axis normal to incident monochromatic X-ray beam. (b) similar image after the noise reduction mentioned in the text.

Figure 6. Reciprocal lattice image obtained by the MSGC.

Figure 7. Side view of the 10cm square capillary and the 10 cm square MSGC.

Figure 8. Energy spectrum of Cu characteristic X-rays obtained by the 10cm square capillary and the 10 cm square MSGC, where the peak generated by a single MSGC and that by combined MSGC and capillary plates are obviously distinguished.

Figure 9. Rate Capability of the conductive capillary plate.

Figure 10. Comparison of the image performance between the MSGC + conductive capillary (a) and Imaging Plate (b) using the powder diffraction of sugar for same exposure times.
Fig. 1.

Fig. 2.
Fig. 3.

Fig. 4.
Fig. 5.

(a) (b)

Fig. 6.
Fig. 7.

Fig. 8.
Fig. 9.

Gaseous gain vs. Rate [cps/mm$^2$]

Capillary

Fig. 10.

(a) (b)