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Electro-optical analysis in determining the field emission characteristics of carbon nanofibers on an acute tip substrate

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ABSTRACT

The shape of an acute tungsten (W) tip substrate coated with palladium (Pd) and carbon nanofibers (CNFs) was optimized in order to generate efficient field emission (FE) currents. By adjusting the apex angle of the tip, we succeeded in controlling the FE properties and electron beam convergence. When the apex angle was close to 50º, a narrow convergence of electron beams was observed. By employing an original computation tool based on the surface charge method, we conducted a numerical analysis of the convergence mechanism of the FE device; this was dependent on FE properties, and displayed its maximum around the same apex angle. By simulating the electrical field distribution above the CNF, we concluded that the optimum values of the electro-optical properties of CNFs on the tip substrate were found at an angle of approximately 50º with a narrow divergence angle. After determining the relationship between the divergence angle and the tip apex angle, the electron emission property was optimized. Analysis of the characteristics of the maximum electron emission state using our computation method indicated that an acute tip covered with CNFs has potential for use as a cathode in electrical devices which require a large FE current with low power consumption.

1. Introduction

To assemble a device for determining field emission (FE) performance of high efficiency, it is important for that device to emit electrons with a high efficiency and a low drive voltage. Previous studies have evaluated the conditions required to achieve good FE properties; for instance, these authors have studied the control of carbon nanofiber (CNF) synthesis morphology without using lithography [1,2]. Other researchers have focused on optimizing the design of carbon nanotubes or CNF (CNT/CNF) growth patterns to obtain better FE performance numerically [3–12]. However, these studies have been conducted only on a plane substrate.

To be able to concentrate electrical fields on CNTs/CNFs in order to obtain good FE properties more effectively, the authors surmised that it is important to optimize CNT/CNF morphologies and to design the shape of the substrate point like an acute tip. Such a configuration was used for a device in Haga et al. [13] and Kita et al. [14] which used CNFs as an FE source synthesized on a palladium catalyst deposited on an acute tungsten tip, in their studies on a radiography X-ray system. The reason for employing an acute tip in the radiography system is that its shape enabled a high-efficiency field current with low power consumption to be obtained. Although Sakai et al. [15] evaluated the electron trajectory and electrical convergence characteristics of an emitter with CNFs on the tip, no detailed analysis of FE properties and electron radiance controlling the point shape of a CNF coated tip has been carried out.

In this study, we analyze the electron convergence effect of field concentration on the tip by optimizing the tip shape to obtain better FE performance electro-optically, and confirm the relationship between the FE properties for the electron emission convergence and the shape of the tip substrate both experimentally and by using an original computation method.

2. Experimental procedures and FE characteristics of CNF on an acute tip

2.1. Specimen and measurement system for FE characteristics

The FE properties of CNFs on a tip were evaluated by Morita et al. [16] using a variety of tip apex angles covered with catalysts to maximize the FE current. Fig. 1 shows photographs of a tip covered with CNFs with a top apex angle of θ. The apex angle θ is expected to influence the concentration of the electrical field on the tip. The shape of the tip substrate was formed by electropolishing, and the CNFs were deposited by plasma-enhanced chemical vapor deposition to form a structure of 100 nm in diameter and 1000 nm in length.

The measurement system for the current–voltage characteristics of FE shown in Fig. 2 was originally employed for the development of a miniature X-ray tube [13]. The system is based on a triode consisting of an emitter with CNFs accompanied by electrode #1 for the extraction of field-emitted electrons, and electrodes #2 and #3

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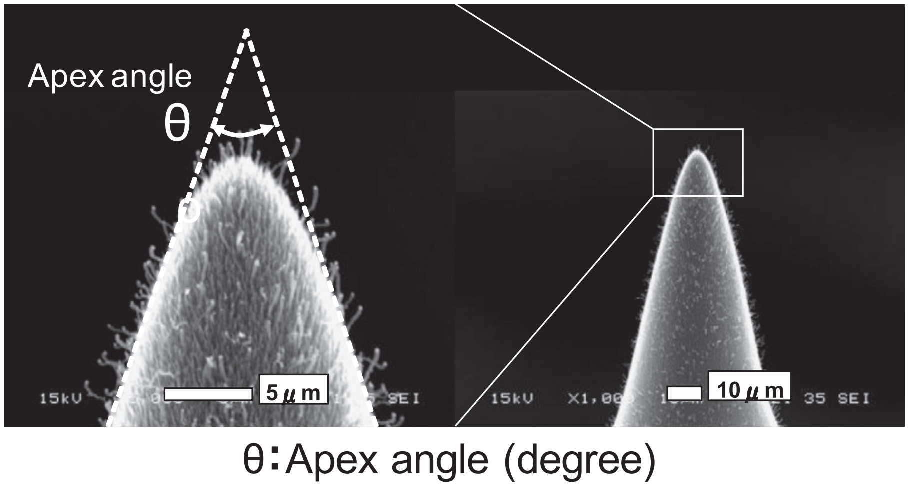

Fig. 1. Photographs of a field emitter tip made of CNFs on Pd-coated W [17]. The emitter has an acute tip with an apex angle θ.

for electron collectors [16]. All the electrodes are made of stainless steel. Electrodes #1 and #2 have an orifice of 2 mm in diameter and 1 mm in length at the center for the passage of electrons. An emitter tip about 2.6 mm long, with CNFs on its apex, is fixed at the holder and loaded with a negative voltage of up to −10 kV for electron emission. Each electrode monitors FE current. The distance between the tip apex and electrode #1 is set at 5 mm. The divergence angle from the emitter to the orifice in electrode #1 is 400 mrad; that from the emitter to electrode #3 is about 40 mrad. Secondary electrons are expected to be suppressed due to the short, wide path of the primary electrons.

2.2. FE current with controlled apex angle of a tip

Fig. 3 shows the current–voltage relations for electron field emission from CNFs on a Pd/W tip in a vacuum under 1×10^{-6} Pa, obtained using the measurement system shown in Fig. 2 [16]. The vertical axis indicates the sum of the field emission currents measured in electrodes #1/2/3 or #2/3. The solid dots are the total currents collected using all the electrodes ($I_{total}=I_1+I_2+I_3$) which are equal to the currents flowing from the emitter tip in Fig. 2, whereas the open dots indicate the currents flowing into electrodes #2 and 3 (I_{2+3}) when the apex angle (θ) of the tip is 30º, 50º and 120º respectively. The FE properties expressed by the ratio I_{2+3} to I_{total} in Fig. 3 vary with the apex angle θ as shown in Fig. 4. The ratio I_{2+3} to I_{total} in Fig. 4 is defined as the ratio of the maximum FE current values measured at the same bias voltage, where both I_{total} and I_{2+3} coexist for the same apex angle. This ratio showed its maximum value at an apex angle close to 50º. We surmise that the strength of the current is related to the balance between the electron emission divergence angle and the FE properties of the CNFs on the tip. We later analyzed this relationship by developing a computational model. Fig. 5 shows the relationship between the bias voltage when I_{total} equals 10 μA and the apex angle of the tip. The solid line in Fig. 5 is an approximate line, and its function was used in calculating the field strength in the computational model.

3. Electro-optical analysis of FE property on an acute tip

3.1. Computation program and construction of a three-dimensional model

In this work, a computation program was developed using a numerical code based on the surface charge method; this is an integral element method that is the same as that used for modeling CNF bundles on a horizontal plane catalyst [17]. This calculation method for the electrical or magnetic distribution, makes it easier to construct three-dimensional models freely because it is unnecessary to make mesh in the space around complicated three-dimensional models involving the many small CNF rods that would be required if using finite element methods [18]. The source code and calculation module were

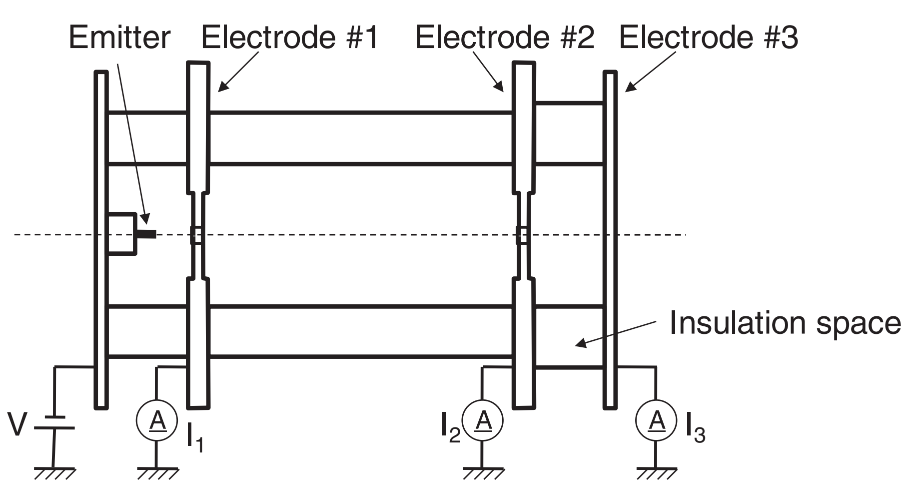

Fig. 2. The measurement system for the current–voltage characteristics of field emission [17]. An emitter with CNFs is fixed at the holder and a negative voltage is added for electron emission. Electrodes #1, #2 and #3 are used for capturing emitted electrons and connected to the earth to monitor FE current. Electrodes #1 and #2 have orifices 2 mm in diameter and 1 mm in length for the passage of electrons.