A Novel Detector for 2D Ion Detection in Low-Pressure Gas and its Applications

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Abstract—A detector array for single-ion registration was developed and studied. The detector array was operated with various working gases, including propane, air, and water vapor at low gas pressure (a few mbar) in a limited Geiger mode, providing single ion sensitivity. The patterned detector structure, comprising sub-millimeter hole diameter, millimeter pitch, ground and 2D readout electrodes, were manufactured using standard PCB technology. A glass cathode was utilized to allow the limited discharge mode of operation. Essentially, the new detector is a combination of a hole-type micro-pattern detector and a resistive plate counter operating at reverse polarity in a low pressure gas. It was demonstrated that the unique combined properties of these well established individual detectors in the low pressure gas environment allows for single ion registration through ion-impact induced discharge confined inside an individual cell (hole) of the detector array. Possible applications of the new ion detector in gas chromatography - mass spectrometry and track structure imaging for radiation protection and hadron therapy are briefly discussed.

I. INTRODUCTION

ION detectors have been used extensively with great success in research and industry for many decades. Several types of ion detectors presently exist; the two most common types, and also the oldest, are the Faraday cup and electron multipliers. Limitations of these detectors are well known, and the development of new ion detectors which eliminate the performance bottlenecks and expand their applications into newly emerging technologies has been ongoing for many years [1]. Particularly, positive ion detectors able to operate in a gas environment with single-ion sensitivity and high efficiency would find broad application in gas chromatography-mass spectroscopy as well as in instrumentation for precise imaging of the track structure of ionizing radiation. However, in spite of the advances in detector research, such positive ion detectors are not yet available. To provide the single ion sensitivity, the detector must utilize an ion pre-acceleration in a strong electric field and/or an internal amplification mechanism such as charge multiplication in electron multipliers or phase transition in cryogenic detectors. These amplification processes are difficult to implement in a gas environment, and existing ion detectors with internal amplification only operate in a high vacuum.

In recent years, significant progress has been achieved in the development of so-called Gas Electron Multipliers (GEM) – hole-type gaseous detectors able to operate stably at high gains in different gas mixtures including humid ambient air [2]. These detectors are capable of registering ionizing particles and photons with high efficiency through charge multiplication in the detector working gas (avalanche) initiated by secondary electrons, but not applicable for the detection of low energy ions which are not ionizing the working gas. In order to make such ion detectable by GEM, one needs to force it to create a free electron in the detector working gas. One possibility is utilization of the ion-induced impact ionization for this purpose. It is known that under a low pressure and a high electric field operating condition the contribution of ion impact processes to ionization can be substantial, and in some cases even exceed that of electrons, e.g., in He at about 0.1 Torr, and E/p over 10^4 V/cm Torr [3]. Here we show that with an appropriate detector design, i.e., a hole-type detector structure, such conditions can be realized. In this work, we present progress on the design of a novel detector for positive ion registration in various low pressure gases based on these principles. The new detector utilizes a charge multiplication mechanism initiated by ion impact ionization in a thick GEM-like structure providing single-ion sensitivity and 2D readout.

II. DETECTOR OPERATIONAL PRINCIPLE AND DESIGN

The detector structure and operation principle is schematically shown in Fig. 1. It consists of a large number of cells, comprising small (about 1 millimeter in diameter) holes perforating a metal-clad dielectric sheet (of a few mm thickness) with millimeter pitch. These dimensions allow the utilization of standard printed circuit board (PCB) technology for detector manufacture. The upper electrode is formed by strips common to each row of holes and is kept at ground potential. A second layer of orthogonal strips, located just below the top strip layer, provides 2D readout of individual cells. The multilayer PCB technology allows us to implement additional readout layers, e.g., a 3rd layer of readout strips oriented at 45 degrees to the first two layers can be added to resolve hit ambiguity.

Positive ions produced in the low pressure (1-10 Torr) working gas above the detector plane drift to the detector plane under a relatively weak (~ 10 -100 V/cm) electric field provided by the anode (not shown) connected to a positive power supply. The focusing of the primary ions into the detector cell (hole), their acceleration and subsequent charge multiplication process in the cell gas is controlled by applying

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a negative voltage to the bottom cell electrode (cathode), providing a very high reduced electric field across the cell.

Figure 1. Schematic structure of the ion detector array.

In order to prevent damaging discharges and sparks the bottom electrode is made of highly resistive material (glass) and each detector cell operates under a voltage well below the field emission breakdown threshold. For the prototype detector of 3 mm thickness (shown in Fig. 1) operating in propane, air or water vapor at 1 to 5 Torr pressure, the voltage applied to the cathode was in 650-850V range. The resulting reduced electric field, E/p , in the cell is of the order of 10^3 V/cm Torr , well above charge multiplication thresholds for electrons and ions ($\sim 30 \text{ V/cm Torr}$ and $\sim 70 \text{ V/cm Torr}$ in propane, respectively). A restricted avalanche in the cell hole starts by positive ion impact ionization and develops due to ionizing collisions of secondary electrons and positive ions; the former are responsible for most of the charge multiplication. Ionization cross sections for positive ion impact at low energies (10-1000eV) are scarce; available data for light ions (H, He) indicate that they are about a factor of 2-10 smaller than for electrons of the same energy. According to our estimates, and based on observations of ion-induced charge multiplication in low pressure gas with an ion-counting gas detector [4], the probability of at least one gas ionization on a 0.1-mm ion path in 1 Torr propane under an electric field of the order of 1000 V/cm is below 10%. Therefore the typical micro-pattern detector thickness (0.1mm) is too small for high efficiency of single positive ion registration, and one needs to go to a much thicker (a few mm) detector structures to ensure close to 100% probability of ion impact ionization as the ion passes through the cell. The second option of a higher electric field can cause field emission breakdown, permanently damaging the detector structure. After the ion-induced ionization occurs, the secondary electron(s) accelerating in the high electric field across the cell initiate an avalanche propagating to the top of the cell. In such a high electric field, the process, once started, goes on until practically all gas in the cell is ionized; an uncontrolled discharge can be prevented by restricting the electric field by space charge effects and/or by external means, e.g., a resistor in the HV bias chain, as in

the Geiger counter. In our design, the discharge stops when the voltage across the cell drops due to the high-volume resistivity of the cathode; this is similar to the limited streamer process occurring, e.g., in Resistive Plate Chambers (RPC) [5]. The discharge is restricted not only in time but in space, as it remains confined to the cell where it started. Propagation of the discharge due to UV photon feedback is limited by the cell walls and the detector reverse polarity prevents photoelectron emission from the anode. The avalanche electrons are confined to the cell because the electric field configuration within a hole changes during the discharge development. It is a dynamic process that can be explained on the basis of the electron trajectories shown in Fig. 2 before and close to the end of the electron part of the discharge.

Figure 2. Electron trajectories before (left) and close to the end (right) of discharge.

The electric field in the fired cell breaks down because the vast majority of secondary electrons produced at the top of the cell (avalanche head) are promptly collected on the readout strips and the non-compensated positive charge of the avalanche ions is screening the negative potential of the cathode at the bottom of the cell. The field of non-fired neighboring cells expands to the vacant region, trapping remaining electrons within the fired cell, and deflecting any subsequently arriving ions into a nearby vacant cell. The remaining electrons in the fired cell are collected on the strips in the weak field configuration, or recombine with the ions in the positive charge cloud slowly moving down toward the cathode.

The recovery time of the fired cell depends on the charge collection time and recharging time, the former is estimated to be in the sub- μs to the μs range, while the latter depends on the cathode conductivity properties and can be much longer. This should not affect the ion detection efficiency at low ionization density because ions will arrive well spaced in time. This is due to low drift velocities (e.g. $\sim 0.25 \text{ mm/microsecond}$ in 2 Torr propane at 100 V/cm), and, as mentioned above, ions arriving during cell discharge are 'automatically' deflected to the neighbor cells. It should be noted that the readout strip (or additional common) layers can be utilized as elements of ion optics, focusing ions into the cell to maximize the ion collection efficiency. To this purpose, an AC readout scheme can be implemented, and correspondingly increasing potentials applied to the consecutive strip layers.

Figure 3. Photo of ion detector structure manufactured using multilayer PCB technology. Active area of 2x5cm counts 576 cells (holes), detector thickness 3.2mm. Top: cell diameter 0.8mm, pitch 2mm, common top electrode and 2 orthogonal readout strip layers below. Bottom: cell diameter 1mm, pitch 2mm, common top electrode replaced with 3rd layer of readout strips.

The signal induced on the readout electrode is determined by the charge accumulated in the cell capacitor: $Q_{\text{cell}} = C_{\text{cell}} V$. Cell capacitance in our test detector structures is of the order of a few tens fF; so for $V \approx 700\text{V}$ the Q_{cell} values in the tens pC range are expected.

III. EXPERIMENTAL SETUP FOR THE OPERATION STUDY AND PRELIMINARY TEST RESULTS

A detector prototype manufactured using standard PCB technology with a common top electrode (Fig. 3) was used to verify the operation principle. The experimental setup is shown in Fig. 4. The detector PCB was mounted on a Teflon base with embedded glass cathode, so the HV electrode surface was exposed to working gas only through the detector holes. The detector assembly was installed into a drift chamber enclosure providing controllable gas environment of 0.1-10 Torr pressure and drift fields up to 1000V/cm. The chamber was also equipped with a collimated Am-241 alpha source and Si detector defining an alpha particle beam of

about 2 mm in diameter parallel to the detector plane and 5 mm above it.

Figure 4. A schematic drawing of experimental set-up.

With this set-up, we registered negative pulses of about 200-400 ns duration and amplitudes in the 1 to 10 mV range on 50 Ohm load on the top electrode, which gives an estimate on the average avalanche electron charge of the order of 20pC. In these measurements, we used propane at 2 Torr as the working gas, the drift field was set to 20V/cm, and the HV across the detector structure was 700V. Figs. 5 and 6 show printouts from the digital oscilloscope screen with the detector signal observed under these conditions. The observed signal corresponds to avalanche charge of the order of 10^8 electrons, well above Raether limit for the breakdown in gases. This means that each cell operates as an independent Geiger micro counter, but at the same time significant variation in the signal amplitude indicates that the discharge region in the fired cell is restricted and probably its size depends on the initial ion induced ionization location along the cell axis.

The detector response was verified in the 0.1 to 10 Torr propane pressure range at the same operating voltages. It was observed that the signal amplitude slightly rises with increasing pressure (~ 2 times for a 4 fold pressure increase), while the individual cell signal duration decreases proportionally. At operating gas pressure below 1 Torr, the signal on the readout strips first disappears, and then, below about 0.7 Torr, appears again as a broad positive pulse with amplitude of about 1 mV. This can be explained by an expansion of the avalanche above the cell: avalanche electrons propagating above the cell induce a positive signal on the top readout strip, while the signal induced on the anode remains negative (see Fig. 7).

Measuring ion arrival time at different anode voltages, i.e., changing the ion drift velocity, we verified that the registered ions came from the alpha particle track. The ion drift time distributions measured at anode voltages corresponding to the drift field of $\sim 6\text{V/cm}$ and $\sim 20\text{V/cm}$ are shown in Fig. 8.

Figure 5. Detector response to an alpha-particle track in propane at 2 Torr. Yellow (Ch1): trigger signal from Si PIN diode/charge sensitive preamplifier; Red (Ch3): integrated signal induced on the anode (at +20V), 10 MOhm load; Blue (Ch2): signal from the readout electrode on 50 Ohm load. The estimated gas gain is $\sim 10^8$.

Figure 6. Detector response to an alpha-particle track. Time-expanded view.

Figure 7. Detector response to an alpha-particle track in propane at 0.5 Torr. Other operational parameters are the same as in Fig. 5.

Figure 8. Ion drift time distributions in propane at 2 Torr measured at drift fields of ~ 6 V/cm (left) and ~ 20 V/cm (right).

We also measured the total background rate of our detector caused by sporadic discharges and ions from cosmic and background radiation. In these measurements, we used working gas sensitive volume of 2.5cm x 5cm x 5cm filled

with propane at 2 Torr, and found that the background rate did not exceed 1Hz for all 576 cells.

Similar measurements were performed utilizing ambient air and water vapor. A broad negative pulse of about 1 mV amplitude on the readout strip was observed for ambient air at 2 Torr operating pressure (Fig. 9). A similar signal was registered in water vapor at 2 Torr (Fig. 10).

Figure 9. Detector response to alpha-particle track in ambient air at 2 Torr.

Figure 10. Detector response to alpha-particle track in water vapor at 2 Torr.

IV. CONCLUSIONS

With this work, we introduced the design principle of a novel class of 2D positive ion detectors, able to operate in a low pressure (0.1-10 Torr) gas environment with high gas gain. The detector output signal in the tens of pC range allows the utilization of simple and inexpensive readout electronics. We described a 2D detector prototype and presented successful results of its tests in propane, air and water vapor. While systematic studies of the detector performance as well as optimization of the detector design for different application are in progress, the preliminary results make us believe that this new generation of positive 2D ion detectors will have many useful applications. In our opinion, the preliminary

results strongly support their feasibility as planar positive ion detectors in mass spectrometry, gas chromatography and ion mobility spectrometers. High internal gain and design simplicity will allow its application as a highly sensitive, cost-effective sensor for flammable and explosive gases.

The new detector opens the possibility to build an ion time projection chamber, i.e., a novel instrument capable of precise imaging of ionizing radiation track structure with the ultimate resolution of single ions, which can find applications in many fields such as medicine, physics, radiobiology, and engineering. Examples for potential applications in medicine include optimization of treatment planning for radiotherapy and evaluation of space radiation for cancer risk estimates. Applications in physics include solar neutrino studies, dark matter search, x-ray polarimetry and validation of theoretical models of radiation interaction with matter. In electronics the instrument could be utilized to access damage to micro- and nano-electronic elements in intense radiation fields in accelerator, nuclear power plant and outer-space environments. Direct measurements of spatial ionization patterns produced by arbitrary radiation fields will also find applications in radiation protection, environmental radiation monitoring, and industry utilizing radiation, e.g., for material modification, sterilization, food preservation, etc. Therefore, we consider this development as very promising.

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