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Short communication

Metrological properties of an ionization gauge with carbon nanotube cathode in different gases

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ABSTRACT

A novel CNT-cathode ionization gauge was developed in this work, and its vacuum metrological characteristics in different gases were studied systematically. A good measurement linearity between normalized ion current and gas pressure is achieved from 10^{-8} to 10^{-4} Pa in N_2, H_2, O_2 and air, respectively, and the linear response region for He only lies in the range from 10^{-7} to 10^{-4} Pa. The lowest measureable pressure with this gauge is about 1×10^{-8} Pa in O_2 gas, which is one order of magnitude lower than the reported same gauge type with CNTs cathode. It is also found that the gauge sensitivities are closely dependent upon gas species and anode voltage, and a high sensitivity factor as high as 0.205 Pa^{-1} is acquired for N_2 under an anode voltage of 300 V, which is the first reported CNT-cathode ionization gauge whose sensitivity is higher than the parent hot cathode one.

In recent years, cold field emitters have been received much attention for various vacuum electronic device applications, which are hoped to overcome the limitations of conventional thermionic electron source [1]. Among the numerous cold field emission materials, CNTs are regarded as the best candidates for electron source in various related vacuum devices, including in x-ray tube [2], ionization gauge [3–7], flat panel display [8], microwave power amplifiers [9] etc, due to their excellent electrical properties, thermal conductivity, chemical inertness, tensile strength and unique structure characteristics. In particular, CNT emitter-based ionization gauge have received steadily growing interest since they have great advantages over the conventional hot cathode ionization gauge such as low power consumption, fast response, free from thermal outgassing and light radiation, and this novel CNT-cathode ionization gauge would probably address the long-standing problems in ultrahigh vacuum (UHV) even extremely high vacuum (XHV) measurements [3,6]. However, it is well known that a high sensitivity is necessary to measure extremely low pressure for an ionization gauge with low cathode emission current [3]. In this sense, the commercially available ionization gauges such as Bayard–Alpert gauge (B-A gauge) and extractor gauge have unique advantages due to their elaborate structure design. Recently, there have been several studies on the metrological properties of ionization gauge with CNT cathode [5,10–14], most of them, however, used organic binder during the cathode making process. The organic binders can still remain even after baking at high temperature for a long time, and their outgassing would cause additional troubles in obtainment UHV, let alone the pressure measurement. On the other hand, relatively limited experimental works have been carried out in the literature concerning the metrological behaviors for ionization gauge with CNT cathode in different gases even though it is frequently necessary and desirable to measure pressure in a environment which contains different gas species [14–16]. Thus it is very interesting to evaluate the metrological characteristics of high sensitivity ionization gauge with CNT cathode in various gases to determine the application scope of this novel cathode ionization gauge.

In this work, the CNTs directly grown on stainless steel substrates were used as an electron source in commercialized ionization gauge (IE414), and its metrological characteristics, including linear measurement range and sensitivity, in different gases were evaluated systematically.

The vertically aligned CNT arrays were grown on conductive stainless steel (type 202) substrates by CVD apparatus using C_2H_4

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and H_2 as working gases. The microstructures of the CNTs were characterized by field emission scanning electron microscope, high resolution transmission electron microscope and Raman spectroscopy, respectively.

The ionization gauge used in this study was a commercialized Leybold IE414 BAG, whose hot filament was replaced by a field emission electron source. The electron source consisted of a CNT array grown on stainless steel substrate and a gate electrode, and which was installed beside the helix-shaped grid. The CNT array had a size of 2.8×2.8 mm^2, and the gate electrode was a 4×4 mm^2 stainless steel mesh with ~70% physical transparency. The distance between gate and anode was ~2.5 mm. The metrological behaviors of this novel cathode BAG were investigated on an UHV system. The testing gas was admitted into the vacuum system via a needle inlet valve to obtain the desired pressure. A calibrated extractor gauge (Leybold, IE514) was selected as reference gauge in the experimental period, and the pressure reading for different gases was corrected according to the sensitivity factors for the corresponding gases relative to nitrogen [17]. The background signal was subtracted during data processing like to Takahashi et al. [18].

The microstructures of the as-received CNT and CNT array were studied by means of different techniques, and the corresponding results are demonstrated in Fig. 1. It can be seen from Fig. 1a and its inset that the as-received CNTs are highly tangled with each other and formed cone-like structures on top layer, which is actually very benefit for field emission due to the weak screening effect. The crystallization and structural perfection of the present CNTs were estimated by using Raman spectroscopy, and the typical spectra of the CNT arrays grown on different substrates with same experimental run are demonstrated in Fig. 1b. It is evident that the present spectra are characterized by D peak (disorder) and G peak (graphitic) appearing at 1340 and 1590 cm^{-1}, respectively, which are the typical features of multi-walled CNT. The D peak is closely related with disordered carbon while the G peak indicates crystalline graphite [19,20]. Generally speaking, the intensity ratio of the G and D peaks, I_G/I_D, is usually used as a parameter characterizing the crystallinity in CNT structures. In our cases, the I_G/I_D varies among different samples in a relatively wide range from 1.7 to 2.2, indicating that the CNT arrays grown on different substrates have dissimilar crystallinity. However, it is worth pointing out that the values of I_G/I_D for the present CNTs arrays are comparable to or even larger than the previously reported high-quality CNTs [21], indicating that the present CNTs have a high crystalline perfection. The further HRTEM analysis indicates that the resultant products have hollow tubular nano-structure with different diameters, and the ordered graphitic layers with spacing of 0.32 nm are resolved on the CNT body region (Fig. 1c). The cross-sectional view of the CNT array grown on stainless steel substrate is demonstrated in Fig. 1d. It is clear that the resultant CNTs are vertically well aligned on the substrate due to the crowding effect between adjacent nanotubes, and the length of the CNTs are found to be approximately 20 μm by measuring the height of the CNT array. The vertical CNT array with a uniform height would provide excellent field emission properties [22].

To demonstrate the outstanding electrical characteristics of the CNT array grown on stainless steel substrate, its field electron emission properties were estimated by a simple diode-type setup, and the corresponding results are exhibited in Fig. 2. A series ballast resistor of 1 MΩ was typically used in the field emission measurements to protect the power supply against short circuit. The current density–anode voltage characteristics of the studied CNT array are shown in Fig. 2a. Here, the first field emission test was carried out after conditioning process (1st, black square in Fig. 2a), after that the field emission stability over 10 h was performed (Fig. 2b). The second test (2nd, red dot in Fig. 2a) was made when the field emission stability was finished. The inset in Fig. 1a is the corresponding Fowler–Nordheim (F–N) plots. The turn-on voltages for CNT array before and after stability test are approximately 309 and 271 V, and the corresponding threshold voltages are 622 and 604 V, respectively. Here, the turn-on and threshold voltages are defined as the voltage required to realize the current density of 10 μA/cm^2 and 10 mA/cm^2, respectively. It can be seen that the CNT array after stability test shows better field emission behaviors, including the lower turn-on and threshold fields, which is probably ascribed to the fact that CNT emitters reacted with stainless steel substrate to form conductive metal carbide in the interface during

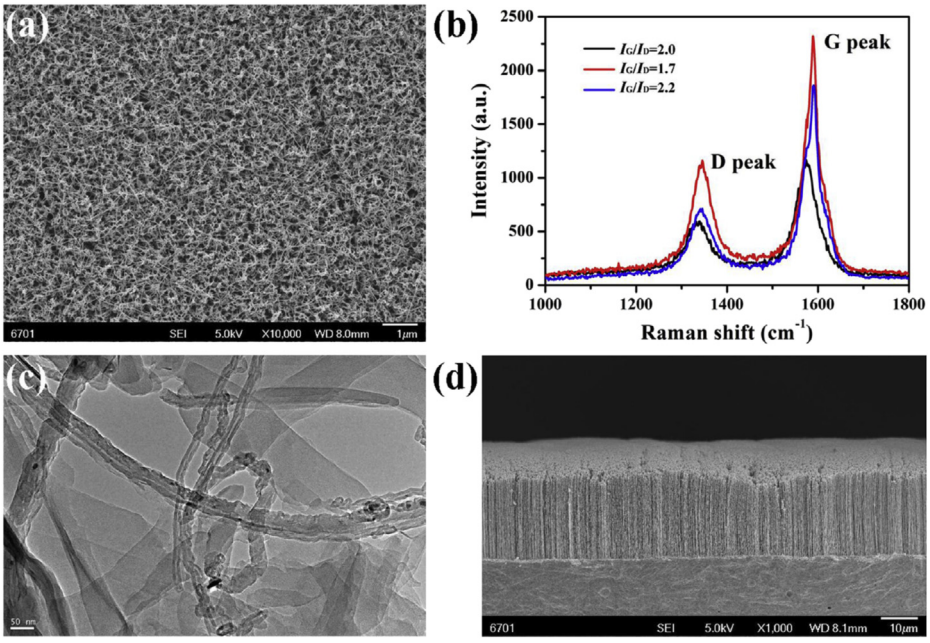

Fig. 1. The microstructures of the as-received CNT grown on stainless steel substrate.