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Preliminary Study of Electron Gun Based on Field Emission of Carbon Nanotubes*

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Abstract The paper reports the preliminary study of an electron gun based on the field emission of carbon nanotubes. The result of the field emission experiment shows that the carbon nanotubes are excellent field emitters, yielding current densities higher than 0.5mA/cm^2 with operating field about 2.7MV/m.

Key words field emission, electron gun, carbon nanotubes

1 Introduction

Since the first report of carbon nanotube in 1991[1], carbon nanotubes have attracted much attention as field electron emission materials because of their good emission stability, long emitting lifetime and the potential to operate at low voltage. The potential of carbon nanotubes as electron field emitters was already apparent from the first articles reporting extremely low turn-on field and high current densities in 1995[2—4]. And in 2001, J.M.Bonard[5] had summarized the first five years' field emission of carbon nanotubes. During this period, there were many scientists working in this field and their work prompted the application of carbon nanotube as the field emitter. In 2000, Y.Saito[6] et al. reported the field emission from carbon nanotubes and its application to the electron source also reported. In 2004 and 2005, Y.Hozumi[7, 8] reported the development of a pulsed electron gun with carbon nanotube cathode which produced an electron pulse with the pulse length of 8ns and the peak current of 480mA.

In this paper, we report the preliminary experimental study on a continuous DC electron gun for accelerator with carbon nanotubes field emission cathode. The experimental setup for electron gun based on field emission of carbon nanotubes is introduced in Section 2, the preliminary experimental results and discussions are reported in Section 3, and a conclusion is finally given in Section 4.

2 Experimental setup

The experiment was carried out in the laboratory of the electron gun test platform shown in Fig. 1 and Fig. 2, which consists of an electron gun assembly, a focus lens, focus coil, fluorescent screen, and Faraday cup. Here, a Pierce girded type electron gun structure[9] was used. The structure of the electron gun assembly is shown in Fig. 3.

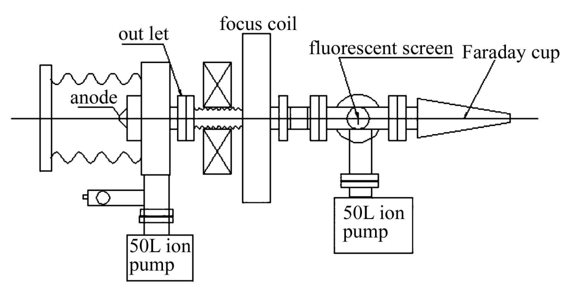

Fig. 1. Layout of the electron gun test platform.

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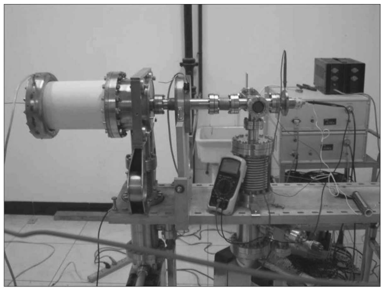

Fig. 2.　Photo of the experimental setup.

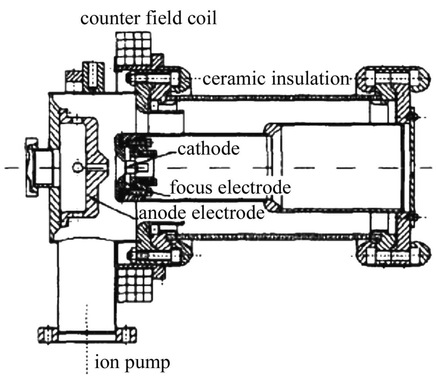

Fig. 3.　Structure of the electron gun assembly.

The distance from the anode to the cathode may be changed from 1.45cm to 2cm, and a maximum voltage between the anode and cathode is -50kV. The radius of anode aperture is about 4mm, while the effective emission area used in the experiment is about 0.5cm^2. In the experiment, the vacuum pressure of the electron gun is below 10^{-6}Pa.

Figure 4 shows the carbon nanotubes cathode used in the experiment, which is fabricated by the Key Laboratory of Nuclear Analysis Techniques of SINAP. First, the stainless steel was washed in the acetone by the ultrasonic wave for half an hour, and then the surface of the stainless steel was covered with a film of nickel of about 20nm, after that the nickel film was disposed by the H^+ plasma under the temperature of 450° for twenty minutes to form the nickel grain as the catalyst for carbon nanotubes growth. The carbon nanotubes were grown by the thermal chemical vapor depositions (TCVD) for 30 minutes. During the growing period of the carbon nanotubes, the acetylene (C_2H_2) gas was used as a precursor of nanotube synthesis.

Figure 5 is the scanning electron microscope (SEM) image of the carbon nanotubes. From the SEM picture, we can see that carbon nanotubes were not uniform on the surface of the stainless steel.

Fig. 4.　The carbon nanotube grown on the stainless steel.

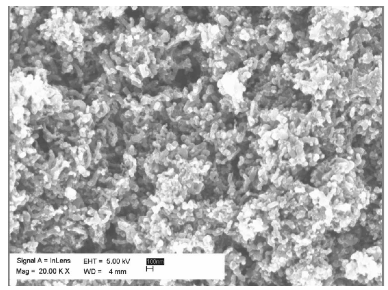

Fig. 5.　The SEM picture of the carbon nanotubes.

3　Preliminary experimental results and discussion

The emission current and applied voltage were measured in the experiment. Fig. 6 shows the emission current versus the applied electric field, in which the distance between the anode and the cathode is about 1.45cm, the emission area is about 0.5cm^2. From Fig. 6, we may see that the emission current density of the carbon nanotubes was about 0.2mA/cm^2 with the operation field at about 3.8MV/m.

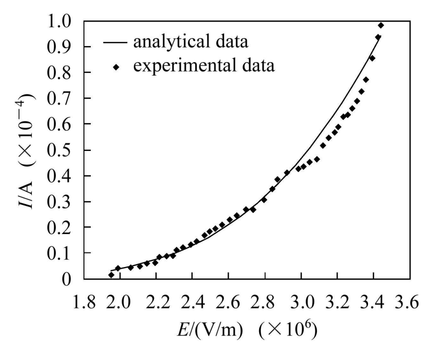

Fig. 6.　Comparison between the analytical values and the experiment achieved data.

Conventional field emission analysis usually uses the Fowler-Nordheim (F-N) equation[10].

$$J=\frac{A(\beta E)^2}{\phi}\exp\left[-B\frac{\phi^{\frac{3}{2}}}{\beta E}\right]. \qquad (1)$$

In Eq. (1), $J(\mathrm{A/m^2})$ is the emission current density, $E(\mathrm{V/m})$ is the average electric field applied between the cathode and the anode, A and B are the constants related to the cathode material and the shape of the cathode, usually, in our experiment, A is 1.56×10^{-6} $\mathrm{A(eV)^{-3/2}V}$, and B is 6.83×10^9 $\mathrm{V(eV)^{-3/2}m^{-1}}$, β is the enhancement factor, ϕ is the work function of the cathode material. The Fowler-Nordheim equation can thus be written in terms of experimentally measured quantities as

$$\ln\left(\frac{I}{V^2}\right)=\ln a-b\left(\frac{1}{V}\right). \qquad (2)$$

Here I is the total emission current, V is the applied voltage between the cathode and the anode, while a and b are the constants which are related to the material and the experimental status. From the equation, a line of the $\ln(I/V^2)$ vs the $1/V$ can indicate the field emission of the material.

From Fig. 6, we can see that the experimental data are consistent with the anaylital value.

Figure 7 is usually called F-N plot of the experiment data. From the plot of the experiment data, the value of a and b of Eq. (2) can be obtained through the analysis. In our experiment date, the value of a is 84.6×10^{-11}, b is 18167. And β is about 670.

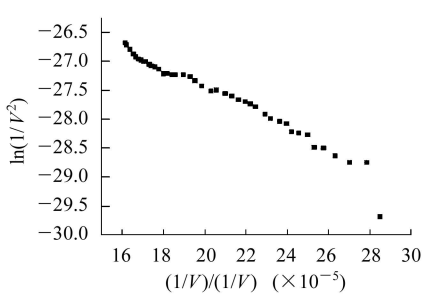

Fig. 7. F-N plot of the experiment data.

During the electron gun test experiment, we also got the profile of electron beam from the electron gun on the fluorescent screen installed after a focus coil. In this experiment, we had achieved a higher emission current of 0.27mA which corresponds to the current density of $0.54\mathrm{mA/cm^2}$ at the operation field of about 2.7MV/m. Fig. 8 shows the electron beam profile on the fluorescent screen produced by field emission from the electron gun with carbon nanotubes cathode, where electron beam energy is about 50keV.

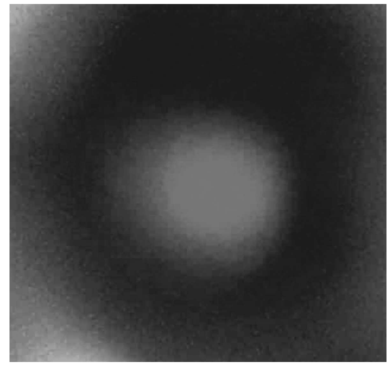

Fig. 8. The emission profile of the carbon nanotube.

Since October 2005, we have also conducted an experiment to test the lifetime of carbon nanotubes cathodes. The electron gun was operating continuously for two weeks after the emission current was stable. However, we could not conduct this experiment further, because of the power supply and some other reasons.

4 Conclusions

We have performed a preliminary experimental study on the carbon nanotubes cathode electron gun. It shows that the carbon nanotubes are excellent field emission materials. In the preliminary experiments, 0.27mA field corresponds to the emission current density of $0.54\mathrm{mA/cm^2}$ when the applied field of emission current is achieved, which 2.7MV/m. The maximum current is limited by the power supplies, which cannot suffer the larger current. In the next phase, we will change the power supply to achieve much higher current carbon nanotubes cathode electron gun.

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基于碳纳米管场致发射的电子枪的初步研究*

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摘要　给出了基于碳纳米管场致发射电子枪的初步研究结果. 碳纳米管场致发射试验证明碳纳米管是一种很好的场致发射材料. 试验中, 在极间场强2.7MV/m的情况下得到的电流发射密度为$0.5mA/cm^2$.

关键词　场致发射　电子枪　碳纳米管

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