Development of ~~the~~ a micro- pixel chamber based on MEMS technology

T. Takemura[1] -[a], A. Takada[1], T. Kishimoto[1], S. Komura[1], H. Kubo[1], Y. Matsuoka[1], K. Miuchi[2], S. Miyamoto[1], T. Mizumoto[1], Y. Mizumura[1], T. Motomura[4], Y. Nakamasu[1], K-. N.akamura[1], M. Oda[1], K-. O.hta[4], J-. D.. Parker[1], T. Sawano[3], S. Sonoda[1], T. Tanimori[1], D. Tomono[1], and K. Yoshikawa[1]

[1] Kyoto University, Japan [2]Kobe University, Japan [3]Kanazawa University, Japan [4]Dai Nippon Printing Co., Ltd.

Abstract. ~~A~~ M~~m~~icro- pixel chambers ~~called /~~ (μ-PIC) ~~is our original~~are gaseous two-dimensional imaging detectors originally manufactured ~~by~~ using ~~Printed~~ printed ~~Circuit~~ circuit ~~Board~~ board (PCB) technology. ~~It is using~~They are used in MeV gamma-ray astronomy, medical- imaging, neutron imaging, the search for dark matter ~~search~~, and dose monitoring. ~~A~~ The position resolution of the present μ/-PIC is ~~~~approximately 120 μ/m (RMS);, however, some ~~the~~ applications require a fine position resolution of less than 100 μ/m. ~~For this purpose~~To this end, we have started to develop a μ/- -PIC based on ~~Micro-~~ micro~~E~~electro- M~~m~~echanical ~~System~~ system (MEMS) technology, which provides better manufacturing accuracy than PCB technology. ~~The~~ Our simulation ~~expected~~ predicted ~~that~~ the gains of MEMS μ/-PICs ~~are t~~to be twice ~~higher than that~~ those of PCB μ/-PICs at the same anode voltage. We manufactured two MEMS μ/-PICs and tested them ~~in order~~ to study their behavior ~~ofMEMS / PICs~~. In these~~is~~ experiments, we ~~succeeded to~~ successfully operated the fabricated MEMS μ/-PICs; we~~and we~~ ~~obtained~~ achieved a maximum gain of ~~~~approximately 5 ~~×~~ 10^3 and collected their energy spectra under ~~the~~ irradiation of X-rays from ^{55}Fe. However, the measured gains of the MEMS μ/-PICs ~~are~~ were less~~lower~~ than half of the values predicted in the simulated gains~~ions. We ~~consider~~ postulated that the gains of the MEMS μ/-PICs ~~reduce due to~~are diminished by the effect of the silicon used as a semiconducting substrate~~or~~.

KEYWORDS: gaseous detector, Micro-pattern detector, Micro Electro Mechanical System

1 Introduction

A micro- pixel chamber ~~called /~~ (μ-PIC) [1] is a gaseous two-dimensional imaging detector (. Figure 1 ~~shows the schematic view of a / PIC~~). Each pixel of the μ/-PIC~~, which~~ has an anode ~~via~~ with a diameter of 60 μ/m and a cathode ~~electrode~~ with a hole diameter of 250 μ/m and~~,~~ is ~~placed~~ positioned with a pitch of 400 μ/m. A gas avalanche occurs near the anode ~~via due to~~because of the strong electric field between these electrodes; therefore, each pixel~~s~~ ~~works~~ functions as a proportional counter. The a~~A~~node ~~via~~s are connected to an anode strip electrode on the back of the substrate, and the cathode~~s is~~ are formed in strip electrodes on the front surface. A t~~T~~wo-dimensional

Comment [Editor1]: Tip: Serial comma
In American English, a comma (called serial or oxford comma) is inserted before “and” in a series.

Comment [Editor2]: Tip: Scientific notation and convention
Use a multiplication sign (×) instead of the letter x to at such instances. Note that a space should be inserted before and after the sign.

readout ~~is available~~can be fabricated using anode and cathode strips arranged orthogonally. ~~A~~ μ~~/~~-PICs are~~is~~ manufactured by ~~PCB (P~~printed ~~Circuit~~ circuit ~~Board~~board ~~()~~ PCB) technology and ~~is~~ are composed of copper electrodes and 100-μm-thick polyimide substrates ~~with the thickness of 100 /m~~. PCB technology ~~allows us to~~enables the low-cost manufacturinge ~~cheaply of a~~ large~~-~~-area μ~~/~~-PICs (10 ~~×~~× 10 cm^2 [2] or 30 ~~×~~× 30 cm^2 [3]). ~~The~~ PCB μ~~/~~-PICs feature ~~has~~ a fine position resolution (RMS {3.1 [JP] 省略形の表記をご確認ください} ~~≃~~≈ 120 μ~~/~~m) [4], a high gas gain (nominal 6000, maximum 15,000) [5], and ~~a~~ good gain uniformity (RMS ~~≃~~≈ 5%). ~~The~~ PCB μ~~/~~-PICs ~~is~~ have been used in a wide range of applications including~~applied in a wide field, for example,~~ MeV gamma-ray astronomy [6], medical imaging [7~~],~~], the search for dark matter ~~search~~ [8], neutron imaging [9], and dose monitoring [10]. However, n~~N~~eutron imaging applications require a position resolution of less than 100 μ~~/~~m

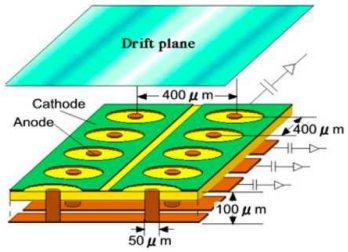

Figure 1. Schematic ~~view~~ of a μ~~/~~-PIC based on PCB technology [1]. The μ~~/~~-PIC is composed of copper electrodes and a 100-μm poly~~-~~imide substrate ~~of 100 /m~~. Each pixel of the μ~~/~~-PIC~~, which~~ has an anode ~~via~~ with a diameter of 60 μ~~/~~m and a cathode ~~electrode~~ with a hole diameter of 250 μ~~/~~m and~~,~~ is ~~placed~~ fabricated with a pitch of 400 μ~~/~~m. A gas avalanche occurs near the anodes ~~via due to~~because of the strong electric field between these electrodes~~;~~ therefore~~,~~ each pixel~~s~~ functions~~works~~ as a proportional counter.

and MeV gamma-ray astronomy requires precise tracking of charged particles with an angular resolution of less than 5~~°~~ ~~degrees~~. ~~For this~~Satisfying these requirements ~~aim, we need to~~necessitates the development of a μ~~/~~-PIC with a fine position resolution.

Because of the limitations of the manufacturing accuracy of PCB technology, the diameter of μ-PIC anodes ~~via~~ is limited to ~~~~approximately 50 μ~~/~~m.

Comment [Editor3]: Remark: Please check if the edit retains the intended meaning.

Comment [Editor4]: Remark: Please check if the edit retains the intended meaning.

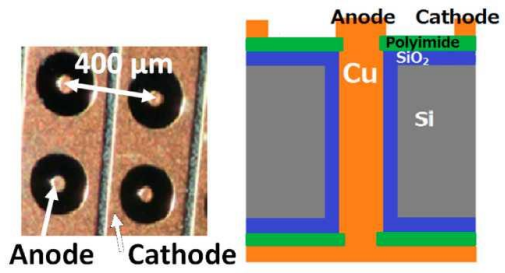

Figure 2. ~~A p~~Photograph (left) and ~~a~~ schematic ~~view~~ of the cross ~~-~~

section (right) of a MEMS µ~~/~~-PIC. ~~A~~ The substrate of the MEMS µ~~/~~-PIC

~~is~~ compri~~o~~se~~sd of~~ a silicon layer with ~~the~~ a thickness of 400 µ~~/~~m, a thin SiO_2 layer, and a thin polyimide layer. The t~~T~~hin SiO_2 ~~layer~~ and polyimide layers are insulated on the MEMS µ~~/~~-PIC ~~for~~ to enhance the discharge tolerance.

Comment [Editor5]: Remark: Please check if the edit retains the intended meaning.

Therefore, ~~we need other~~a more advanced technology is needed ~~technology~~ for manufacturing ~~a~~ fine-pitch µ~~/~~-PICs. Micro~~-E~~lectro ~~-M~~mechanical ~~System~~ system (MEMS) technology is one such ~~of such expecting~~capable technology~~ies~~. ~~Recently, the~~MEMS technology is well established, and ~~the~~ MEMS manufacturing costs have been reduced to ~~similar~~ levels similar to ~~that of~~those of PCB technology. ~~Additionally~~In addition, MEMS technology enables ~~us to~~the use ~~the~~ of thicker substrates ~~than~~ compared with those for PCB technology. In the case of µ~~/~~-PICs, the gain depends on the thickness of the substrate: a~~. The two~~ two-times~~fold~~ thicker substrate improves the gain ~~to~~ by a factor of two [11]. Thus, a MEMS µ~~/~~-PIC is expected to ~~have~~ exhibit a fine position resolution and a high gas gain. However, the substrates used in~~of~~ MEMS technology ~~is composed~~ comprise ~~of~~ silicon, which is a semiconductor; thus, ~~, so that we need to investigate~~ the effect of ~~the difference between~~ a semiconducting~~or~~ substrate being substituted for ~~and~~the insulating substrate of µ-PICs should be investigated~~or~~. In this work, w~~W~~e manufactured two MEMS µ~~/~~-PICs ~~in order~~ to ~~study~~ investigate their behavior. Here, we report the results of both the simulations and ~~the first measurements~~experiments.

2 Simulation study of MEMS µ~~/~~-PIC

We ~~made~~ fabricated a MEMS μ/~~-~~PIC ~~which is similar to the~~with a structure similar to that of a PCB μ/~~-~~PIC ~~in oder~~ to focus on the effect of ~~the difference between~~using a semiconducting~~or~~ instead of~~and~~ an insulating substrate~~or~~. Figure 2 shows a photo and a schematic ~~view~~ of the cross~~-~~section of the manufactured MEMS μ/-PIC. The differences between a PCB μ/-PIC and a MEMS μ/-PIC ~~are~~ lie in the substrate material and its thickness ~~of the substrate~~, which are listed in Table 1. For simulation purposes, t~~A~~he ~~substrate of~~ MEMS μ/~~-~~PIC substrate ~~is~~ was assumed to compo~~r~~ise~~d~~ ~~of~~ a 400-μm-thick silicon layer ~~with the thickness of 400 /m~~, a thin SiO_2 layer, and a thin polyimide layer ~~in contrast to that of~~; by contrast, the PCB μ/~~-~~PIC substrate was assumed to ~~is~~ compose~~d~~ of a polyimide layer with ~~the~~ a thickness of 100 μ/m. The t~~T~~hin SiO_2 layer and polyimide layer are insulated on MEMS μ/~~-~~PICs ~~for~~ to enhance their~~the~~ discharge tolerance. We varied the thickness of the SiO_2 layer in t~~T~~he manufactured MEMS μ/~~-~~PICs ~~are different in the thickness of SiO_2 layer in order~~ to study ~~the effect of~~ its effects on device performance~~SiO_2 layer.~~ Other parameters (such as the thickness of the strips, ~~the~~ pitches of pixels, ~~the~~ diameter of the cathode hole, ~~the~~ diameter of the anode ~~via~~, and ~~the~~ width of ~~a~~ the cathode strip) ~~is almost~~were approximately the same.

Comment [Editor6]: Remark: Please check if the edit retains the intended meaning.

We evaluated the geometries of the PCB and MEMS μ/-PICs ~~in order~~ to study their gains ~~of PCB and MEMS /-PICs~~. We

Table 1. Thickness and relative permittivity values used in simulations of each layers in the μ/-PICs.

material	relative permittivity	MEMS [μm]	PCB [μm]
copper electrode	10^{10}	15	15
polyimide	3.2	4	~100
silicon	11	400	—
SiO_2	4.5	1 or 10	—

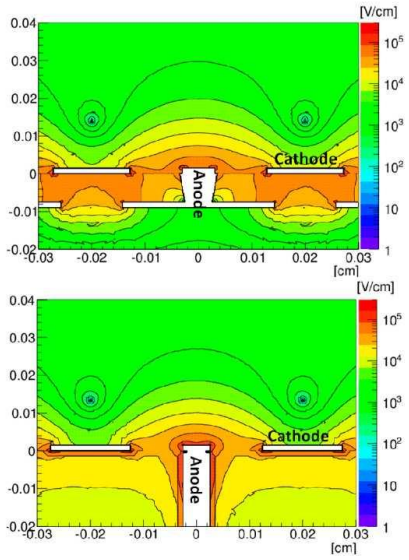

Figure 3. Electric fields of the cross section of a PCB μ-PIC and a MEMS μ-PIC calculated using the program Elmer ~~in~~ for the case of an anode voltage of 460 V. The drift electric field and cathode voltage were fixed at 1.0 kV/cm and 0 V, respectively.

fabricated ~~a~~ μ-PIC pixel electrodes using the Gmsh program [12] and calculated ~~an~~ the electric field around the μ-PICs using the Elmer program [13]. We simulated the avalanche and obtained gas gains using the Garfield++ program with ~~the~~ a three-dimensional mesh [14]. We used ~~the~~ a gas of Ar/C_2H_6 (pressure ratio 90:10) at 1 atm and adopted a penning ~~–~~effect rate of 0.31 [15]. The drift electric field and cathode voltage were fixed at 1.0 kV/cm and 0 V, respectively. Figure 3 shows the electric fields of the cross sections of the PCB μ-PIC and MEMS μ-PIC ~~in~~ for the case of an anode voltage of 460 V. The electric field at 1 μm above the edge of the anode ~~via is~~was 1.7 ~~×~~ 10^5 V/cm for the PCB μ-PIC and 2.2 ~~×~~ 10^5 V/cm for the MEMS μ-PIC. The thick substrate of the MEMS μ-PIC concentrates the electric field lines to an anode ~~via~~, because the thick substrate obstructs the electric field lines between the cathode ~~strip~~ and ~~the~~ anode strips. Therefore, the MEMS μ-PIC ~~has~~ exhibits a stronger electric field. The dependence of the simulated avalanche size ~~of dependence~~ on the anode voltage is shown in Figure 4. In this figure, the dashed and solid lines represent the simulated gains of the PCB [16] and MEMS μ-PICs, respectively. The measured gains of the PCB μ-PICs ~~are excellent agreement~~agree well with the simulated gains [16]; ~~there~~ we

Comment [Editor7]: Remark: Please check if the edit retains the intended meaning.

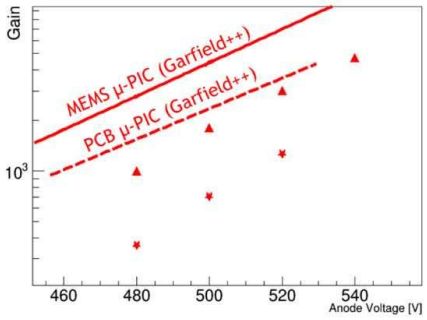

Figure 4. The simulated and measured gains of PCB and MEMS μ-PICs. The dashed and solid lines represent the simulated gains of a PCB μ-PIC and a MEMS μ-PIC, respectively. The simulation ~~expected~~ predicted~~that~~ the gains of the MEMS μ-PIC ~~are twice higher than that~~to be twice those of the PCB μ-PIC ~~in the situation at the~~of same anode voltage. Stars and triangles represent the measured gains of the MEMS μ-PIC with ~~1~~1-μm and ~~10~~10-μm SiO_2 layers, respectively. The gains ~~are~~ were measured ~~using~~in the setup shown in ~~of~~ Ffigure 5.

~~fore it is~~therefore considered ~~that~~ Garfield++ to be ~~is~~ a reliable simulator in avalanche around a μ-PIC. The simulation ~~expected~~ predicted ~~that~~ the gains of the MEMS μ-PIC ~~are twice~~to be twice those ~~higher than that~~ of the PCB μ-PIC ~~in the situation of~~at the same anode voltage. ~~A~~In addition~~ally~~, we studied the effect of the SiO_2 layer in the simulation~~, so~~ and observed that the gains of the MEMS μ-PIC ~~has no dependence~~were independent of ~~on~~ the thickness of the SiO_2 layer when the layer thickness was less than 15 μm.

3 Measurements of the gas gains of MEMS μ-PICs

~~For confirming of~~To confirm the simulation results, we operated the manufactured MEMS μ-PICs ~~for the first time with~~using the setup shown in Figure 5. The active area of the MEMS μ-PIC ~~is~~ was 5 ~~x~~× 10 mm^2, and it ~~has~~ comprised 6 cathode and 10 anode strips. The MEMS μ-PIC was ~~set~~ placed in a sealed aluminum vessel filled with ~~a normal pressure~~ Ar/C_2H_6 gas (~~the~~ in a pressure ratio of 90:10) at atmospheric pressure. We ~~placed~~ positioned a gas electron multiplier (GEM) [17] ~~at~~ 3 mm above the μ-PIC. The GEM has a polyimide substrate with a thickness of

Comment [Editor8]: Remark: Please check if the edit retains the intended meaning.

100 μm, and its hole diameters is 70 μm with a pitch of 140 μm; the active area of the GEM is 10 × 10 cm^2. We operated the GEM at a gain of approximately 20; the electric field of the induction field was1 kV/cm. The drift plane was 3 mm above the GEM, and the electric field of 250 V/cm was applied in the drift space. Therefore, the volume of the detection space was 5 × 10 × 3 mm^3; this space is indicated by the hatched area in Figure 5. The signals from anode and cathode strips were read out by a CMOS ASIC chip [18]. This ASIC has 16 analog input channels, 16 digital output channels, and an analog sum signal. The analog sum signal is fed to an 8-bit FADC {3.1 [JP] 省略形の表記をご確認ください} operated at 25 25-MHz clocks. The details of the data acquisition system used in these experiments have been described elsewhere [18].

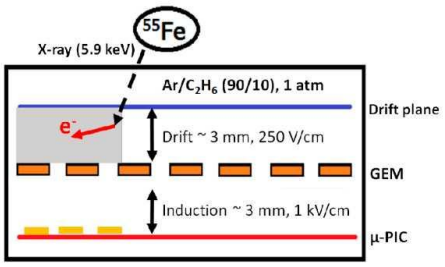

Figure 5. Schematic view of the setup of the test operation. The details are described in the text.

We first operated the MEMS μ-PIC with SiO_2 layer with thickness of a 10-μm SiO_2 layer under the irradiation of 5.9 keV X-rays from ^{55}Fe. Figure 6 shows the signal when the anode voltage was 460 V. The MEMS μ-PIC was stably operated at a discharge rate of less than 0.03 Hz and at an anode voltage of 560 V. In the case of the MEMS μ-PIC with a 1-μm-thick SiO_2 layer, the leak current was approximately 160 nA under the applied anode voltage; the leak current remained greater than 20 nA for longer than 4 hours. The discharge rate of the MEMS μ-PIC with a 1-μm-thick SiO_2 layer was greater than 0.5 Hz at an anode voltage of 530 V. Therefore, an SiO_2 layer is essential for its stable operation.

Comment [Editor9]: Remark: Please check if the edit retains the intended meaning.

Figure 7 (a) and (b) show the ~~energy spectra of~~ ^{55}Fe energy spectra of ~~a~~ PCB ~~/ PIC~~ (25 ~~×~~× 25 mm^2) and ~~a~~ MEMS μ~~/~~-PICs, respectively. The energy resolution of the PCB μ~~/~~-PIC at 5.9 keV ~~is~~ was 40~~-~~%, with ~~the~~ a gain of 1.1 ~~×~~× 10^3; by contrast~~, whereas~~, the energy resolution of the MEMS μ~~/~~-PIC (~~1~~ 1-μ~~/~~m-thick SiO_2 layer) at 5.9 keV ~~is~~ was 57~~-~~%, with ~~the~~ a gain of 1.2 ~~×~~× 10^3. The energy resolution of

the MEMS μ~~/~~-PIC (~~10~~ 10-μ~~/~~m-thick SiO_2 layer) ~~is~~ was nearly equal to that of the MEMS μ~~/~~-PIC (~~1~~ 1-μ~~/~~m-thick SiO_2 layer). The detection area of the MEMS μ~~/~~-PIC was ~~one tenth~~10% smaller than that of the PCB μ~~/~~-PIC. Electrons escape from the detection area of the MEMS μ~~/~~-PIC more easily~~;~~, thus, most of the electrons deposit partial energy. Therefore, ~~we consider that~~ the energy resolution of the MEMS μ~~/~~-PIC eventually became worse than that of the PCB μ~~/~~-PIC. In future experiments, w~~W~~e plan to obtain the energy spectrum with imaging for the rejection of escape electrons~~,~~ after we achieve ~~a~~ stable operation with a gain of 10^4.

In Figure 4, stars and triangles represent the measured gains of MEMS μ~~/~~-PICs with 1 μ~~/~~m~~-~~ and 10 μ~~/~~m-thick SiO_2 layers, respectively. The maximum gain of the MEMS μ~~/~~-PIC ~~achieved~~ reached approximately 5 ~~×~~× 10^3. The gains of the MEMS μ~~/~~-PICs ~~of~~ with ~~1~~ 1-μ~~/~~m~~-~~ and ~~10~~ 10-μ~~/~~m-thick SiO_2 layers ~~are~~ were 16~~-~~% and 40~~-~~% that of the simulated gains at an~~the~~ anode voltage of 500 V, respectively. Because ~~a~~ semiconductors contain ~~had~~ charge carriers, the silicon near the anodes and cathodes became negatively and positively charged, respectively~~,~~ ~~when we~~under an applied ~~the~~ anode voltage. ~~Our~~ However, our simulations with the Elmer and Garfield+~~-~~+ programs did not ~~consider~~ account for such an effect. The electric field around the anode ~~via~~ would be weaker than that predicted by the simulate~~d expectation by~~ions because of the charge ~~up~~ing effect of silicon~~;~~, therefore, the gains of the MEMS ~~/~~μ-PIC were reduced. ~~Besides~~In addition, the measured gas gain depend~~sed~~ on the thickness of the SiO_2~~2~~ layer, which ~~was~~ served as an~~in~~

Comment [Editor10]: Remark: Please check if the edit retains the intended meaning.

Comment [Editor11]: Remark: Please note that this sentence repeats information in the figure caption. Please consider deleting it and adding an introductory phrase such as “As shown in Figure 4…” to the next sentence.

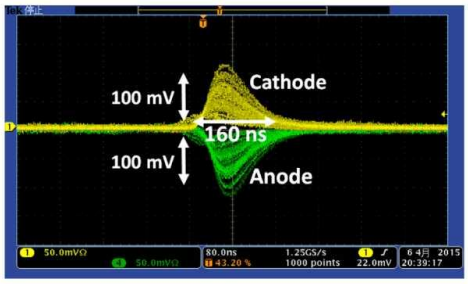

Figure 6. The signals of MEMS μ/-PIC with SiO_2 layer of 10 μ/m by the 5.9 keV X-ray of ^{55}Fe source. Positive and negative signals are obtained from cathodes and anodes, respectively. Voltage between ~~gem~~ GEM top and bottom is 320 V, and anode voltage is 460 V. The filled gas is with a normal-pressure Ar/C_2H_6 (pressure ratio 90:10) gas mixture.

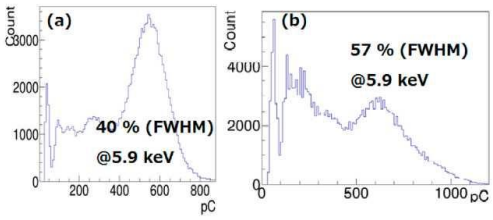

Figure 7. The energy spectrum of the 5.9 keV X-ray of ^{55}Fe source PCB /-PIC (a) and (b), respectively.

insulator ~~placed~~ positioned between the electrodes and the silicon substrate. As described in ~~the~~ section 2, the simulated gain ~~had no relation to~~is independent of the thickness of the SiO_2~~2~~ layer; however, a~~. The~~ thinner SiO_2~~2~~ layer results in ~~is, the more strongly the char~~a greater charging~~ge up~~ effect ~~appeared~~. The leak current during start-up is ~~the~~ additional evidence of ~~the charge up~~this charging effect. To ~~realize~~ achieve both ~~the~~ stable operation and ~~the~~ a high gain ~~of~~ with a MEMS μ/-PIC, we need to reduce the charge ~~up~~ing effect of the silicon. We considered two solutions to~~of~~ this issue. One is to fabricate a MEMS μ/-PIC ~~with~~ using a~~the~~ glass substrate ~~which~~ that contains no semiconductor. We can manufacture a MEMS μ/-PIC ~~with~~ on a~~the~~ glass substrate, but ~~the cost will be~~doing so is

expensive. ~~Another~~ The other solution is ~~the~~ to fabricate a MEMS μ~~-~~PIC with ~~the~~ a thick SiO_{2}~~$_{2}$~~ layer. We believe that we can ~~manufacture~~ fabricate a MEMS μ~~-~~PIC ~~having the~~with a SiO_2 layer ~~with the thickness of~~ 15~~-30~~-30-μ~~-~~m thick, and we plan to manufacture them in the future. ~~When we realize these~~We expect that the resulting MEMS μ~~-~~PIC~~, MEMS / PIC~~s will~~will have~~ be useful ~~high activities~~ in various applications.

Comment [Editor12]: Remark: Please note that if you have actually reported manufacturing such a μ-PIC, please consider adding a citation to your previous work.

Comment [Editor13]: Remark: Please check if the edit retains the intended meaning.

4 Summary

The applications of μ~~-~~PICs require a finer position resolution than that of current PCB μ~~-~~PICs. To satisfy this ~~request~~requirement, we ~~manufactured~~ fabricated and studied ~~the~~ MEMS μ~~-~~PICs. Specifically, we~~We~~ ~~made~~ fabricated ~~a~~ MEMS μ~~-~~PICs ~~which~~ with a structure~~is~~ similar to that of ~~the structure of~~ a PCB μ~~-~~PIC ~~in oder~~ to focus on the effects of ~~the difference between a~~using a semiconducting~~or and~~ instead of ~~a~~ an insulating substrate~~or~~. ~~The~~ S~~s~~imulations ~~expected~~ predicted ~~that~~ the gains of the MEMS μ~~-~~PICs ~~are~~ to be ~~twice higher than that~~twice those of PCB μ~~-~~PICs ~~in the situation of~~at the same anode voltage. The MEMS μ~~-~~PIC with a ~~1~~ 1-μ~~-~~m-thick SiO_{2}~~$_{2}$~~ layer ~~is~~ was unstable, ~~and this result shows~~demonstrating that a~~n~~ SiO_{2}~~$_{2}$~~ layer is essential to the stable operation of MEMS μ-PICs. For the first time, we successfully obtained ~~the~~ a signal and ~~the~~ energy spectra using MEMS μ~~-~~PICs ~~with~~ under ~~the~~ irradiation of X~~-ray~~ rays from ^{55}Fe. The maximum gain of the MEMS μ~~-~~PICs ~~achieved~~ reached approximately 5 ~~×~~~~×~~ 10^3. However, the gains measured ~~gains~~ at an anode voltage of 500 V ~~are~~ were 16% ~~-~~40-% that of the simulated ~~gains~~values ~~at the anode voltage of 500 V~~. We considered that the gains of the MEMS μ~~-~~PICs ~~reduce due to~~were diminished by the effect of the semiconducting silicon substrate ~~as a semiconductor~~. To ~~reduce~~ minimize the effect of the semiconductor, we ~~will~~ plan to manufacture ~~the~~ MEMS μ~~-~~PICs with thicker SiO_{2}~~$_{2}$~~ layers or ~~with the~~ glass substrates.

Acknowledgements

This work was supported by the "UCHUGAKU" project of the Unit of Synergetic Studies for Space, Kyoto University.

References

[~~1~~1] A. Ochi, et al., Nuclear Instruments and Methods in Physics Research Section A 471, 264-276 (2001).

[2] H. Kubo, et al., Nuclear Instruments and Methods in Physics Research Section A 513, 94-98 (2003).

[3] A. Takada, et al., Nuclear Instruments and Methods in Physics Research Section A 573, 195-199 (2007).

[4] T. Nagayoshi, et al., Nuclear Instruments and Methods in Physics Research Section A 525, 20-27 (2004).

[5] K. Miuchi, et al., IEEE Transactions on Nuclear Science 50, 825-830 (2003).

[6] T. Tanimori, et al., The Astrophysical Journal 810, 28 (2015).

[7] S. Kabuki, et al., Nuclear Instruments and Methods in Physics Research Section A 623, 606-607 (2010).

[8] K. Nakamura, et al., Progress of Theosetical and Experimental Physics~~,~~ 043F01 (2015).

[9] J. D. Parker, et al., Nuclear Instruments and Methods in Physics Research Section A 697, 23-31 (2013).

[10] T. Mizumoto, et al., Journal of Instrumentation 10, C06003 (2015).

[~~1~~11] T. Nagayoshi, et al., Nuclear Instruments and Methods in Physics Research Section A 546, 457-465 (2005).

[12] http://geuz.org/gmsh.

[13] http://www.csc.fi/english/pages/elmer.

[14] http://garfieldpp.web.cern.ch/garfieldpp.

[15] O. Sahin, et al., Journal of Instrumentation 5, P05002 (2010).

[16] A. Takada, et al., Journal of Instrumentation 8, C10023 (2013).

[17] F. Sauli, Nuclear Instruments and Methods in Physics Research Section A 386, 531-534 (1997).

[18] T. Mizumoto, et al., Nuclear Instruments and Methods in Physics Research Section A 800, 40-50 (2015).

?????????