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Carbon nanotubes based vacuum gauge

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Abstract. We have created an ionization type Vacuum gauge with sensor element based on an array of vertically aligned carbon nanotubes. Obtained asymmetrical current-voltage characteristics at different voltage polarity on the electrode with the CNTs. It was found that when applying a negative potential on an electrode with the CNTs, the current in the gap is higher than at a positive potential. In the pressure range of 1 ÷ 10^3 Torr vacuum gauge sensitivity was 6 mV/Torr (at a current of $4.5 \cdot 10^{-5}$ A) and in the range of 10^{-5} ÷ 1 Torr was 10 mV/Torr (at a current of $1.3 \cdot 10^{-5}$ A). It is shown that the energy efficiency of vacuum gauge can be increased in the case where electrode with CNT operates as an emitter of electrons.

1. Introduction

The formation of carbon nanotubes (CNTs) with given geometric parameters and the study of their properties are considered to be a really important task, both in terms of basic research and their future application in electronic devices [1, 2]. CNTs possess a number of unique features, such as stable emission characteristics, electrical conductivity, high aspect ratio and chemical stability, which allows us to use them to create sensitive elements for micro- and nanoelectronic devices, gas sensors and vacuum gauges [3-8].

To determine the degree of vacuum we can use capacitive, thermocouple, thermistor and ionization gauges [9-12]. Thermistor and thermocouple ones are often used in microelectronic process equipment where they operate in the pressure ranges of 10^{-3} – 760 and 10^{-12} - 10^{-1} Torr, respectively [13-14]. Ionization vacuum gauges, whose operating principle is based on the ionization of gas molecules in the discharge gap and the following measurement of the ion current flowing between the electrodes, are also considered promising [15]. The use of an array of vertically aligned CNTs to ionize gas molecules can significantly reduce the operating voltage and power consumption of the ionization vacuum gauges [16].

In order to create the arrays of vertically aligned CNTs on contact pads and thus make such structures suitable for ionization gauge sensor elements, plasma-enhanced chemical vapor deposition (PECVD) can be used [17].

Our aim is to create and study the parameters of a vacuum gauge prototype with a sensor element based on an array of vertically aligned CNTs.

2. Experiments and methods

To create experimental samples, we used Si (100) wafers with resistivity 0.001 - 0.005 Ω·cm (Universitywafer, USA). RCA chemical cleaning was carried out by means of Amerimade (Amerimade Technology Inc., USA). The deposition of the contact layer (Ti, 250 nm), the barrier layer (Cr, 20 nm) and the catalytic layer (Ni, 10 nm) was carried out using the AUTO 500 magnetron sputtering set (BOC Edwards, UK). The topology of the lower electrode with CNTs was created by means of photolithography on the Ti film using the SUSS MJB4 set (Suss MicroTek, Germany). Cr and Ni films were deposited in a single cycle through a mask. The resulting Ni/Cr/Ti/Si structure was later placed into the chamber of the PECVD module of the nanotechnology complex NANOFAB NTK-9 where we grew the array of vertically aligned CNTs with a height of about 3 µm. The description of process condition can be found in [18].

To manufacture the upper electrode, we used a Si (100) wafer with resistivity 0.001 - 0.005 Ω·cm where, similarly to the first step, we formed a Ti film with a thickness of 250 nm. Then we deposited a Si3N4 layer with a thickness of ~6 µm using the plasma chemical deposition set STE ICPd81 (SemiTEq, Russia). After that, we formed dielectric supports by means of photolithography. At the final stage the upper electrode was connected to the lower one. The design of the prototype provides a ~3 µm gap between the upper electrode and the CNTs, which is shown in Figure 1.

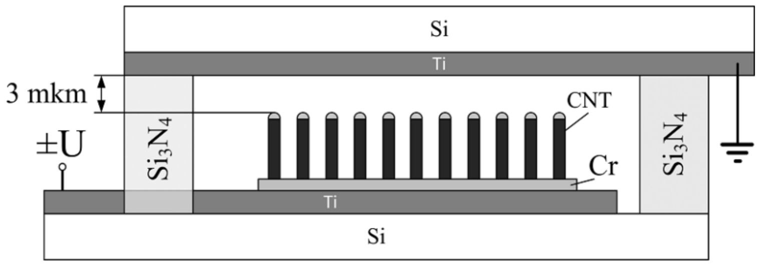


Figure 1. The design of the prototype.

We studied the work of the gauge using a measuring stand constructed on the basis of a chamber with the ultimate vacuum of $8 \cdot 10^{-6}$ Torr. The measurement was carried out using the VAC picoammeter Keithley 6487 (Keithley Instruments Inc., USA) with the upper electrode grounded and a voltage of ±20 V applied to the lower electrode with CNTs at a temperature of 300 K. The pressure in the range of 760 – 10^{-5} Torr was controlled using a calibrated gauge MKS Series 999 Quattro. To carry out the comparative analysis and qualitative assessment of the influence of the electrode with CNTs on the gas gap brakedown, we created a prototype of the sensor with a similar structure (Figure 1) but with no CNTs on the lower electrode. To ensure that the measurement conditions were identical, the gap between flat electrodes was decreased to 3 µm.

3. Results and discussion

Having analyzed the SEM images of the lower electrode with CNTs (Figure 2), we found that the CNTs we had grown had a diameter of 80±9 nm and a height of 2.9±0.13 µm, which, taking into account the thickness of the contacts, confirms the fact that the value of the gap between the CNTs and the upper electrode was ~3 µm.

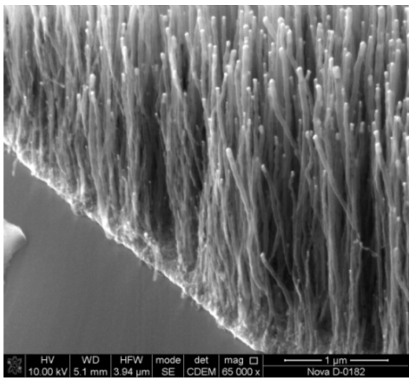
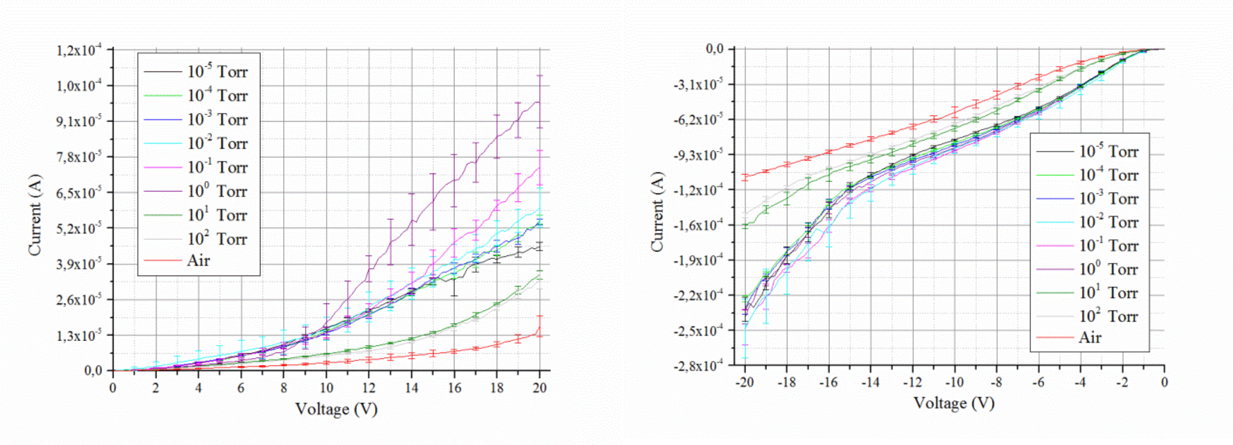


Figure 2. The CNT array grown on the lower electrode.

The analysis of the current-voltage characteristics of the prototype (Figure 3) shows the effect of the pressure on the flowing current. Notably, the forward and reverse branches of the CVC graph are asymmetrical.



a) b)

Figure 3. The CVC of the prototype at different pressures with a) positive and b) negative voltage polarity.

Having analyzed the current-voltage characteristics of the prototype (Figure 3), we got the opportunity to plot the current against the pressure at a range of voltages (±20 V) applied to the lower electrode with the CNTs (Figure 4).

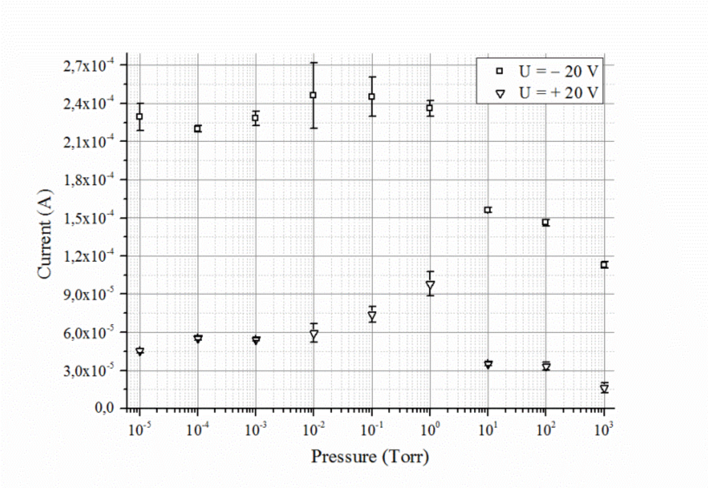


Figure 4. The dependence of the current on the pressure at different voltages applied to the electrode with CNTs.

Figure 4 shows that, with equal absolute values of the voltage, the current has greater values when a negative voltage is applied to the electrode with the CNTs compared to the case when we applied a positive voltage. This effect is associated with an additional electron emission taking place as a result of the concentration of the electric field at the tops of CNTs due to their small diameter and high aspect ratio [19]. Notably, the prototype of the sensor with planar electrodes, i.e. with no CNTs on the lower electrode, did not show the presence of any current even when the range of the voltage applied was 0 ÷ ±50 V.

Figure 5 shows the dependence of the voltage on the pressure at constant currents and a positive voltage applied to the electrode with CNTs. Its shape can be accounted for by the fact that at a fixed value of the gap between the electrodes and the pressure values increased from 10^{-1} to 10^{3} Torr, the number of collisions between electrons and neutral atoms and molecules increases accordingly, which results in the reduction of energy of electrons accumulated along the mean free path. We should also note that it is necessary to increase the voltage applied in order to maintain the current.

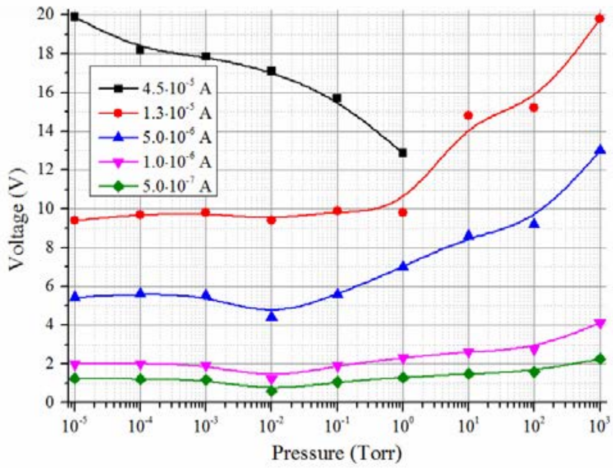


Figure 5. The dependence of the voltage on the chamber pressure at various currents.

According to [20], at pressures of less than 10^{-1} Torr the mean free path increases and so does the accumulated energy of the electrons whereas the number of collisions drops, which reduces the probability of impact ionization. Therefore, to maintain a constant current it is necessary to increase the electron energy on the mean free path by increasing the voltage. However, our experiments showed that within the pressure range of 10^{-5} – 10^{-1} Torr and at currents of $5{\cdot}10^{-7}{\div}1.3{\cdot}10^{-5}$ A the voltage remains practically unchanged, which does not show consistency with the results obtained in [20]. The result we achieved may be explained by the fact that the distance between the electrodes (~3 µm) in our prototype is much smaller than the mean free path of electrons, which is about 500 µm at low vacuum [21]. Thus, there are only emitted electrons which contribute to the total current, and they cover the interelectrode distance almost unhindered in vacuum. In order to maintain a predetermined current when the CNTs act as electron emitters (there is a negative voltage applied to the CNT electrode), it is necessary to apply a voltage 4 times lower than in the case where electrons are emitted from a planar electrode (Figure 6).

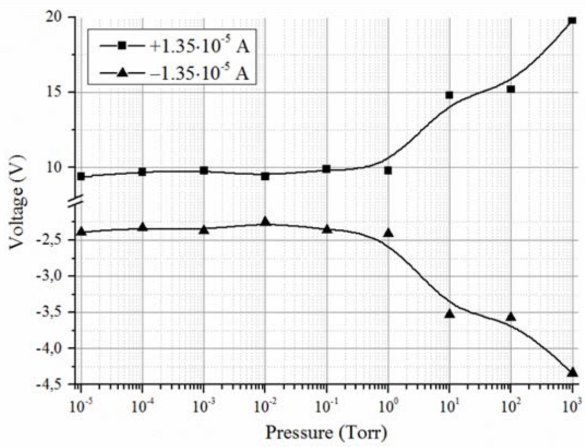


Figure 6. The dependence of the voltage on the pressure.

The analysis of the results presented in Figure 5 shows that for the prototype discussed we can talk about two sensitivity ranges: 10^{-5} – 1 Torr and 1 – 10^{3} Torr, for which the sensitivities are 6 mV/Torr (at an operating current of $4.5\cdot10^{-5}$ A) and 10 mV/Torr (at an operating current of $1.3\cdot10^{-5}$ A), respectively.

4. Conclusion

We created and studied a prototype of the vacuum gauge with a sensor element based on an array of vertically aligned CNTs. Within the pressure ranges of 1 – 10^{3} Torr and 10^{-5} – 1 Torr the prototype showed a sensitivity of 6 mV/Torr at an operating current of $4.5\cdot10^{-5}$ A, and 10 mV/Torr at an operating current of $1.3\text{x}10^{-5}$ A, respectively. We discovered that the energy efficiency of the sensor can be increased when the CNT electrode acts as electron emitter. In such a mode it is necessary to apply a lower voltage (4 times lower for our prototype) in order to maintain a predetermined current value, compared to the case where we used a planar electrode without CNTs to act as electron emitter. The power consumption of our prototype was less than 7 mW, which provides an opportunity to use it in mobile devices.

Acknowledgments

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