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Simulation and modeling of alignment-free field emission X-ray tubes ☆

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ABSTRACT

A new hemispherical-geometry cathode for field emission (FE) X-ray tubes was designed and simulated in this study. The electric field strength distribution on the hemispherical-geometry cathode was calculated and used to predict the emission current. Because of their unique FE properties, carbon nanocoils were used as the electron emitters for simulation and modeling. The results show that a large tolerance is permitted, and the performance attained with ±20° cathode misalignment was nearly identical to that without misalignment. The maximum emission current can be achieved using a hemispherical-geometry cathode with a radius of 1 mm. Additional advantages of FE X-ray tubes with hemispherical-geometry cathodes are higher FE currents, shorter response times, and smaller X-ray spot sizes. In addition, lower power consumption, longer lifetimes, and higher resolutions are expected with this simple and low-cost design.

1. Introduction

Conventional X-ray tubes used in industrial applications and medical diagnoses generally employ the thermionic emission (TE) design. This design generally involves a metal filament (cathode) that emits electrons when heated over 1000 °C and a metal target (anode) that emits X-rays when bombarded by the accelerated electrons [1]. The X-ray intensity is proportional to the electron current and the square of the acceleration voltage [2]. Because the filament within the X-ray tube must be heated by the control voltage, thermionic cathodes tend to have long response times and high energy consumption. Moreover, the cathode is operated at high temperatures and can easily react with gaseous molecules, mainly H_2O and oxygen, to form metal oxides. Such contamination of the metal filament reduces the lifetime of the X-ray tubes. The average lifetime of a conventional TE X-ray tube is less than a year, and a majority of X-ray tube failures arise from

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filament-related damages. In addition, the electrons from the cathode are emitted in random directions. This non-Gaussian emission of electrons reduces X-ray image resolution; however, the emission can be focused using an external electric field.

By contrast, field emission (FE) electrons are generated through electron tunneling near the Fermi level when a high electric field is applied; therefore, electron emission through FE is at room temperature (cold emission) and the output current is voltage controllable. The FE cathode operates at room temperature, thus extending the cathode lifetime and lowering energy consumption. FE X-ray tubes are the next generation of X-ray tubes and will replace TE X-ray tubes. FE theory is elaborated upon in Section 2. Moreover, the electron emission from a cold cathode is always along the vector of the applied electric field, and the Gaussian electron emission distribution is advantageous in X-ray imaging. Furthermore, FE cathodes have found application in various vacuum electronic devices, such as FE displays and transmission electron microscopes.

The concept of cold cathode X-ray tubes has been explored using several materials, including diamond-like carbon and carbon nanotubes (CNTs). In recent years, researchers have found that FE from carbon nanocoils (CNCs) is more advantageous than those from CNTs in terms of long-term current emission stability, current density, and operation lifetime. Paired with the benefit of CNCs, FE is a more effective method of extracting electrons than TE because of room temperature electron emission and voltage-controllable output power. Instead of a flat-plane cathode, a novel hemispherical-geometry cathode for FE X-ray tubes was designed and simulated in this study.

2. Theory and methodology

2.1. FE theory

The theory of FE was proposed by Fowler and Nordheim in 1928 [3]. Compared with TE, FE is advantageous because electrons are emitted at room temperature (i.e., cold cathode) and FE current is voltage controllable; in addition, the low operating temperature in FE extends the cathode lifetime. FE cathodes are used in several applications such as display panels [4,5], flat panel displays for producing backlight [6,7], FE lamps [8–12], and X-ray tubes [13–18].

FE results from the tunneling of electrons through the potential barrier near the Fermi level when a high electric field is applied. The image force is a Coulombic force of attraction pulling the emitted electron toward the surface because of the induced surface charge on the metal. The net potential energy of the electron is the sum of the image force potential and the potential created by the applied external electric field at the surface. The potential barrier is infinitely thick in the absence of an electric field, but it becomes triangular with a considerably narrowed width when a large electric field is applied [19–23].

The slope of the potential and consequently the width of the potential barrier depend on the amplitude of the local electric field on the surface. This local electric field is considerably enhanced if the electron emitter is a sharply pointed wire with a high aspect ratio.

The FE mechanism can be summarized by the Fowler–Nordheim (F–N) equation [3], which is shown in (1).

$$I = \alpha A(\beta^2 E^2/\varphi)\exp(-b\varphi^{3/2}/\beta E), \tag{1}$$

where I, A, E, φ, and β are the emission current, effective FE area, macroscopic electric field (in the absence of the local structure that causes enhancement), work function, and field enhancement factor, respectively; b is a constant. The field enhancement factor β is the most crucial factor determining the performance of FE and is often introduced in the F–N equation to represent the geometrical effects at the cathode surface. The value of β can be extracted from F–N plots, as shown in Fig. 1.

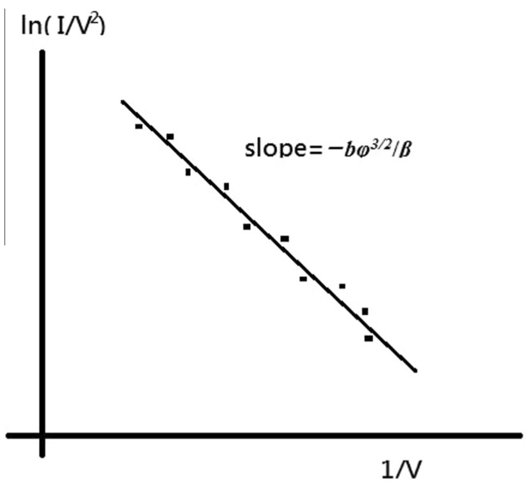

Fig. 1. Conventional F–N plot used to extract the β value of FE emitters.

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