A MEMS-Based Ionization Gas Sensor Using Carbon Nanotubes and Dielectric Barrier

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Abstract—We have demonstrated here the successful operation of an ionization gas sensor with gap spacing 2~10 μm and using CNTs (carbon nanotubes) as the electrode material. By set up an appropriate threshold current, the application of less than 20 V DC bias could generate electric field enough to effectively ionize various gases in atmospheric pressure. Working by the fingerprinting ionization characteristics of distinct gases, the sensor can effectively distinguish several gases by their various breakdown voltages and serves as an effective human breath monitor. TiO₂ dielectric barrier is introduced to the discharging system to improve the performance of the device. Experimental tests prove that with the dielectric barrier discharge mechanism has improved both the stability and ionization capability of the device.

Keywords—CNT (Carbon Nanotubes); Gas sensor; Dielectric barrier layer

I. INTRODUCTION

Ionization gas sensors operate based on fingerprinting ionization characteristics of different gases. Compared to absorption-based gas sensors, they are not limited by the electrophilicity or absorption energy of gases; instead, ionization-based sensors are sensitive to the gaseous ionization and drift property, which gives them many properties such as faster response, quicker recovery, hard to be poisoned, and sensitive to many inert gases. Traditional ionization sensors are limited by their huge, bulky architecture, high power consumption and risky high-voltage operation. Recently, some experimental and theoretical studies have proved that the gas discharge onset voltage can be significantly reduced by decreasing the gap size [1]. Further more, because of CNT’s unique one-dimension structure and negative electrophilicity, the utilization of CNTs (Carbon Nanotubes) as electrodes can efficiently converge the electric field energy and initiate discharge at a voltage lower than tradition ionization device [2, 3]. On the other hand, the stability and reproducibility of the traditional ionization devices are limited by the huge current and high temperature accompanied with the electrical breakdown [4]. DBD (Dielectric barrier discharge) mechanism has been widely used in plasma industry to control plasma activity and maintain the processes of charged particles stay in silent discharge. Therefore, DBD structure would be useful in ionization devices to improve the stability and reproducibility of the ionization devices. [5, 6]

In this work, an ionization gas sensor, which equipped with short-gap spacing, carbon nanotube electrodes and DBD mechanism, is designed and realized through conventional microfabrication facilities. The gas discharge test shows that the device can be functioned at quite low supply voltage and power consumption. In addition, DBD layer (a thin TiO₂ film) not only improves the reproducibility of the device but also remarkably decreases the breakdown voltage.

II. DEVICE DESIGN AND FABRECATION

The schematic diagram of the manufacture processes is shown in Fig.1.
The device is a flat parallel slots structure with the height of each beam about 10μm and the spacing between electrodes of 2~10μm, the whole device is 9mm*9mm, including 10 gaps of different cathode-anode spacing. As indicated in Fig.1, firstly, a Cr/Cu seed layer of 180nm in thick was sputter deposited on a glass substrate, then be patterned by wet etching (Fig.1a), then deposited nickel beams of 10μm in height on the seed layer (Fig.1b). CNT film was deposited by electrophoresis method [7], the thickness of film was 0.3±0.1μm (Fig.1c). The density of the CNTs was controlled by deposition time in order to make sure the distance between the CNT tips was the same as the height of these out-of-plane tips. This was the best compromise between enough number of emitting cathodes and the field-screen effect of too many tips [3]. Finally a thin film (80±20nm) of TiO2 dielectric barrier was deposited by magnetron sputtering serving as DBD (dielectric barrier discharge) layer (Fig.1d).

The SEM image of the edge of device is show in Fig.2. There are lots of out-of-plane CNTs deposited on the edge of the beams, whose sharp tips would effectively encourage electric field. As it has been pointed out before, considering the field-screen effect, the depositing amount of the CNTs has been set to a proper density.

### III. DEVICE PERFORMANCE

The gas discharge electrical characteristics are monitored directly by Agilent 4156C. Fig. 3 demonstrates the typical discharge I-V curves of air. As it shows in the picture, breakdown happens at the voltage of 28.3V. There is an acutely increase of current from 200nA to over 10μA. The performance supports that the incorporation of CNTs into the short-gap electrode system can achieve a considerable decrease of the onset voltage of ionization sensors. However, since the current is multiplied by nearly 50 times happened in less than 0.01s, it is easy to cause damage to the device. Although lots of the device could survive the test, sometimes, this breakdown phenomenon would cause perpetual destructions, that make the device became a constant resistance or alter the I-V curve and breakdown properties of the devices. We believe it is because that the instant current at the breakdown point may be much more large than 10μA, and may cause high energy release in a small space, this could consequently alter the structure of metal electrodes or the position of CNTs on the surface of electrodes.

To improve the reproducibility of test results, we believe the test should concentrate on pre-breakdown area, where the current has already been increasing acutely, meanwhile the avalanche of electrical particles are still under control. In this case in Fig.3, the test should stop at the voltage of 26.5V, while the current of 500nA should be set as threshold current. Since the current here has already been increasing very quickly, experiments proves that, actually, when adding constant voltage of 26.5V, with the accumulation of ions, the self-sustain Townsend discharge would happen in seconds.

Fig.4. The discharge I-V curves of 6 different gases.
After set a proper threshold current, CNT based ionization device could be used to distinct the identities of several gas species, such as helium, argon, nitrogen, oxygen and air by their various breakdown voltages, under a working voltage of 30V, as the I-V curve shows in Fig.4. The tests were handled in a vacuum chamber at 280–300 K. In order to obtain a high-purity (> 99.9%) gas, the chamber was pumped to $8 \times 10^{-3}$ Pa, then target gas was introduced to 1 atm; this procedure was repeated for three times to increase the purity. 6 different gases were tested under the threshold voltage of 10nA with a device of 8µm in gap width, as it shows in Fig.4. The sensor could successfully distinguish these different kinds of gases by their distinct breakdown voltages, including the inert gas like helium and nitrogen which is hard to detect with absorption-based sensors. For different devices or different gaps in one device, the breakdown voltage is various, because the cathode-anode distance and the distribution of CNTs could not be exactly uniform, yet the tendency is the same: the smaller the gap is, the lower the breakdown voltage would be. In most devices with the gap of 5µm, the breakdown voltage of air is about 5V, while it needs 28V to charge air at the gap of 15µm.

Fig.5. The gas discharge I-V curves of the same device before and after TiO2 coated.

Dielectric barrier of a thin layer of TiO2 with thickness of 80±20nm is deposited on the surface of the CNT film to improve the stability of the device. The DBD (dielectric barrier discharge) layer serves as a resistance or deceleration layer to stop the cold plasma growing into hot plasma too quickly, since the electrons or other electric particles will be resisted by the DBD layer, but not directly reach the electrodes. The by-product of this phenomenon is the accumulation of charges on the surface of DBD layer. After coating the DBD layer, as shown in Fig.4, the reproducibility of the device is significantly improved then it does before DBD layer coated as shown in inset diagram of Fig.3, the I-V curve in this case could repeat itself lots of times by the exactly same way. Meanwhile, we notice that after the dielectric barrier deposition, the working voltages of the devices are significantly decreased. We suggest the contribution of charges remaining on the surface of electrodes (Malter Effect) should be considered in this case.

Both the devices with or without DBD layer have a good sensitivity to human breath because of the abundant ionized particles in it. Fig.6 shows the response of three times of human breath, each peak of the curves reflects to one breath, meanwhile the device do not response significantly to nature wind as the green line shows in the picture. However, the capability of monitoring human breath is improved in DBD coated devices, which could response to human breath by a larger current at a lower working voltage. As it shows in Fig.6, the device can detect human breath at the working voltage of 1V by the distance of 30cm away from nose, the bias voltage used to be at least 5V to achieve the same scale of response before dielectric layer deposited. Although the working voltage is much less than the breakdown voltage (the breakdown voltage of air in this device is about 10V), the device could magnify the charges in breath by avalanche processes in the electrodes field. Furthermore, the device could even response human breath without any working bias voltage in a short while after the last measurement (Fig.5, red curve, first peak), after the remaining charge in the electrodes is large enough to accelerate and magnify the charges in human breath. However, this phenomena would disappear for a short while after the last test, when the charges are neutralized, it shows in Fig.5, red curve, it fails to reflect the second and third breaths as it does in black and blue curves 8 sec after the previous test.

IV. CONCLUSIONS

An CNT based and dielectric layer included ionization gas sensor is introduced in this paper. The incorporation of CNTs, DBD layer and the short gap electrode system achieves a considerable decrease of working voltage. Besides, the DBD layer effectively improves the reproducibility of the device. The gas sensor could not only distinguish gases by their distinct breakdown voltages, but also performance a good sensitivity of human breath.
REFERENCES


