Development of a \(\mu\)-PIC with glass substrate aiming at high gas gain

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Abstract. Micro pixel chambers (\(\mu\)-PICs), which are a type of the micro-pattern gas chambers, are usually manufactured using the printed-circuit-board (PCB) technology. However, recent application projects have begun to require higher gas gains and finer position resolution than those obtainable with current \(\mu\)-PICs. It is difficult to improve the electrode structure to achieve these improvements because PCB technology limits the precision of electrode fabrication and the thickness of the substrate. We have therefore adopted micro-electro-mechanical-systems (MEMS) technology and developed the first prototype of a through-glass-via (TGV) \(\mu\)-PIC. This prototype TGV \(\mu\)-PIC worked well, achieving a maximum gain of approximately 20,000 and an energy resolution of 20.6% (FWHM) at 5.9 keV over the whole 5×5 cm\(^2\) detection area.

1. Introduction

A micro pixel chamber (\(\mu\)-PIC) [1], whose development began in the early 2000s, is a gaseous two-dimensional imaging detector based on the printed-circuit-board (PCB) technology. The properties of a \(\mu\)-PIC are high gain greater than 6,000 in stable operation [2], fine positional resolution of 120 \(\mu\)m [3], and large detection area of 30×30 cm\(^2\) [4]. Such detectors have broad applications in fields such as MeV gamma-ray astronomy [5], neutron imaging [6], dark-matter search [7], medical imaging [8], space dosimeter [9], and environmental monitoring [10]. Recently, such applications have begun to require a higher stable gain over 15,000 and a finer positional resolution less than 100 \(\mu\)m to upgrade of the positional or angler resolution with more detail tracks of the charged particles. To obtain such improvements, we began the development of \(\mu\)-PICs based on micro-electro-mechanical-systems (MEMS) technology, which can produce finer and more accurate electrodes than those made by PCB technology. In addition, the thickness of the substrate is limited to 100 \(\mu\)m in PCB technology, whereas MEMS technology can process thicker substrates. From past simulation studies, a substrate thicker than 200 \(\mu\)m can supply a few times higher gain because of suppression of the electric field produced by the backside anode strips [11]. In our previous work, we produced a \(\mu\)-PIC using a through-silicon-via (TSV) [12]...
as the first approach based on MEMS technology. This TSV μ-PIC worked well with a gas gain of approximately 10,000 under low intensity radiation from radioisotopes, but the gain stability was not good under high intensity neutron beams [13]. Moreover, the gas gain depends strongly on the thickness of the SiO$_2$ layer coated onto the silicon substrate, whereas this dependence does not appear in simulations with Elmer [14] and Garfield++ [15], which did not consider the difference between an insulator and a semiconductor. We therefore adopted an alkali-free glass substrate and developed and tested a μ-PIC based on through-glass-via (TGV). We produced two types of TGV μ-PICs and confirmed their performance with both simulations and experiments. In this paper, we report the performance of these first-produced TGV μ-PICs.

2. Design of a TGV μ-PIC
We designed the electrodes of the TGV μ-PIC with the same geometrical parameters of the conventional μ-PICs in order to facilitate the comparison. Figure 1 shows photographs and schematic cross section views of the PCB, TSV, and TGV μ-PICs. The anode and cathode electrode structures are almost the same for all types, but the substrate of the PCB μ-PIC is thinner than the substrates of the TSV/TGV μ-PICs. There are three types of TSV μ-PICs, which differ in the thickness of the SiO$_2$ layer, two types of TGV μ-PIC: with or without a polyimide layer. For electrode production, it is difficult to plate copper directly onto glass, so we fabricated two types of TGV μ-PICs. One (type A) has a polyimide layer between the glass substrate and the copper electrode, and the other (type B) has the copper electrode plated directly onto the glass substrate. We expect that type B exhibits hardness to discharges because of the inorganic substrate.

As a first step, we estimated the gas avalanche size of the TGV μ-PICs utilizing simulations with Elmer and Garfield++. We adopted the typical dielectric constants listed in Table 1. To calculate the static electric fields, we require the DC dielectric constants. However, we were not able to obtain them because of the difficulty of the measurements, so instead, we employed the dielectric constants obtained at a frequency of 1 MHz. The solid and the dotted lines in Fig. 2
Table 1. Dielectric constants of the materials used in our simulation.

| material | dielectric constants | comments |
|----------|----------------------|----------|
| polyimide | 3.5                  | at 1 MHz |
| glass    | 5.8                  | at 1 MHz |
| silicon  | 11                   |          |
| SiO₂     | 4.5                  |          |

Figure 2. Gain curves for various types of μ-PICs. The solid and dotted lines represent the estimate for the type A and type B TGV μ-PICs, respectively.

represent the estimated avalanche size as a function of the anode voltage for type A and type B, respectively. This figure shows that the two types of TGV μ-PICs have almost the same gas gain, which is twice the avalanche size of the PCB μ-PIC (the filled circles in Fig. 2) at the same anode voltage. The reason is that the thick substrate spreads the avalanche region because of suppression of the electric field caused by the backside anode strips, as in past simulation results [11]. The polyimide layer, which is the difference between type A and type B, does not affect the gas gain of the TGV μ-PICs. For the TSV μ-PICs, however, the gas gain has a strong dependence on the thickness of the SiO₂ layer on the surface of the silicon substrate. In Fig. 2, the open squares, filled triangles, and filled squares show the gas gains of the TSV μ-PICs with SiO₂ layer thicknesses of 1, 10, and 15 μm, respectively. The thicker SiO₂ layer yielded a higher gain in the experiments, whereas the simulations (the dot-dashed line in Fig. 2) with Elmer and Garfield++ cannot describe this effect because our simulations did not consider the difference between an insulator and a semiconductor. We speculate that the dependence on the SiO₂ layer thickness is caused by carrier transfer in the semiconductor substrate. The TSV μ-PIC with an SiO₂ layer thickness of 15 μm has twice the higher gas gain of the PCB μ-PIC. However, it is difficult to create an SiO₂ layer thicker than 10 μm, so there is little chance of fabricating large sized detectors. Therefore, we anticipate that the TGV μ-PIC, which we expect to have both high gain and simple fabrication process, will become the next standard detector replacing the PCB μ-PIC.

3. Experimental results
The first TGV μ-PIC has a detection area of 5.12×5.12 cm² with 128×128 pixels. The left panel in Fig. 3 shows a schematic view of the setup for the performance test. We placed the TGV μ-PIC in a sealed aluminum vessel filled with detector gas (Ar 90% + ethane 10%) at a pressure of 1 atm. To obtain a high and stable gain, we included a gas electron multiplier (GEM) [16, 17] as an additional electron multiplier, and we placed it at a distance of 4 mm from the TGV μ-PIC. The distance between the drift plane and the GEM was 7.5 mm, and this space is named ”Drift space”. The electric field in the drift space was 250 V/cm, and the induction space was 1 kV/cm. As the readout circuit, we adopted the data acquisition system for the time projection chamber (TPC) of the MeV gamma-ray telescope [18]. Under irradiation
with X-rays emitted from $^{55}$Fe, we confirmed the signal and the spectrum as shown in the center and right panels of Fig. 3, respectively. The energy resolution of the TGV $\mu$-PIC was 20.6% (FWHM) at 5.9 keV for the whole area. Additionally, the energy spectrum in the right panel of Fig. 3 consists of two components: events absorbed in the drift space and in the induction space, respectively. The drift space is only about twice as large as the induction space, and the TGV $\mu$-PIC gain is sufficiently large, so the peak of events absorbed in the induction space appears clearly in the spectrum. We calculated the gas gain due to the GEM utilizing the ratio between the charges of these components, to estimate the gas gain of the TGV $\mu$-PIC alone. Figure 4 shows the gas gain of the TGV $\mu$-PIC. The gain of type B was roughly consistent with the value estimated from the simulations, and it was twice that of the PCB $\mu$-PIC. The maximum gain of type B was approximately 20,000, which satisfies the requirement for the MeV gamma-ray telescopes. On the other hand, type A had only 40% of the gain of type B. By comparison with simulations, we concluded that the polyimide layer between the insulator and the electrode affected the avalanche size of the TGV $\mu$-PIC.

The dielectric constant probably is the most uncertain parameter in the simulations. Generally, the dielectric constant increases at low frequencies [19]. The dielectric constant of polyimide has little dependence on the frequency, but the dependence in the case of glass is relevant. We therefore investigated how the avalanche size changes for different substrate dielectric constant. Figure 5 shows the dependence of the relative gain on the dielectric constant of the substrate. We set the avalanche size to 1 for a dielectric constant of 5.8. This figure shows that the gas gain decreases versus increasing dielectric constant of the substrate. This is the reason why the voltage of the anode via affects the electric field in the avalanche area through the substrate, and the electric field in the avalanche region becomes weaker as the dielectric constant increases. By comparing type A and type B, we found out that the loss ratio of the gas gain of type A is larger than that of type B. If the actual dielectric constant of the substrate is larger than the value assumed in the simulation, we can describe the difference between the gas gains of two types TGV $\mu$-PIC. Figure 6 shows the electric equipotential surfaces of TGV $\mu$-PICs with large substrate dielectric constants. For type B, the direction of the electric field line near the surface in the substrate is approximately parallel to the border between the gas and the glass substrate, and it almost does not appear in the gas region. On the other hand, the electric field lines refract at the border between substances having different dielectric constants so that some field lines from the cathode of type A are pulled into the substrate toward the anode via. Therefore, the number of electric field lines around the anode of type A decreases in comparison.
Figure 4. The gain curves of the TGV $\mu$-PICs. The open squares and filled squares represent the measured gas gains of type A (with the polyimide layer) and type B (without the polyimide layer), respectively. The dashed line and the solid line are the estimated avalanche sizes of the PCB $\mu$-PIC and the TGV $\mu$-PIC, respectively. The gas gain of type B is roughly consistent with the estimated value, whereas type A has only half of the simulated avalanche size.

Figure 5. Dependence of the avalanche size of a TGV $\mu$-PIC on the dielectric constant of the glass substrate. The open circles and filled triangles represent the gains of type A and type B, respectively. The dielectric constant of polyimide was fixed at 3.5 for these calculations.
Figure 6. The electric equipotential surfaces of a TGV $\mu$-PIC (left, type A; right, type B). In this calculation of the electrostatic field, the dielectric constants of polyimide and glass are taken to be 3.5 and 20, respectively. The anode and cathode voltages are 400 V and 0 V, respectively.

4. Summary
To obtain higher gas gains than those of conventional PCB $\mu$-PICs, we have been studying a new type of $\mu$-PIC based on MEMS technology. We adopted glass as the substrate in this work because the gas gain of a TSV $\mu$-PIC depends strongly on the isolation of the semiconductor substrate. We first fabricated two prototype TGV $\mu$-PICs. Type A has a polyimide layer between the glass substrate and the copper electrodes, and type B has the copper electrode plated directly onto the glass substrate. Both types of TGV $\mu$-PICs worked well as radiation detectors. In particular, type B achieved a maximum gas gain of approximately 20,000 and an energy resolution of 20.6% (FWHM) at 5.9 keV over the whole 5×5 cm$^2$ detection area. The gas gain of type B was roughly consistent with the value estimated from the simulations, but that of type A was 40% less than the estimated value. We suggest that the difference between the experiment and the simulation may be caused by the difference in the dielectric constant of the substrate. If the actual dielectric constant of the substrate is larger than the assumed value—which is a typical value at a frequency of 1 MHz—we can ascribe the gas gain loss ratio of type A to the suppression of the electric field around the anode caused by the refraction of the electric field lines at the polyimide layer. In future, we are planning to develop new electrode structures based on type B in order to obtain tracking with finer space resolution for charged particles.

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