Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.830-831

P11-5

Vacuum Pressure Sensors Using Carbon Nanotubes as Electron Emitters

S. J. Kim[1], N. K. Choi[1], J. O. Jeon[1], S. H. Lee[1] and C. J. Lee[2]

[1]Kyungnam University, Div. of Electronic and Electrical Engineering
449 Wolyoung-dong, Masan, Kyungnam 631-701, Korea
Phone:+82-51-249-2646, E-mail:sjk1216@kyungnam.ac.kr
[2] Hanyang University, Department of Nanotechnology
Hangdang-dong, Seongdong-ku, Seoul 133-791, Korea

1. Introduction

Recently, carbon nanotubes (CNTs) have provided a various range of applications such as electron emitters[1], transistors[2], hydrogen storage for cell-driven vehicles[3] and chemical sensors[4]. Among these applications, much interest has been concentrated to the electron emitters in displays such as field emission displays (FEDs) with commercial expectation. CNTs own excellent field emission due to their needle-like shape and thermal stability.

The field emission from electrodes has been treated widely in electron devices, electron microscopy, MEMS systems and vacuum electronics besides displays. Especially field emission in vacuum electronics has played a role as an alternative to thermionic emission with advantages such as dramatically higher efficiency, less scatter of emitted electrons, faster turn-on times and compactness.

In this paper, we introduce fabrication technology of gas pressure sensors using CNTs as electron emitters, and discuss their static current-voltage behavior for vacuum measurement.

2. Device Fabrication

The sensor is composed of three parts; electron emitters, a spacer and an anode. Highly doped 4-inch n^+-type (100) silicon wafers were used as substrates for electron emitters. Iron (Fe) was deposited as a catalyst metal to the thickness of 10nm on the Ti-coated substrates using an electron-beam evaporator. CNTs were grown by thermal chemical vapor deposition (thermal CVD). During the thermal CVD process, C_2H_2 gas was supplied with a flow rate of 30 sccm for 10 min at the temperature of 850°C. The area of the CNTs grown on the Fe film is 3x3mm^2. A structural diagram of the electron emitters is shown in Fig. 1(a). As next step, spacer layer was prepared with pyrex glass of 500μm thickness for insulation. It was engraved to form air openings on the surface with a mask and a sand blast method, as shown in Fig. 1(b). Finally, the substrates for the emitters and the anode of the highly doped n^+- and p^+-type silicons, respectively, were combined into two steps with the patterned pyrex glass by an anodic bonding process at 400°C, as shown in Fig. 1(c).

Fig. 2(a) shows the image of spacer layers patterned on a thin glass plate with 4-inch diameter, by the process as mentioned in Fig. 1(b), and Fig. 2(b) shows the image of a sample which is combined by the anodic bonding between the spacer and the substrate for the emitters before the final anodic bonding between the spacer and the anode.

3. Result and Discussion

The proposed sensor operates by figuring out the change of initial breakdown voltage as a function of vacuum pressure based on Paschen's law. We measured static current-voltage characteristics in the vacuum pressure range from 1 to 10^{-3} Torr. High dc voltage was applied through feed-through electrodes, and the maximum voltage was 1000V which led to the electrical field of 2x10^{6}V/m.

By the Paschen's law, the initial sparking breakdown voltage in an air gap, V_s, is decided by a function of the product of gas pressure, p, and distance between two electrodes, d, and is expressed as

$$V_s = f(\mathrm{pd}). \qquad (1)$$

Breakdown in an air gap is generally caused from current multiplication by ions and electrons generated through collisions between neutral gases and electrons accelerated by electrical field. Therefore, the breakdown voltage is affected on the magnitude of charges produced by ionization, where the ionization coefficient depends strongly on gas pressure and identity.

Fig. 3 shows the dependence of the initial breakdown voltage measured with our devices for air and argon gases. For simplification, the initial breakdown voltage is defined here as the voltage necessary for 0.1mA current. As the result, it was shown that the initial breakdown voltage for two gases was increased with decreasing pressure in the chamber because the current multiplication is proportional to the density of neutral gas which can generate a positive ion and an electron by collisions.

By the way, the breakdown voltage in argon compared with air was decreased due to relatively large secondary ionization coefficient. In general, electronegative gases such as SF6, Freon, oxygen and nitrogen reattach the electrons very quickly after ionization, and then become neutral. Therefore they have relatively low secondary ionization coefficient, consequently the current multiplication becomes lower than that of inert gases.

4. Conclusion

In this work we showed a fabrication technology of gas pressure sensors using CNTs as electron emitters for vacuum measurement. The sensors were fabricated using the silicon-glass anodic bonding along with the typical Si process, and their initial breakdown characteristics were measured as a function of vacuum pressure. As the result, even though it should be realized that there are many other factors which have an effect on the breakdown of a gap, the sensors led to similar result as predicted by Paschen's law, and showed a possibility as gas pressure sensors applicable in a vacuum range from 1 to 10^{-3} Torr.

Acknowledgement

This work was supported by grant No. R05-2003-000-11165-0 from the Basic Research Program of the Korea Science & Engineering Foundation, and we appreciate Prof. Nakayama Lab at Department of Physics and Electronics, Osaka Prefecture University in Japan, for the process support of Ti and Fe depositions.

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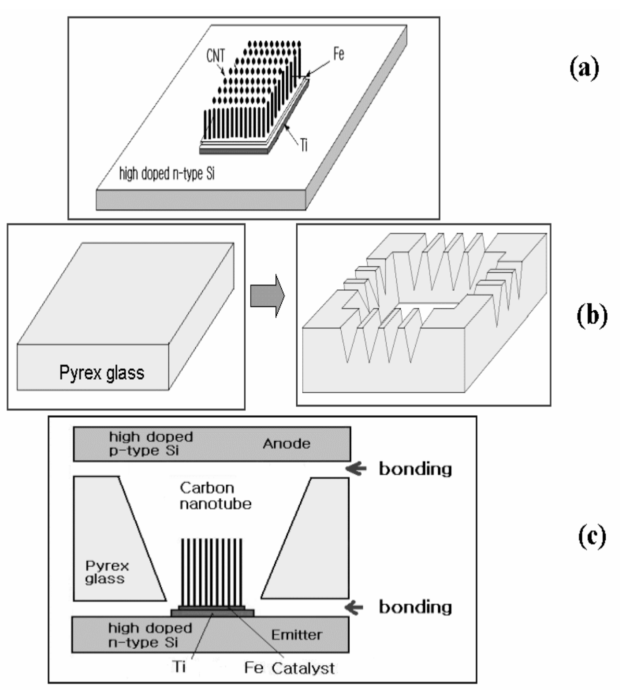

Fig. 1 Fabrication process: CNT electron emitters (a), glass patterning by the sand blast method (b), and Si/glass anodic bonding (c)

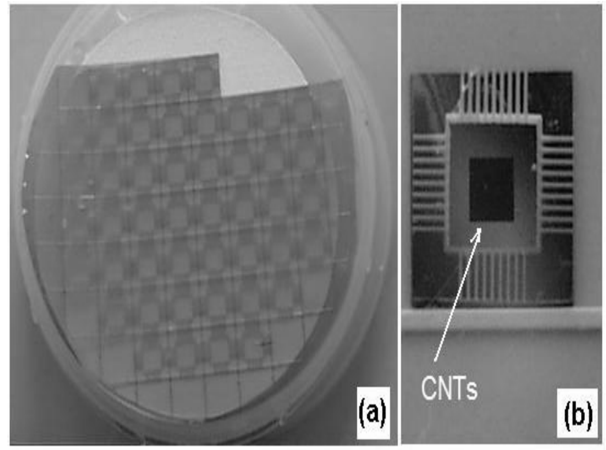

Fig. 2 Images of a patterned pyrex glass (a) and a sample combined by the anodic bonding process between a Si substrate and patterned glass (b)

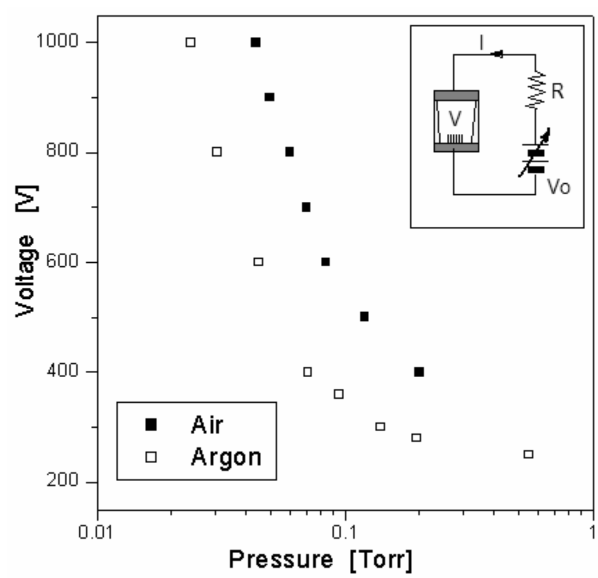

Fig. 3 Dependences of initial breakdown voltage on vacuum pressure for different gases: air and argon