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Ionization vacuum gauge with a carbon nanotube field electron emitter combined with a shield electrode

Huarong Liu [a,b,*], Hitoshi Nakahara [b], Sashiro Uemura [c], Yahachi Saito [b]

[a] Nagoya University VBL, Furo-cho, Nagoya 464-8603, Japan
[b] Department of Quantum Engineering, Nagoya University, Japan
[c] Noritake Co. Ltd., Japan

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ABSTRACT

The applicability of carbon nanotubes to an electron source for a Bayard–Alpert type vacuum gauge has been investigated. Three gauge configurations are designed to optimize the gauge performance. The optimized gauge, in which an additional shield electrode is fixed on a gate electrode, exhibits good measurement of linearity between ion current and system pressure from 10^{-7} to 10^{-2} Pa. A gauge sensitivity of 0.05 Pa^{-1} has been achieved under 100 μA emission current for nitrogen, comparable with 0.07 Pa^{-1} of commercial ionization gauges.

1. Introduction

Thermal electron sources are widely used in commercial ionization vacuum gauges. Thermal cathodes have high power consumption and cause outgassing from the hot filaments and heated materials around the gauge. Also, the thermal radiation induces gas desorption from the inner walls of a vacuum chamber. These phenomena cause an increase in pressure and disturb the vacuum measurements [1]. In addition, some chemical reactions with gas molecules on the hot cathode surface have been reported [2] and they might cause variations in the gas composition. These problems become more serious especially in ultrahigh and extremely high vacuum conditions.

Field emission (FE)-based electron sources are therefore considered as candidates to replace those thermal cathodes for vacuum electronic devices so as to effectively overcome the related thermal effects [3–6]. Previous reports exhibited vacuum gauges equipped with Spindt-type field emitter arrays and microtips [5,6]. As a promising candidate for cold FE materials, carbon nanotubes (CNTs) possess many remarkable properties, such as high aspect ratio, high electrical and thermal conductivity, strong mechanical strength, and high chemical inertness [7–10]. Many reports exhibited excellent performance for CNT film emitters, and large emission currents can be induced even at relatively low applied fields [11–13]. Dong and Myneni [7] demonstrated an extractor gauge with a CNT film cold cathode, and achieved a gauge sensitivity of ~0.03 Pa^{-1}. However, much higher gauge sensitivities are necessary in order to obtain detectable ion currents under an ultrahigh vacuum condition. The low sensitivity in Ref. [7] was mainly caused by the low ionization cross-section of gas molecules due to the high electron energy (~650 eV). In this article, we show the possibility to increase the gauge sensitivity by adding a shield electrode and to keep an optimum electron energy of ~200 eV. Here, a hot filament of a Bayard–Alpert (B–A) vacuum gauge is replaced with a CNT cold cathode. This type of gauge shows a good measurement linearity from 10^{-7} to 10^{-2} Pa with a sensitivity of 0.05 Pa^{-1}.

2. Experimental

A multi-walled nanotube film (provided by Noritake Co.), synthesized by thermal CVD (chemical vapor deposition) method, was used in this experiment. The synthesis method is described in Ref. [14]. Fig. 1 shows the corresponding scanning electron microscope (SEM) images of the film. This film was covered by a gate electrode with a transparency of 60% and a cathode-gate gap was 0.5 mm. This type of emitter has a long lifetime over 19,000 h under constant current driving with a base pressure of ~10^{-5} Pa, and it has been used for the electron sources for lamps and field emission displays [14,15].

* Corresponding author. Department of Quantum Engineering, Nagoya University, Japan. Fax: +81 52 789 3703.
E-mail addresses: huarong.liu@gmail.com (H. Liu), ysaito@nagoya-u.jp (Y. Saito).

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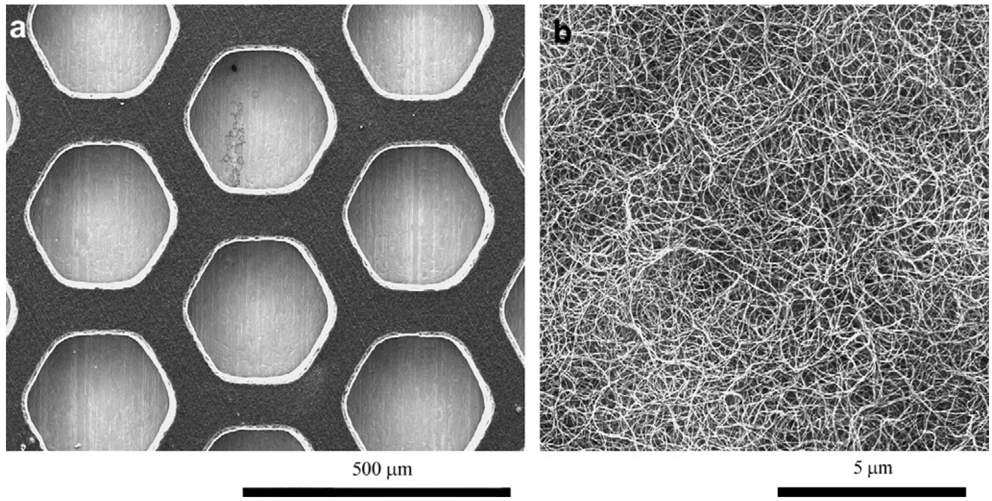

Fig. 1. (a) SEM image of a carbon nanotube cold cathode. (b) Enlarged image showing nanotubes.

Fig. 2(a) exhibits a schematic of a commercial B–A ionization gauge (TYPE: M-922HG ANELVA) [16]. In this experiment, this hot filament was replaced with the above CNT film emitter, as shown in Fig. 2(b). The modified gauge was installed in a vacuum chamber with a base pressure of 10^{-7} Pa. Its performance was tested in nitrogen atmosphere. The system pressure was adjusted by a variable valve and was detected by another M-922HG vacuum gauge. Three current meters were used to measure currents from a grid (I_G), a gate (I_{Gate}), and an ion collector (I_{ion}), as shown in Fig. 2(b).

Aiming at a reproducible gauge performance, we firstly carried out a 2-h aging with a gate current of ∼1 mA to stabilize the emission. The gate potential was gradually raised to 900 V during the aging. Subsequently, the linearity between the ion current and the pressure (I_{ion}–P) could be reproducibly achieved below 10^{-2} Pa.

Furthermore, using the same emitter, two other gauge configurations (see Figs. 4(a) and 5(a)) were tested so as to optimize the gauge sensitivity. Finally, measurements were conducted in a large pressure range from 10^{-7} to 10^{-2} Pa for the optimized gauge configuration.

3. Results and discussion

For ionization vacuum gauges, the collected ion current (I_{ion}) is represented as

$$I_{ion} = S \times I_E \times P \tag{1}$$

where S is the sensitivity coefficient of the gauge for N_2 gas, and I_E is the emission current [17]. A high S value is necessary to obtain a detectable ion current in an ultrahigh vacuum condition.

Note that there is a clear difference for the CNT cold emitter adopted in this experiment, compared to the conventional hot filament. For the CNT emitter, a large proportion of the emission current (I_{Gate}) is collected by the gate anode according to Fig. 2(b), and it cannot contribute to the ionization of the residual gases. Therefore, in this paper the grid current I_G is used instead of I_E to calculate the gauge sensitivities for our CNT gauges.

We firstly consider the performance for the gauge configuration in Fig. 2(b), which is similar to the configuration presented in Ref. [7]. The measurement was conducted with a gate potential of 800 V. At this time, a total emission current of 250 μA was obtained from the CNT cathode, and it was the sum of the gate and grid

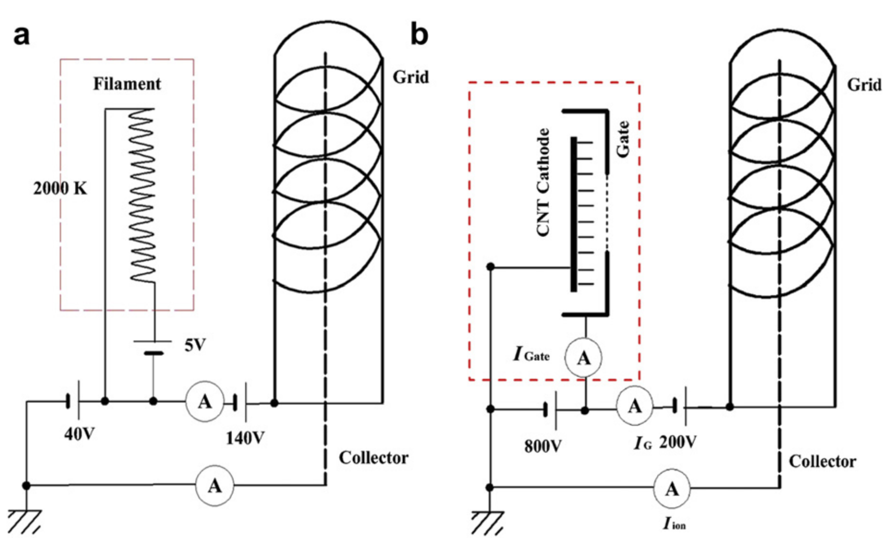

Fig. 2. (a) A schematic of a vacuum gauge with a hot filament cathode. (b) A schematic of a vacuum gauge with a nanotube cold cathode.