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Effect of a concave grid mesh in a carbon nanotube-based field emission X-ray source

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ABSTRACT

This study introduces a simple approach to improve the X-ray image quality produced by the carbon nanotube (CNT) field emitter X-ray source by altering the geometrical shape of the grid mesh from the conventional flat shape to a concave one in a typical triode structure. The concave shape of the grid electrode increases the effective number of the grid cells in the mesh, which exerted an electric field in the direction of the emitted electrons, thereby increasing the emission current reaching the anode. Furthermore, the curved mesh (concave grid mesh), which was responsible for the extraction of electrons from the field emitter, exhibited a focusing effect on the electron beam trajectory thereby, reducing the focal spot size impinging on the anode and resulted in a better spatial resolution of the X-ray images produced.

1. Introduction

Due to their excellent field emission properties, carbon nanotubes have been widely employed in X-ray imaging applications [1–4]. The quality of X-ray images depends largely on the increase in spatial resolution, which can be realized by a reduction in the electron beam focal spot size, impinging at the anode [5,6]. Smaller the focal spot size, better and higher is the spatial resolution of the X-ray images [7]. To this end, several studies have been conducted on geometrical parameters and design, the two most significant factors of the typical triode structure of the CNT field emitter X-ray source to effectively improve its electron beam focusing behavior, e.g. the use of concave shape structures in the cathode [8–10].

In the current study, a simplified approach has been introduced to improve the focusing effect of the field emission triode structure for X-ray imaging, by modifying the conventional flat grid mesh of the gate into a concave shaped one. This set up offers a more economical and less tedious means of focusing concerns of the electron beam trajectory. The current research attempts to deal with the focusing ability and basic field emission characteristics of the model introduced via computer simulation using commercially available electrical optics software (OPERA-3D) and determine its effect through actual X-ray imaging applications.

In the present work, typical multi-walled carbon nanotube (MWCNT) based field emission source, with the conventional triode structure was used for X-ray generation. The triode structure consisted of MWCNT field emitter and three electrodes, viz. (i) a cathode assembly, which is responsible for the electron field emission consisted of a stainless steel (SUS 304) substrate, a ceramic spacer, and the CNT emitters; (ii) an anode, from where the electron beam would impinge to produce the X-rays and was made of tungsten-embedded copper material; (iii) the grid electrode (gate) made of a mesh of molybdenum wires. The molybdenum mesh, which is responsible for the controlled extraction of electrons from the field emitter, consisted of 70 μm diameter fine wires with a 500 μm-spacing between the wires. Two types of grid mesh were used in this study, viz. the flat grid mesh, whose plane was parallel to the cathode assembly and the concave grid mesh. Fig. 1 illustrates the theoretical explanation of our flat grid mesh (a) versus concave grid mesh and (b) structures. The emitted electrons will follow the direction of the electric field lines. This electric field lines are perpendicular to the equipotential lines as seen in Fig. 1(a) and (b). Due to the concave structure of the grid mesh, a converging path is created as to confine the electron towards the center. Fig. 2 shows the conventional triode structures for the flat grid mesh (a),

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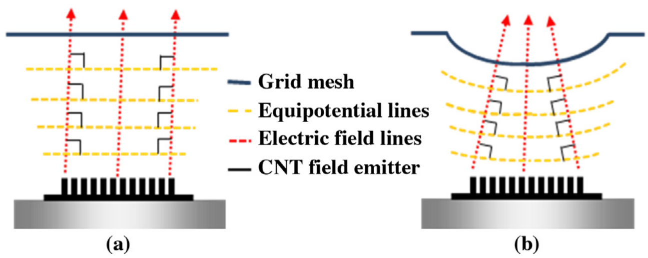

Fig. 1. Illustration of the electron emission trajectory using (a) the flat grid mesh, and (b) the concave grid mesh. The emitted electrons will follow the direction of the electric field lines. This electric field lines are perpendicular to the equipotential lines. Due to the concave structure of the grid mesh, a converging path is created as to confine the electron towards the center.

and the concave grid mesh (b), respectively. These two grid meshes were compared with respect to their focusing performances and field emission characteristics.

2. Experimental

This section is divided into two parts – the computer simulation using electrical optics software and the experimental details of the study.

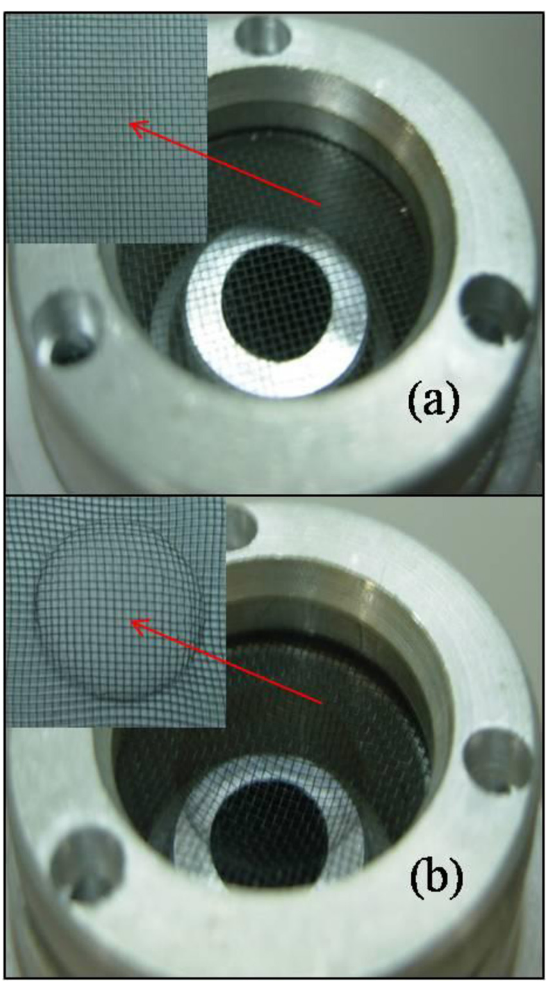

Fig. 2. Images of (a) the flat grid mesh, and (b) the concave grid mesh set up. The grid mesh is located 0.5 mm away from the tip of the CNT field emitters. The triode strucure consists of the cathode- made up of a stainless steel (SUS) substrate; the grid mesh- consisting of 70 μm diameter fine molybdenum wire spaced 0.5 mm from each other; and the tungsten embedded copper anode.

2.1. Computer simulation

Opera 3D computer simulation program was employed to conduct this study similar to prior reports [8,10]. The detailed characteristics of the actual structure were not strictly followed during the course of the simulation. This software has the ability to measure the electron beam radius impinging in the anode plate. Additionally, during the simulation, the CNT field emitter source was treated as a collective plate of emission layer with a concave grid electrode, positioned in a parallel plane to the cathode assembly. The emitter characteristics input were as follows: (1) the emitter type followed the Fowler–Nordheim model, (2) the emitter temperature was set at 1000 °C, (3) the emitter work function was set to 4.5 eV, and (4) the field enhancement factor was set to 1200. The cathode assembly voltage was set at −2 kV, the grid mesh electrode at 100 V and the anode at 10 kV.

With all the parameters set, the simulation program was started and the results are shown in Fig. 3. This figure shows the three-dimensional electron beam trajectories for the two grid electrode structures. From the simulation results, the concave grid mesh showed a focusing effect at gate bias of 100 V. This focusing effect may be attributed to the concave shape of the grid mesh. The concave design of the grid electrode guided the direction of the electric field toward the center of the curvature. The direction of this electric field was perpendicular to the equipotential lines of the conductive grid mesh and led the emitted electrons from the CNT field emitter toward the direction of the electric field. This claim was further analyzed quantitatively by measuring the electron beam radius impinging at the anode. Figs. 3(c) and 2(d) show the simulated electron beam trajectories (i.e. measuring the beam radius that impinge on the anode plate) of the cold cathode X-ray source with a flat and concave grid mesh, respectively. From the simulation program, the beam radius of the triode structure with the concave grid mesh was measured to be 1.38 mm as compared to the 4.70 mm for the flat grid mesh. Besides the focusing capability of the structure itself, this result may be attributed to the effective increase in the number of grid cell in the mesh when it was concave.

2.2. CNT fabrication and experiment

The multi-walled CNT emitter, with an average length of 20 μm, was fabricated using microwave plasma enhanced chemical vapor deposition (MW PECVD) as described elsewhere [11] and summarized as follows; titanium nitride (TiN) was first deposited on a stainless steel (SUS) substrate followed by sputtering of Ni catalyst. TiN served as a barrier layer between Ni and SUS substrate. The substrates were then loaded into a vacuum chamber under 3×10^{-6} Torr. During the pretreatment process, ammonia (NH_3) was introduced as a carrier gas for plasma treatment inside the chamber at a flow rate of 40 sccm at 4.5 Torr. Subsequently, acetylene gas (C_2H_2) was immediately introduced inside the chamber, to serve as a carbon source, at a flow rate of 10 sccm and mixed with the ammonia for 15 min. Finally, nitrogen (N_2) was introduced at 60 sccm to synthesize CNTs with heating the substrate at 700 °C.

As another part of the current work, the triode structure was housed inside an evacuated vacuum chamber with a base pressure of 1.8×10^{-8} Torr and a working pressure of 1.5×10^{-7} Torr. X-ray images were then produced using both the flat grid mesh and the concave grid mesh. The distance of separation between the CNT emitter and that of the gate was 1 mm. The nearest portion of the concave grid mesh was about 0.5 mm away from the CNT emitter, akin to that between the flat grid mesh and the field emitters.