Ionization Gauge by Carbon Nanotube Field Emission

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A newly developed ionization gauge using carbon nanotube(CNT) field emission effect has been designed and manufactured. The fabricated ionization gauge is of a triode type, consisting of a cathode (carbon nanotube field emitter arrays), a grid and a collector. The principle involved here is that for a constant number of electrons available for ionization emitted from carbon nanotube arrays by the grid potential, a constant fraction of gas will be ionized and the number of ions collected in the collector will be proportional to the number of gas molecules in the chamber traversed by the electrons. Due to the excellent field emission characteristics of CNT, it is possible to make a cost effective cold cathode ionization gauge. A screen-printing method has been used to make the CNT cathode. The glass grid with Cr deposited by E-beam has been put on the cathode with a gap of 200 μm between the two electrodes. Using the voltage applied to the grid, the electrons emitted from the carbon nanotube ionize gas molecules in the chamber and the ionized molecules are gathered in the collector. At this time, the collector voltage is maintained at a lower level than that of the grid voltage to obtain a large ionization ratio. The current detected in the collector is proportional to the pressure in the chamber. The ionization characteristics are dependent on the gas and the voltage applied to the grid and collector. In this paper we have shown the various metrological characteristics of the simple pressure sensor utilizing carbon nanotube.

Key Words : Carbon Nanotube, Ionization Current, Screen Printing Method, Pressure Sensor, Field Emission

1. Introduction

Essentially, an ionization gauge has been used in the fields of semiconductor industries to measure vacuum condition in a chamber. The main principles of an ionization gauge are that a constant fraction of the gas is ionized for a constant number of the electrons available for ionization and that the number of ions detected in the collector is proportional to the number of gas molecules in the space traversed by the electrons.

Schematic diagrams of conventional ionization gauges are shown in Fig. 1. General ionization gauges consist of an ion collector, an electron collector (grid) and an electron source (filament). Electrons that are able to ionize gas molecules in the chamber can be thermally generated by the filament. In order to extend the

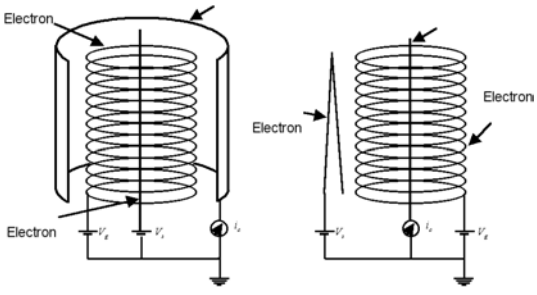

Fig. 1 Schematic diagram of (a) normal triode, (b) Bayard-Alpert ionization gauge; i_c : collector current, V_g : grid voltage, V_s : source voltage

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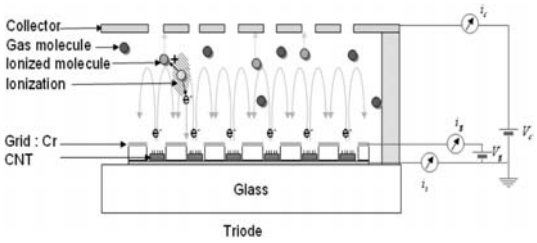

Fig. 2 Schematic diagram of CNT-based ionization Gauge ; i_s : source current, i_g : grid current, V_c : collector voltage

range of ion gauges to lower pressure, the Bayard-Alpert (B-A) gauge was introduced. The B-A gauge can reduce the soft x-ray generation probability since the wire type collector was moved inside and the filament was moved outside the grid. However, thermal electron generation can cause heat problems and the radiation of light. Also, the gauges are limited by their huge, bulky architecture, and high power consumption. (Harland G. Tompkins)

Miniaturized gas ionization sensor using carbon nanotubes (CNTs) has been proposed to overcome the problems mentioned above. The structure consists of two electrodes such as a multi-walled nanotubes (MWNTs) film anode and an Al plate cathode. The sensor utilized the electrical breakdown voltage variation dependent on a range of gases. However, the breakdown voltage variation is not sensitive enough in relation to the gas density, compared with the performance of the triode ionization gauges. (Modi et al., 2003)

In this study, the filament was replaced by the CNT arrays which have a similar structure to that of a Field Emission Display (FED). The CNT-based ionization gauge uses a triode structure like the planar FED, consisting of a cathode to emit electrons, a grid to attract and give sufficient energy to the electrons, and a collector to attract the ionized molecules and measure the resulting current. The FED needs to keep the collector potential greater than the grid potential in order to accelerate the electrons emitted from the CNTs and to obtain energy high enough to radiate light. However, for ionization gauge usage, different voltage combinations are required. The schematic diagram of the triode type ionization gauge developed in this study is shown in Fig. 2.

2. Fabrication and Emission Characteristics

2.1 Fabrication

CNTs are very advantageous for use as emitters due to their high aspect ratio and small radius of curvature at the tip. There have been many studies on fabrication of micro cathodes using CNTs as the field emission source. As in (Pirio et al., 2002), a single mask, self-aligned technique can be used to pattern the gate, insulator, and catalyst for CNTs growth, and then, vertically aligned CNTs can be grown inside the gate structure by plasma-enhanced chemical vapor deposition (PECVD). However, the vertical length and diameter of CNTs appropriate for micro cathodes can not be controlled easily on the base electrode when the gate structure is manufactured using MEMS process. In addition, vertically aligned CNTs can be produced by thermal chemical vapor deposition (CVD) with Ni, Co, and Fe catalysts. Similarly, it is difficult to obtain the integrated CNT tip grown on the base electrode. (Guilorn et al., 2002)

In this study, instead of direct CNT growth, purified single-walled nanotubes (SWNTs) have been used and fabricated in arrays by a screen printing method, which is mixed with an organic mixture of nitrocellulose. The paste of well-dispersed CNTs was squeezed onto the metal patterned soda lime glass through mesh with 10 μm thickness and then annealed at 350℃ for 15 min. to remove the organic binder. Photolithography using thick film photoresist and E-beam deposition processes were used to make the metal grid. The fabricated grid having the same pattern as the mesh for the CNTs being squeezed was loaded on the CNT array and arranged well. The screen printing method is preferable to the CNTs growth method using thermal CVD and PECVD because it can be patterned easily and is more appropriate for mass production. (Choi et al., 1999)

After the Cr grid was combined with the CNT array cathodes, two kinds of ion collectors were used to detect the field emission ; one used phosphors deposited on an Indium Tin Oxide (ITO) transparent electrode for verifying field emission characteristics visually, and the other used only a wire mesh for detecting the ionization current. Since a planar collector can limit the movement of gas molecules in the ionization domain, an ion collector with a wire mesh pattern is more appropriate for the gas ionization.

2.2 Field emission characteristics

A collector potential must be higher than a grid potential in the case of an FED, in order to accelerate the electrons emitted from CNTs as mentioned previously. However, for an ionization gauge, the collector potential must be lower than that of the grid potential to attract the gas molecules ionized by the electrons. In the former case, that is, in the electron emission mode, electrons may pass through a chamber with high vacuum condition with little ionization of gas molecules and arrive at the collector directly. In the latter case, that is, in the gas ionization mode, electrons return to the grid due to the negative electric field, and the ionized molecules are attracted to the collector. In both modes, the emission images on ITO phosphors can be observed, but the latter is more appropriate for the ionization gauge.

Fig. 3 shows the emitting images induced by the electrons and by the ions, respectively. The brightness is dependent on the applied grid voltage and the collector voltage. In Fig. 3(b), the collector voltage was 0V in order to create a negative electric field. Even when the collector voltage becomes negative, the emission image can be observed. However, since the electron emission from the CNT arrays and the ionization of gas molecules can be interrupted in the negative collector voltage, an optimal potential in the collector may exist and it must be determined experimentally. The current, ic detected in the collector is negative in the case of Fig. 3(a) because the emitting image is caused by the accelerated electrons. On the other hand, the current in the case of Fig. 3(b) is positive because the emitting image is caused by the ionized molecules. The latter can be used to measure the gas density in a vacuum chamber.

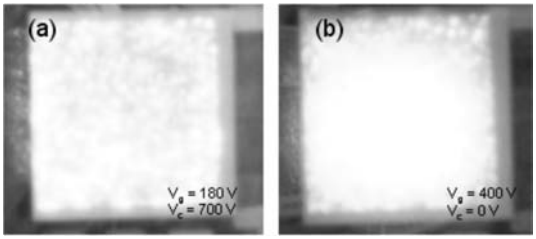

Fig. 3 Emitting images (a) in the electron emission mode and (b) in the gas ionization mode

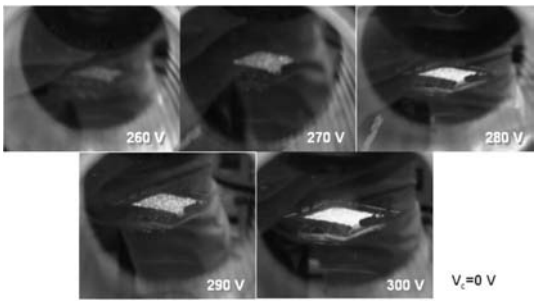

Fig. 4 Emission characteristics according to the grid voltages

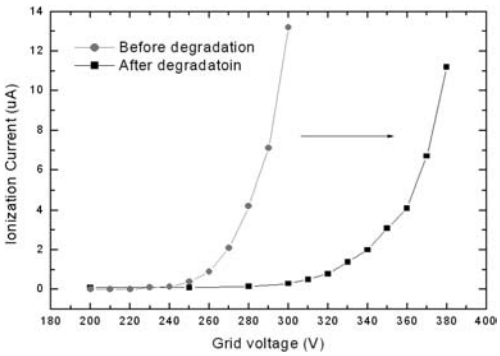

Fig. 5 Ionization current with respect to the grid voltage

The brightness in the ionization mode is dependent on the grid voltage since the number of ionized molecules increases according to the number of electrons emitted from the CNTs by the grid. Fig. 4 shows the brightness variation dependent on the grid voltage at V_c=0V.

Similarly, the ionization current which is detected in the collector increases like the above brightness. Fig. 5 shows the collector current variation with respect to the grid voltage at V_c= 0V. The ionization current in the collector starts to increase at a relatively low grid voltage. However, the emission performance decreases gradually as the length of time it is being used increases. This degradation characteristic is a very common problem in the CNT-based field emission.

2.3 Degradation

As mentioned above, micro cathodes manufactured from CNTs degrade gradually. One of main reasons for this degradation is that CNTs can be burned and removed under high electric fields. In order to reduce the degradation characteristics, pulse input can be applied to a device in the electron emission mode. Another main reason for CNT degradation is that the strong electric field between the grid and collector can attract the electrons in the ionization mode or the ions in the electron emission mode to the CNTs array. In this case, CNT arrays can be damaged directly by the accelerated ions or electrons, and indirectly by heat generation due to the ions and electrons impact on the grid. If the CNT array is damaged, the number of electrons emitted decreases rapidly. The rapid ionization current degradation according to time is shown in Fig. 6.

Fig. 7 shows the image of a grid damaged by electrons. This problem can be solved by placing another grid between the grid and the collector to act as an electron filter. The second grid can trap

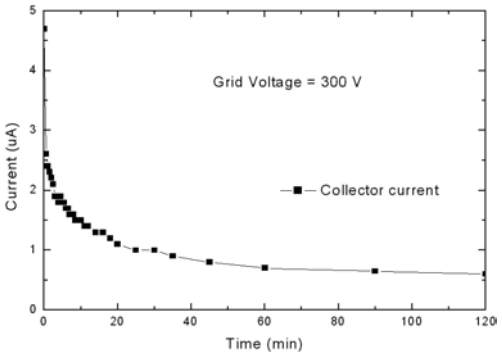

Fig. 6 Degradation in the ionization mode

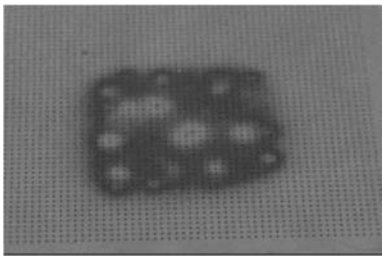

Fig. 7 Grid damaged by returned electrons

the electrons around it if there is potential between the grid and the collector. Also, since trapping the electrons enhances the probability of the ionization of gas molecules, the sensitivity performance of the gauge will be improved.

3. Experiments

3.1 Ionization characteristics according to the grid and collector potentials

As mentioned previously, if the collector voltage is much higher than the grid voltage, most of the electrons emitted from the CNTs reach the collector directly. In the electron emission mode, ions can be detected in the grid, not the collector due to the negative electric field. Some of the electrons can reach the grid directly from the CNT array. On the other hand, if the collector potential is lower than the grid potential, the electrons mainly return to the grid and the ions can be detected in the collector. However, if the electric field intensity is too high, the gas molecules in the chamber have no chance to be ionized since most of the electrons return to the grid as soon as they are released. This means that an optimal collector voltage exists to obtain a maximum ionization rate with respect to the grid voltage.

Fig. 8 shows the ionization experiment results when the collector voltage changes with respect to a few constant grid voltages. In the experiment, the ambient gas was N_2 and the pressure in the chamber was 3.0×10^{-6} Torr. The graph shows that after the collector current increased, it decreased again as the collector voltages increased. Also, the collector voltage values at the maximum collector current increased according to the grid

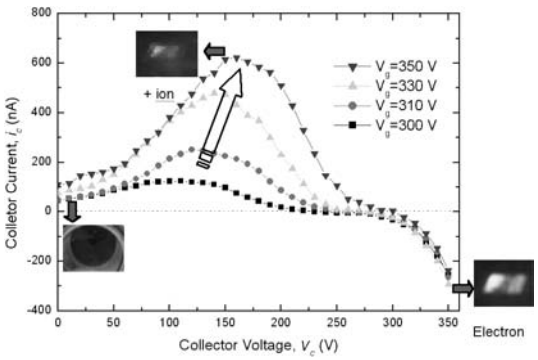

Fig. 8 Collector current variation according to the grid and the collector voltage

voltage. This means that the maximum ionization characteristic is dependent on the voltage difference between the grid and the collector.

During the experiment, the emitting image could be observed two times. In the low collector voltage below 50V, as shown in Fig. 8, the emitting image is not observed even though the collector current increases little by little. After that, the collector current increases more quickly and a strong emitting image can be observed in the maximum current. Also, as the collector voltage increases continuously, the total current decreases rapidly, and the light is turned off because the electrons can not be strongly accelerated any more due to the small potential difference. If the collector voltage increases to the grid voltage and even further than that, most of the ionized molecules are attracted to the grid and the electrons emitted from the CNTs reach the collector directly. In this case, the accelerated electrons turn on the light again, and it becomes the electron emission mode. The specific values in the graph can be changed according to the prototype, since it is dominantly dependent on gas, device geometry, and CNT emission characteristics.

From this experiment result, we can conclude that the collector voltage must be between the base voltage of the source (0V in this experiment) and the grid voltage in order to obtain maximum ionization characteristic.

3.2 Pressure characteristics

Finally, the ionization characteristics experiment according to pressure variation was carried out. In this experiment, there were two parameters dependent on pressure that must be obtained ; the number of electrons (source current) and the number of the ionized molecules (ionization current). Fig. 9 shows the source current detected in the CNT base plates and the ionization current detected in the collector, with respect to the pressure. The grid voltage and collector voltage were 260 V and 150 V, respectively.

As shown in Fig. 8, the number of electrons emitted is dependent on pressure. Similarly, the ionization current shows almost the same characteristics with the source current. The constant source current is best for the gauge, but ambient gas molecules interrupt the emission of the electrons as the pressure in the chamber increases. So, the ionization or the source current can not be used individually to measure the gas density. Instead, the ionization current ratio should be used, as shown in Fig. 10.

Fig. 10 shows the ionization current ratio of the collector current to the electron source current. As shown in the graph, this prototype device is sensitive to pressure in the range between 0.01 and 1 Torr, although the ratio increases little by little even below 0.01 Torr. Here, the low sensitivity in the low pressure range results from the long mean-free-path of the gas. The configuration of the ionization gauge being developed in this study, is planar, similar to that of the Schultz-Phelps gauge that has a range of 10^{-5} to 1 Torr. If the spacing of the electrodes increases, it will

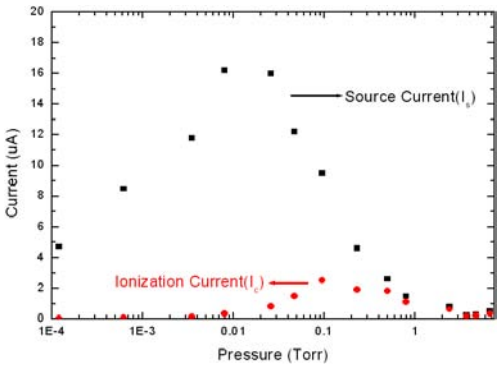

Fig. 9 Ionization characteristics according to pressure change

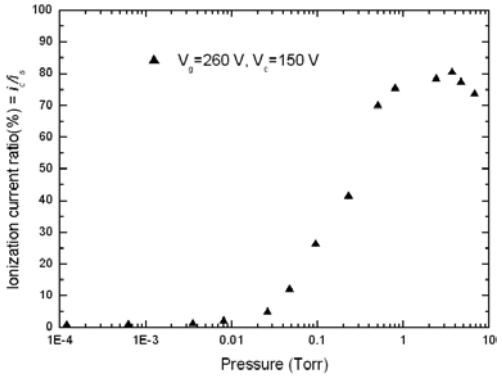

Fig. 10 Ionization current ratio according to pressure change

be possible to measure relatively low pressure.

4. Conclusions

In this study, the electrons emitted from a CNT array, not thermally generated like a conventional gauge, were used to ionize gas molecules in a chamber. Also, the emission characteristics of the CNTs and the ion current induced by the ionized molecules have been studied. The optimal collector voltage could be determined from observing the ionization current. Finally, the preliminary experimental results from the pressure range of 10^{-4} to 1 Torr have been shown. In the near future, the sensitivity variation dependent on the distance between the grid and the collector will be obtained. The device, with an additional grid as an electron filter, will be manufactured and the performance experiments will be carried out.

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