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Investigation of an extractor gauge modified by carbon nanotubes emitter grown on stainless steel substrate

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ABSTRACT

This paper presents an investigation of carbon nanotube (CNT) emitter-based ionization gauge. The metrological performances of this CNT emitter-based ionization gauge were investigated and studied by numerical and experimental methods. The electron source was constructed with multi-wall nanotubes (MWNT), which were grown on stainless steel substrate using thermal chemical vapor deposition (CVD) technique. The influence of anode and reflector voltages on the anode current I_a and ion current I_+ were studied in this work, respectively. The electron transmittance increases significantly along with the increase of anode voltage, and I_+ increases dramatically as the increase of reflector voltage from 0 V to 525 V, but it decreases again with the further increase of reflector voltage to 600 V. The studied gauge with CNT cathode has good measurement linearity from 1.0×10^{-8} Pa to 5.0×10^{-4} Pa and a gauge sensitivity of 0.03 Pa^{-1} for argon is achieved.

1. Introduction

The hot and cold cathodes ionization gauges are used widely in ultra-high vacuum (UHV) measurement. However, several shortcomings in ionization gauge limit its application in cosmic space, high energy physics, cryogenic environment, and so on. The hot filament, consuming dozens of watt, has significant hot degassing effect, thermal and light radiation effects, which lead to additional troubles in UHV measurement [1], for example, (1) increasing the outgassing originating from the envelope by radiation from the hot filament; (2) evaporation of neutrals and positive ions from the hot filament; (3) chemical reactions of gas molecules at the filament surface leading to change in the gas composition. In addition, the hot filament is too fragile to resist mechanical vibration stress. For these reasons, lots of cold cathode gauges were applied in UHV measurement in space exploration [2]. Recent studies demonstrated that the application of cold cathode in ionization gauge could decrease power consumption and eliminate the thermal and light effects simultaneously, however, there are still many drawbacks in this gauge, such as measurement non-linearity, low accuracy, slow response, magnetic effect and discharge delay at very low pressure etc., which limit their applications range to some extents [3–5].

For overcoming these problems in conventional ionization gauge, lots of researches and applications about ionization gauge with field emission cathode (FEC) have been actively carried out during the past years [6]. Typical example of such cathode was Spindt-type field emission array (FEA), which was successfully applied as electron source in ionization gauge and mass spectrometry in ROSETTA spacecraft [7,8]. However, the Spindt-type FEA is susceptible to ion bombardment, resulting in the degradation of emission current in a relatively short period. Recently, carbon nanotubes (CNTs) have attracted considerable interest as field emission electron source due to their excellent physical and mechanical properties together with unique structure [9–11]. Comparing with conventional hot cathode, CNTs electron source has advantages of low consumption, fast response and free from thermal and light radiations. Meanwhile, the emission current of CNTs electron source is more stable than that of FEA. Therefore, the application of CNT emitters in ionization gauge is hoped to solve the troubles in conventional ionization gauge and achieve UHV measurement.

Recently, some successful works have been carried out in CNT emitter-based ionization gauges. So far, however, no ionization gauge with CNT cathode showed a linear pressure measurement range below 4.0×10^{-8} Pa [6]. In all the previous studies about ionization gauges with CNT cathodes, empirical procedures were absolutely predominant, and the influence of electric parameters

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on ionization gauge performances are seldom investigated by combining numerical and experimental methods together. In the present work, the influence of electrode voltages on sensitivity, electron transmittance, and ion collection efficiency are simulated by numerical method, and the metrological performances of ionization gauge are investigated in experiment based on the simulated results. The present ionization gauge with CNT cathode has a lower limit of pressure measurement about 1 × 10^{-8} Pa, which is the lowest one in all the reported CNT emitter-based gauges.

2. The simulation and experiment

2.1. Theory

The work principle of ionization gauge is the measurement of ion current, which originates from collision of emission electrons and molecules inside of the anode space. Namely, under the action of electric field force generated by gate mesh, part of emission electrons produced by cathode could pass through gate and anode, and impact with the gas molecules between the anode and the collector to generate ions. The generated ions are captured by the collector. The relationship between ion current and the pressure can be expressed as Equation (1).

$$I_+ = I_a S p + I_r \tag{1}$$

Where, I_+ is ion current. S is sensitivity of gauge which is a constant value when the gauge structure and electrodes voltages are given. I_a is the anode current which is the electron current contributing to the gases ionization. I_r is the residual current caused by electron stimulated desorption (ESD), soft X-ray, etc. If I_+ is greatly larger than I_r, the latter can be neglected. p is the test pressure.

For hot ionization gauge, I_a approximately equals to the cathode emission current (I_e). However, in CNT emitter-based ionization gauge, the I_a is not identical to the I_e as a large part of the emission electron is captured by gate mesh. Therefore, the effective fraction of total emission current actually available for gas ionization within the anode cage is significantly lower than I_e and depends strongly on the operating potential and the transparency of the gate mesh. Meanwhile, according to the work principle of the ionization gauge with CNT cathode, S is a key factor to influence the lower limit of pressure measurement by this device. In theory, the mathematical definition of S could be expressed as Equation (2). Where, electron effective length L_e and ionization cross section σ are determined by gauge structure and electrodes voltages.

$$S = \frac{L_e \sigma}{kT} \tag{2}$$

Here, k is Boltzmann constant, T is absolute temperature, σ is related with electron kinetic energy in the ionization space and proportional to the product of collision cross section and ionization efficiency ε.

2.2. Modeling and simulation

The model of ionization gauge based on Leybold IE514 extractor gauge was constructed to optimize the electrodes parameters. As is shown in Fig. 1, the diameter of CNT cathode was 4 mm, and transparency of gate mesh was about 60%. The distance between CNTs array and gate was ~190 µm. Other electrodes structure parameters were similar to that of IE514 extractor gauge. The finite element grids were generated by means of ions optic software Simion 3D 8.0 [12]. Overall number of hexahedron grid unit approaches to 10^8. The length of one grid corresponds to 0.05 mm in real scale.

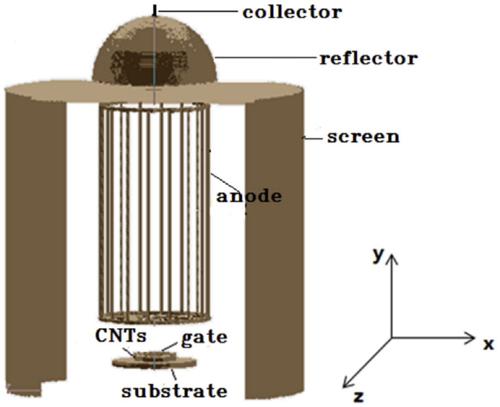

Fig. 1. Physical model of CNT emitter-based extractor gauge.

After ignoring the effect of space charge, the finite difference over-relaxation iteration method was used to solve Poisson equation for analyzing electric field and potential distributions. The trajectories of particles were calculated by classical Runge–Kutta method, and the overall path length L was calculated through “User Program” module. All the nodes coordinates (x, y, z) were stored along electrons motion trajectories. Path length L is the sum of distance ΔL between two adjacent nodes.

In the simulation, 2000 electrons, defined as I_e, were set randomly on the surface of CNT emitter, while 1000 gas ions were set in the ionization space at random. The initial kinetic energy of electrons and gas ions were all set to be 0 eV. With the help of gate extraction field, electrons passing through the gate and contributing to gas ionization process were defined as anode current I_a, and the ratio of I_a and I_e was defined as electron transmittance, which represents the effective contribution of I_e for gases ionization. Meanwhile, ion collection efficiency γ was defined as ratio between ions accepted by collector and initial gas ions, which was mainly influenced by reflector voltage V_r.

Furthermore, as is demonstrated by Equation (2), the gauge sensitivity S is determined by L_e and σ. Under specific temperature, the total length L_t could be determined via summing the overall length of all electrons trajectories. And L_e was calculated from effective trajectories distributed in effective ionization space [11].

For ionization cross section σ, it was closely related with electron kinetic energy E in the ionization space. The mathematical relationship between σ and E was expressed as Equation (3), which was obtained by Lotz according to lots of experimental data about ionization cross section of various neutral particles [13]. The specific experiment results were also reported by Tate et al. The variation curve of σ along with anode voltage V_a possesses classic bell-like shape [14].

$$\begin{cases} \sigma = \zeta_1 \dfrac{a \cdot \ln(E/\chi_1)}{\chi_1 \cdot E} \left[cm^2\right], & if\ \chi_1 \le E \le \chi_2 \\ \sigma = \sum\limits_{i=1}^{N} \zeta_i \dfrac{a \cdot \ln(E/\chi_i)}{\chi_i \cdot E} = \overline{\zeta} \dfrac{a \cdot \ln(E/\overline{\chi})}{\overline{\chi} \cdot E} \left[cm^2\right], & if\ E \ge \chi_N \end{cases} \tag{3}$$

Where, σ is electron impact ionization cross-section, E is electron kinetic energy (eV), χ_1 is ionization potential for outermost shell electrons, χ_2 is the ionization potential for next inner (sub)-shell electrons, etc., $\overline{\chi}$ is a weighted mean of χ_i (i = 1,2,3,……N). a equals to 4.0 × 10^{-14}. As a slowly variable function, ζ_i asymptotically reaches the number of equivalent electrons and is no less than 0.5. ζ_1 means the “effective” or “equivalent” number of electrons in outer shell of atoms which contributes to the cross section. Of