Field Electron Emission from the Tip of a Graphite Fiber

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Abstract. Usually carbon wires cannot be used for obtaining remarkable field electron emission because of the difficulty of sharpening its tip with a sufficient small radius of curvature to fit the electrical field. However, a large number of small fragments are formed on tips of graphite fibers after a discharge treatment with 10 kV DC high voltage on graphite fibers. These fragments observed by SEM and HRFEM are spheres, flakes and needle-like nanostructures with the size around 50 nm. In this case, each of these spheres and flakes can be an emission center in field emissions and some detectable emission currents can be obtained with a low applied voltage. Experimental results show that a single graphite fiber of 20µm diameter can generate near 0.2 mA emission current with 4 kV applied voltage and the stability have been measured to be less than 10 %. It is expected that graphite fibers as a novel cold cathode material will provide a wide range of applications such as in flat panel displays, high-power and high-brightness vacuum electronic devices, and vacuum microelectronic devices.

1. Introduction

For all kinds of vacuum electron apparatus and instruments, obtaining free electrons is a basic condition. Thermal emission is one of the most conventional methods to generate free electrons. These electrons escape by heating from the surface of emitters. Although the way is simple, heating emitters need consuming energy with luminescence of thermal emitters. It usually affects properties of apparatus or instruments. Field emission (FE), a kind of electron emission without heating and luminescence, extracts electrons from the surface of emitters into vacuum under the influence of an applied electric field. Field emission is therefore a better way of acquiring free electrons. There have been moves to use cold cathodes to replace all hot cathodes and more importantly to explore new applications of cold cathodes in areas such as large-area electronics, where hot cathodes are unsuitable [1].

Cold cathodes utilize the local field enhancement at the top of each emitter to lower the threshold voltage enabling field emission. However, the fabrication facility required and the fabrication processes of field emission cathodes are relatively expensive and complicated. In seeking appropriate material and technique, field emission from various carbon structures has attracted attention of many investigators in the field [2-5]. Since the discovery of carbon nanotubes [6], much attention has been paid to explore the use of this ideal one-dimensional nanomaterial as cold cathodes [7-9]. Most of studies have been carried out to characterize the field emission properties of carbon nanotubes. It was reported that carbon nanotubes have excellent property of field emission [10-11]. Relative measurements showed that carbon nanotubes as emitters can yield current density of 4A/cm² [12-13].

We report here on our field emission experiments performed on tips of graphite fibers as electron field emitters. After graphite fibers discharge, it can be observed that many corpuscles with the size...
range of nm-µm appeared at tips of graphite fibers. These tips can emit stable intensive current which has a wide range of potential applications in display techniques.

2. Experimental Details and Results
In field electron emission of graphite fiber, it is the most important thing to prepare the tip of graphite fiber as an emitter (cold cathode). The tip fabrication and measurements carried out in a vacuum coating machine with a glass jar (see Fig.1). Details of preparing process as following: cut an industrial graphite fiber with about 5 mm long and 20 µm diameter, and then adhere one end of this fiber to an angle (<300) top of an acute angle triangle of aluminum piece electrode, and leave another end for a tip to be treated. Then the aluminum piece with a graphite fiber was nipped at the cathode on a vacuum experimental table. There was a plane metal anode with fluorescence material placed around 3cm against the tip. After installing, vacuum glass jar was covered.

![Figure 1](image)

*Figure 1.* The experimental Instrument of Graphite fiber emission. Graphite fiber E was used as an emitter, Symbol A denotes an anode, the voltage is supplied to A and E. Symbol C and M stand for vacuum glass jar and luminescent screen, respectively.

Adjusting the outer power of jar made the anode voltage gradually rise from zero, at that time, because the tip of a graphite fiber was not treated, it didn’t emit even raising the voltage to several thousand volts yet. When the voltage up to ten thousand volts, the emission current increased suddenly from zero to around 1mA, and the tip began to glow and become red. If the voltage was kept at ten thousand volts, the graphite fiber with 5 mm length might be burned out completely and the emission current became unstable, finally became zero. However, if we reduced the anode voltage below to 5 kV when the current just began to change suddenly, not only the tip never became red, but also steady current of several hundred µA could be obtained. The treated tip of graphite fiber can emit much more intense current increasing linearly with the increase of the anode voltage, which was not similar to the beginning process of raising the anode voltage for the untreated tip. The results of measurements were showed at the I-V curve in Fig.2(a), and the morphology of the treated tip with spheres and needle-like nanostructures were also confirmed by high resolution field electron microscope (HRFEM), shown in Fig.2(b). The field emission characters of the graphite fiber would not change as long as the voltage below 5 kV. Experimental results show that a single graphite fiber of 20 µm diameter can generate
near 0.2 mA emission current with 4 kV applied voltage and the stability have been measured to be less than 10%.

![I-V curve](image)

**Figure 2.** I-V curve (a) of field electron emission from the treated tip of a graphite fiber, and the FEM image (b) of field electron emission from the tip of a graphite fiber.

![SEM images and Raman spectra](image)

**Figure 3.** SEM images and Raman spectra of a graphite fiber tip before (a, c) and after (b, d) a discharge treatment.

To understand the emission mechanism of graphite fibers, tips of graphite fibers had observed by scanning electron microscope (SEM) before and after discharge of 10 kV voltages. SEM images of graphite fibers show in Fig.3. It is seen that the untreated tip was clean and only appeared natural rupture trail, but after discharge treatment it formed a compound tip with kinds of fragments between several nm and several µm, shapes as balls, pieces, and nanotubes grown on carbon fibers [14]. The bright dots in Fig.3 reveal sites of emitting electrons from graphite fibers.
3. Discussion
The principle of field emission is based on the application of a very high electric field to extract electrons from emitters. The current generated by the process of field emission is given by the Fowler–Nordheim (FN) equation [14]:

\[ I = \frac{a A \beta^2 E^2 / \Phi}{\exp(-b \Phi^{3/2} / \beta E)} \]  

(1)

where \( A \) is the emitting area, \( J \) is the Fowler–Nordheim current density. Properties of field emission electron are characterized by field emission current density \( J \), the emission current on the unit surface of emitter (cathode), described by the Fowler–Nordheim (FN) law as:

\[ J = CE^2 \times e^{-D/E} \]  

(2)

where \( D = 6.8 \times 10^7 \Phi^{3/2} \), \( E \) is the electric field at the tip apex, \( \Phi \) is the work function, and \( C \) is a constant. For carbon \( \Phi=4.7 \text{ eV} \) and \( C=6.2 \times 10^{-7} \). Most influence for these parameters is both the work function of cathode material \( \Phi \) and field intensity \( E \) at the top of cathodes.

From the above formula, it is important to choose a material with smaller \( \Phi \) value in field emission. For common materials, their work functions \( \Phi \) are about 2-6 eV. Thus, we choose the value of \( E \) at \( 10^7-10^8 \text{ V/cm} \), a very intense electronic field, to gain enough \( J \). At the electrostatic field calculation, it is hardly to yield the electron field with parallel plate electrode. But if an electrode (anode) is a plate electrode, and another one (cathode) is a tip with small ball-like shape and its curvature radius \( R \), shown in Fig. 4 the electron field around the surface of the tip can be approximately calculated by the following formula:

\[ E = V/ (NR) = V/d \]  

(3)

where \( V \) is the voltage at two electrodes, and \( N \) is shape coefficient. For simplicity, we let \( N \) value equal to 2. Hence, the above formula is true due to \( d = 2R \).

According to the formula (3), if the distance \( d \) of metal wire as a cathode is very small, such as \( d = 10^{-4} \text{ cm} \), when the voltage \( V \) equals to several thousand volt, we may get electron intensity needed. Therefore, when the tips of tungsten wire as a cathode is utilized for field emission, the radius \( R \) of the tungsten wire etched is \( 10^{-4} \text{ cm} \). While the voltage between two electrodes is in the range of several kV to several 10 kV, we can acquire expecting emission current density such as \( J=10^4-10^5 \text{ A/cm}^2 \) according to the formula (2).

However, keeping the tip of \( 10^{-4} \text{ cm} \) endure the bombardment from \( 10^4-10^5 \text{ A/cm}^2 \) current and remainder air be not breakdown, only a few of metal wires with refractory such as tungsten suitable
for field emission, and vacuum must be up to $10^{-7}$-$10^{-8}$ Pa for normal work. Even this, it is really available field emission current only 1µA.

Field electron emission from graphite fibers obeys Fowler-Nordhein law, formula (2), but the I-V curve (see Fig.2) from our experiment is linear. It can be explained that the measured current I is practically the total of current emitted by each small corpuscle on the tip according to Fowler-Nordhein law. If we estimate an average value on the size and number of these fragments on the tip, make all corpuscles share the emission current I, at the same time calculate the electronic field $E$ at each corpuscle in their average diameter, the result of calculation is in good agreement with Fowler-Nordhein law.

In fact, we can reasonably estimate from Fig.3 that the tip consists of 1000 small balls and flakes with the size around 50nm. Each of these spheres and flakes can be an emission center in field emissions and some detectable emission currents can be obtained with a low applied voltage. From formula (1) and (2), we could get

$$i = 9.74 \times 10^{-7} V^2 \exp (-7.28 \times 10^4 / V).$$

(4)

When $V$ equal to from 2 kV to 4 kV, we drew the i-V curve for each small corpuscle of the tip of a graphite fiber, shown in Fig.6.

In our experiments, the total of the field emission current from a graphite fiber can up to several hundred µA, and the departure angle of the total electron emission very large, beyond 180°. So field emission electrons from graphite fibers can emit to a large area. The merits make it possible to apply in large-area electronics. As a novel cold cathode material, graphite fibers will provide a wide range of applications such as flat panel displays with high-brightness, vacuum electronic devices, and vacuum microelectronic apparatus, new-type fluorescent sources, and high voltage rectifier. Field electron emission from graphite fibers may finally lead to a very significant change in display techniques.

4. Conclusions
Field emission of graphite fibers has the following merits: First, the total of the field emission current can up to several hundred µA, but that of tungsten as a conventional emitter filament only around 1 µA. Second, the requirement of vacuum is low. It means the tip of graphite fiber can endure the bombardment of remainder air. Third, the fragments distributed on the whole surface of the tip, which are as a result of the discharge treatment of graphite fiber, so the departure angle of the total emission current is very large, beyond 1800. Thus, electrons can emit to a large area. These merits make it possible to apply in broad plane display devices, new type fluorescent sources, high voltage rectifier, and vacuum microelectronic apparatus.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (Grant Nos. U1402273, 11364045, and 11664044), Department of Science and Technology of Yunnan Province (Grant No. 2016FC001), and by Yunnan University (2016MS14).

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