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An X-Ray Tube with Micron-sized Focal Spot using Multi-tipped CNTs

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1. Introduction

A microfocus x-ray is developing as a high resolution imaging applications including diagnostic medical image and industrial inspection. A conventional thermionic x-ray tube is widely used because of its stability of electron emission and its high electron beam current with a large thermionic electron emission area. However, thermionic electrons are hard to focus as a spot due to a wide energy spread. The thermionic x-ray tube is limited to increase x-ray brightness over 10^7 phs/mm^{2}mrad^{2}s. [1] A field emitter that has a low energy spread was considered as a point x-ray source, but the field emission current was relatively low. The electron beam current was limited because electrons were emitted only a single emission point. [2] Carbon nanotube (CNT) is a high brightness electron source [3] and it can be deposited substrate-freely by chemical vapor deposition (CVD). It is possible to fabricate multi emitter, CNTs, on a sharp tip.

In this study, a conical tungsten tip was used as a substrate of the CNTs to reduce the electron emission area and to increase the beam current by a high field enhancement factor. The emitted beam size and current were controlled by a focusing triode electron gun and an electromagnetic lens system to increase the electron beam brightness. X-ray was generated by using a transmission x-ray target that was optimally designed by MCNPX code.

2. Methods and Results

2.1 Electron Beam Trajectory Simulation

The electron trajectory of carbon nanotube (CNT) x-ray tube is shown in fig. 1. The simulation was carried out by E-GUN code. Triode was composed of a 200 ㎛ diameter conical CNT cathode, a 1 mm diameter shielding electrode, and a 10 mm diameter anode. The electron emission voltage was 5 kV and the electron acceleration voltage was 40 kV. The distance and the shape of each electrode were optimized to focus the electron beam. The variable aperture can cut off a bad quality beam, and the solenoid that was positioned below the anode can freely focus the electron beam in the range of focal length. The x-ray target was developed from the optimized simulation results of our previous design study. [4]

2.2 Carbon Nanotube Multi Emitter

The multi-tipped CNT tip was fabricated by electrical etching and chemical vapor deposition. Amorphous tungsten 200 ㎛ diameter wire was electrically etched by 1 Mol/L KOH and DC +15V. Carbon nanotubes layer were deposited on the tip by TiN/Ni sputtering and plasma enhanced chemical vapor deposition (PE-CVD). Carbon nanotubes, the multi field emitter, are densely aligned on the tip surface. The CNT tip is shown in fig. 2.

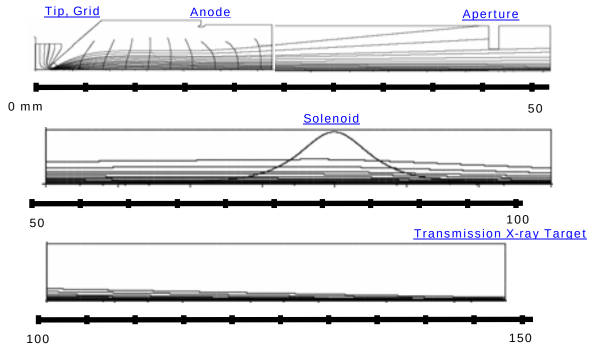

Figure 1. Electron beam trajectory simulation for a microfocus x-ray tube by using a multi-tipped carbon nanotube field emission gun, an electromagnetic lens system, and transmission x-ray target.

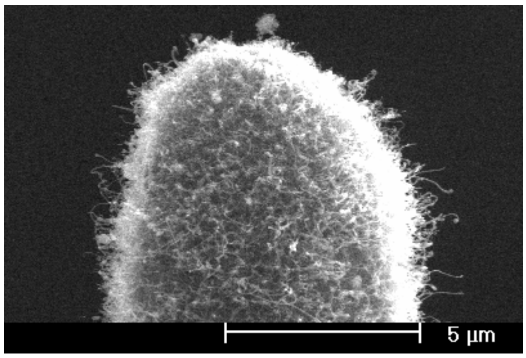

Figure 2. A multi-tipped carbon nanotube field emitter.

2.3 A Microfocus X-Ray Tube

The CNT x-ray tube composition is shown in fig. 3. Each electrode was mechanically centered in the beam axis to prevent beam deflection. The CNT tip was straightly fixed in the tip holder. The shielding electrode was set below 0.0 ~ 0.5 mm distance from the tip. The anode was placed 10 mm below the shielding electrode. An electron beam focusing system, an aperture and the solenoid lens, was aligned with respect to the triode combination. An acceleration and emission voltage were applied as -40 kV and -40 ~ -45 kV. A micro focused electron beam current was measured by using a biased faraday cup. The electron beam spatial distribution was characterized by a phosphorus screen. The micro focused electron beam was bombard on a 3 ㎛ tungsten target below the lens system. An x-ray film and a subject were fixed at a 20 mm distance from the transmission target. An x-ray image was taken using of CCD camera (Andor MCD CCI-010) and an x-ray film (Kodak intensifying screen). Vacuum was 5 x 10-5 Pa using a turbo molecular pump (Turbotronik NT 340M) and monitored by penning gage (Alcatel µ Pascal).

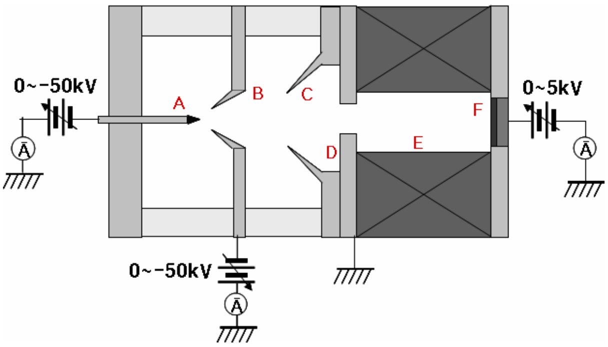

Figure 3. The schematic design of the microfocus x-ray tube. A, CNT tip; B, shielding electrode; C, anode; D, aperture; E, solenoid lens; F, transmission x-ray target.

2.4 Beam Currents and spatial distribution

Almost 50% beam passed through all electrodes, and fewer than 12% beam was collided at the shielding electrode. Left 30~40% beam was blocked at anode, lens aperture, and the inside wall of x-ray tube. The spatial distribution of focused beam is analyzed by using pixel brightness decoding from obtained beam image. The beam size is 100 ㎛ as a FWHM

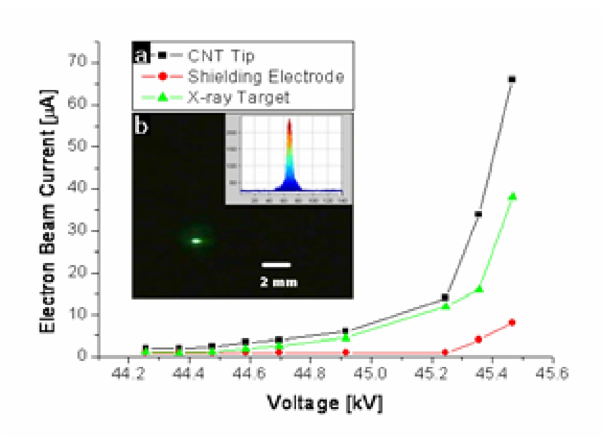

Figure 4. (a) Electron emission current of a cathode, shielding electrode, and x-ray target. The cathode and shielding electrode distance was 0.5 mm, and a 10 mm lens aperture was used. The acceleration voltage was 40 kV. (b) Focused electron beam spatial distribution

2.5 X-Ray Images

Fast imaging process and high x-ray resolution are the main goals of the microfocus x-ray tube. The x-ray image of IC chip (CNY 17-3) is shown in fig. 5. The image was enlarged by an optical lens. All 500 ㎛ electrodes are clearly observed. The exposure time several tens seconds.

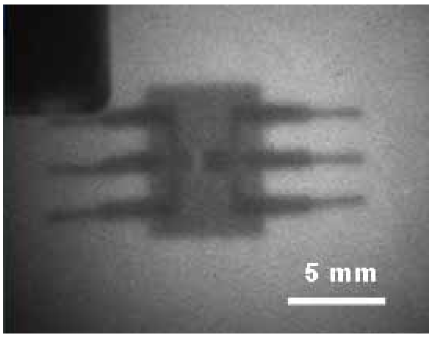

Figure 5. Contact x-ray image of an IC chip. Electron energy: 45 keV; exposure time: 10 sec.

3. Conclusion

The microfocus x-ray tube was developed by using a multi-tipped carbon nanotube multi field emitter, designed electron beam focusing system, and optimized transmission x-ray target. The x-ray source was bright enough to get an image within tens seconds. The x-ray source can be smaller than 10 ㎛ by using an extended strong electromagnetic lens according to our simulation. If the CNT tip is well fabricated as densely and robustly, there are possibilities to utilize it for an ultrafine and high brightness electron microscope.

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