Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Characteristics of Transmission-type Microfocus X-ray Tube based-on Carbon Nanotube Field Emitter

Sung Hwan Heo, Aamir Ihsan, and Sung Oh Cho*
Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-Dong Yuseong-Gu, Daejeon, Republic of Korea
socho@kaist.ac.kr

1. Introduction

A high resolution microfocus x-ray source is widely applied to noninvasive detection for industrial demands, material science and engineering, and to diagnostic study of microbiology and micro-tomography. Carbon nanotube (CNT) is regarded as an excellent electron emitter, which outperforms conventional electron sources in point of brightness.[1] It has been suggested that CNT is used as an electron source of a high resolution x-ray tube according to their low threshold field with atomically sharp geometry, chemically robust structure, and electric conductivity.

Several researchers have reported miniaturized x-ray tube[2] based on diode structure and micro x-ray radiography and computed tomography systems using triode types with precise emission control and electrostatic focusing.[3] Especially, a microfocus x-ray source of 30 μm resolution has been demonstrated recently using an elliptical CNT cathode and asymmetrical Eingel lens.[4] However, to increase the spatial resolution of x-ray source, a smaller CNT emitter is desired. Electron focusing optics must be corrected to reduce aberrations. A thin wire tip end can provide a micro-area of CNT substrate, and a magnetic lens and transmission x-ray target are proper to reduce the lens aberration and a focal length. Until now, CNT based microfocus x-ray source with less than 10 um resolution has not been shown.

Here we report a microfocus x-ray source with 4.7 μm x-ray focal spot consisted of a conical CNT tip, a single solenoid lens, and a transmission type x-ray target. A magnified x-ray image larger than 230 times was resolved with advantage of microfocused focal spot and transmission x-ray target.

2. Methods and Results

2.1 Carbon Nanotube based Microfocus X-Ray Tube

Figure 1 (a) shows the schematic layout of the microfocus x-ray tube, which consists of a CNT cathode tip, a gate electrode, an anode, a solenoid lens, and a transmission x-ray target. An electron beam is generated from the triode gun: electrons are emitted from the CNT cathode by the electric field produced between the cathode tip and the gate electrode and subsequently accelerated by the electric field generated between the gate electrode and the anode. (The electron current emitted from the CNT cathode is controlled by the gate voltage.) The cathode has a sharp tip shape, which increases the electron current at the CNT field emitters compared to a flat cathode because higher electric field are generated at the CNT cathode.

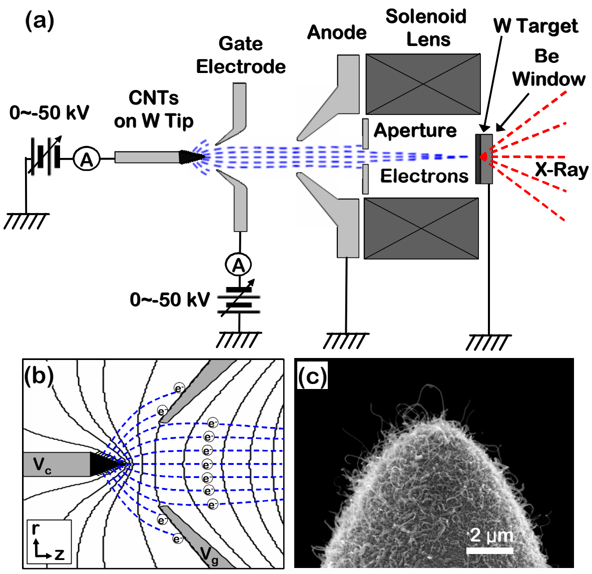

Figure 1. (a) Schematic layout of the microfocus x-ray tube consisting of a triode electron gun, a solenoid lens, and a transmission-type x-ray target. The triode gun is composed of a CNT cathode, a gate electrode, and an anode. (b) Electron trajectory in the triode gun calculated using EGN2 program. (c) SEM image of the CNT cathode. CNTs with the diameter of ~50 nm and the length of ~1 m are uniformly coated on the W tips. The tip has hemispherical shape of ~5 μm curvature radius.

Due to the sharp cathode tip, electrons emitted from the cathode are diverged and some of the electrons are lost on the gate electrode. However, since the gate electrode of the triode gun acts as a lens, the electrons passing the gate electrode are focused, as shown in Fig. 1b. (Fig. 1 (c) shows an electric field simulation of the triode with a conical tip end.) Both the gate electrode and the anode are inclined to the cathode, inducing a focusing electric field and thus the electrons are further focused while they transport between the gate electrode and the anode. The diameter of the electron beam passing after the anode is reduced by the aperture in front of the solenoid lens. Finally, the electron beam is focused down to micrometer size onto the transmission-type x-ray target by the solenoid lens, producing x-ray(s) with micrometer focal spot.

2.2 Emission Current of X-Ray Tube

The electron beam generation and transport characteristics of the fabricated x-ray tube were measured. Figure 2 shows the measured result of the characteristics as a function of the gate voltage. The anode voltage was fixed to 40 kV and the CNT tip-gate distance was 2 mm. Emission current at the CNT tip increases with increasing the gate voltage. Interestingly, 95 % of the emission current passed through the aperture of the gate electrode even though the emission current was increased to 30 μA.

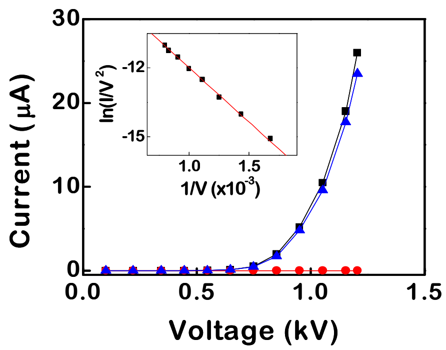

Figure 2. Field emission properties of the CNT cathode in the triode gun and the electron-beam transport characteristics of the fabricated x-ray tube. Voltage in the abscissa is the voltage difference between the cathode voltage and the gate voltage. Currents in the ordinate are the emission current at the CNT cathode (-■-), the beam current lost at the gate electrode (-●-), and the beam current arrived at the x-ray target (-▲-), respectively. The cathode voltage was fixed to -40 kV and the cathode-gate distance was 0.25 mm.

2.3 X-Ray Focal Spot

Figure 3 (a) shows a 145 times magnified x-ray image of a 1000 meshes per inch transmission electron microscope (TEM) grid (gold, 6 μm in width, 25 μm in pitch), which are cannot be resolved in a conventional x-ray radiography system. The width of 6 μm thin mesh is clearly resolved in two orthogonal directions. This image strongly implies that the x-ray focal spot is small. electron is symmetrically emitted from the tip and focused to the transmission target through the designed electron optics. Figure 3 (b) shows a micrograph of a 200 meshes per inch TEM grid (gold, 37 μm in width, 127 μm in pitch). The image is obtained with a higher magnification (230 times) to increase the number of detection pixel on a certain blurred edge. The x-ray focal spot size was measured by means of the mesh image following the European standard (EN12543-5).

Figure 3 (c) and (d) show that the x-ray focal spot is measured to be 4.7 μm (horizontal direction) and 4.9 μm (vertical direction).

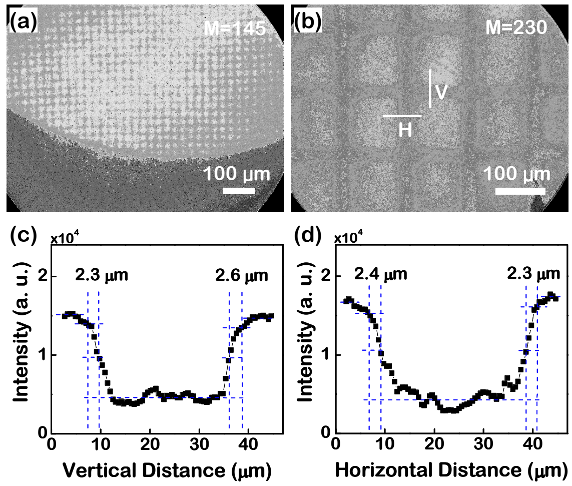

Figure 3. (a) Magnified XR image of a 1000-mesh gold TEM grid (bar width: 6 μm, pitch: 25 μm). Magnification was 145 and exposure time was 2.5 s. (b) Magnified XR image of a 200-mesh gold TEM grid (bar width: 37 μm, pitch: 127 μm). Magnification was 230 and exposure time was 4 s. (c), (d) Intensity profiles along the vertical and horizontal lines in the XR image of the 200-mesh TEM grid.

3. Conclusion

We have demonstrated a microfocus x-ray tube based on the point-like CNT field emission source, the symmetric magnetic focusing unit, and the transmission x-ray target. The high magnification and resolution can be applied to x-ray microscopy and micro-computed tomography. Furthermore, it is expected that nanofocus x-ray source with sub-micrometer x-ray focal spot can be developed by keeping up the research of carbon nanotube nano-emitter and extended electromagnetic focusing system.

REFERENCES

[1] N. Jonge, Y. Lamy, K. Schoots, and T. Oosterkamp, High brightness electron beam a multi-walled carbon nanotube, Nature, Vol. 420, p. 393, 2002

[2] S. Senda, Y. Sakai, Y. Mizuta, S. Kita, and F. Okuyama, Super-miniature x-ray tube, Applied Physics Letters, Vol. 85, 5679, 2004

[3] J. Zhang, Y. Cheng, Y. Z. Lee, B. Gao, Q. Qiu, W. L. Lin, D. Lalush, J. P. Lu, O. Zhou, A nanotube-based field emission x-ray source for microcomputed tomography, Review of Scientific Instruments, Vol. 76, 094301, 2005

[4] Zejian Liu and Guang Yang, Yueh Z. Lee, David Bordelon, Jianping Lu, Otto Zhou, Carbon nanotube based microfocus field emission x-ray source for microcomputed tomography, Applied Physics Letters, Vol. 89, 103111, 2006