High Brightness Electron Beam with Carbon Nanotube (CNT) Cold Cathode

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ABSTRACT

We fabricated high brightness electron beam with carbon nanotube (CNT) cold cathode. The beam brightness strongly depends on the virtual source size of CNT cold cathode. Based on the beam brightness simulation and measurement, we could obtain micro-focused electron beam with higher electron emission current for large area, high resolution imaging.

1 INTRODUCTION

The source of electrons for high resolution imaging requires some important parameters such as beam diameter, emission current, convergence angle. These parameters ultimately influence the performance of the electron microscope depending on the characteristic of the electron source.

The CNTs have nano-meter sized tip apex diameter and has unique electron emission properties. The CNT emitters are suitable as a small area electron source. That can be driven stably up to few micro-amperes of current due to their structural properties with high aspect ratio. [1] In this research, a method of manufacturing a high performance electron source with direct growing CNT field emitter wase studied. Beam performance with various structural properties of CNT emitter was studied. We could summarize the correlation between the brightness of the electron beam and the structure of the emitter.

2 EXPERIMENT

A direct growing CNT emitter was fabricated by using the triode type dc-PECVD and conventional photo lithography process. A nickel (Ni) catalyst was sputtered on the Si substrate and which metal was patterned. The substrate was cut into the 16 mm^2 of square size and 3 μm of single dot pattern was formed. [2]

The single CNT emitter was measured the field emission characteristic in vacuum of 10^{-7} Torr. Based on the structural differences, we evaluated 20 samples. The CNT emitters could be classified as a 3 type of the structural properties and which have different electron emission properties each other with the geometrical factor (β_{geo}). Fig. 1 shows the schematic of the evaluation of the single CNT emitter. A phosphor screen was fixed at the upon the CNT cold cathode with 250 μm of gap. According to the distance between the cathode and phosphor screen, we can analyze the emission pattern of the electron beam and use it to infer the solid angle of the electron beam. [3] We analyzed the emission patterns with commercialized image analysis program as shown Fig. 1.

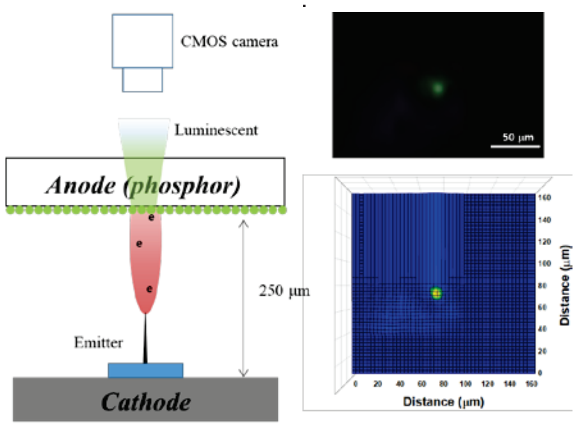

Fig. 1. Schematic diagram of evaluation method for electron emission pattern.

3 RESULTS and DISCUSSION

We analyzed the electron emission characteristics and electron beam patterns of 20 samples. As results, CNT emitters were classified into 3 groups according to their structural properties. These CNT emitters were distinguished with the tip radius and β_{geo}. For analysis of the beam brightness with the β_{geo} value, we could calculate the angular current density and virtual source radius (r_v). The beam performance of 3 group of CNT emitters were summarized at Table. 1.

Table. 1. Summary of electron beam performance for single free-standing one CNT emitters

Group	Properties			
	Tip R (nm)	Turn on (V/μm)	β_{geo}	Brightness (V/m^2srV)
Group 1	25	3.9	2,360	~ 10^{10}
Group 2	56.7	6.2	734	~ 10^{9}
Group 3	139	8.6	282	~ 10^{6}

The electrons emitted from spherical tip of the CNT emitters are caused by the field emission with a work function of 5 eV. The current density is defined by the Fowler-Nordheim equation as follows; [4]

$$J = 1.54 \times 10^{-6} \frac{F^2}{(\phi/e)} exp\left[-6.83 \times 10^{-6} \frac{\phi^{3/2}}{F} \right] \quad \textbf{(1)}$$

The tunneling parameter (d) is also important for calculating the energy spread in field emission and virtual source size, equation as follows: [5]

$$d = 9.76 \times 10^{-11} \frac{eF}{(\phi/e)^{1/2}} \quad \textbf{(2)}$$

Where F is electric field and ϕ is the work function in electron volts. In general, the virtual source size is based on the electron emission form the tip of the spherical tip. The radius of the virtual source size is typically smaller than physical source tip size, and is expressed as: [6]

$$r_v = \left[\frac{3Rd}{ekF} \right]^{\frac{1}{2}} \quad \textbf{(3)}$$

Where R is the prepared source radius and k is the field enhancement factor. In case of No. 12 CNT emitter in group 1 shows the 4 μA of emission current at 1,300 V with 14 μm of the emission pattern. Its angular current density was 156.9 μA/sr and virtual source radius was 0.6 nm which comes from equation 3. So we could obtained the reduced brightness (Br) of 1.42×10^{11} A/m^{2}srV

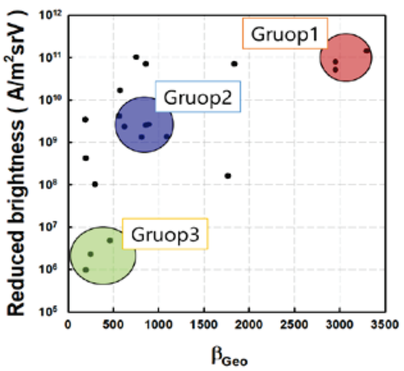

Fig. 2. Summary of the reduced brightness (B_r) with geometrical factor (β_{geo}).

The reduced brightness shows increase with the β_{geo} as an exponential growth function. Which means that the Br shows a characteristic of exponential rise as the decrease of tip diameter and increase of emitter's height. To verify the authenticity of the experimentally calculated values, the characteristic of the CNT emitter were verified using 2D source simulation tool.

Fig. 3(a) shows the trajectory of the electron emission from our model. The work function of emission was 5 eV, and the model has a 50μm of the height, 30 nm of the apex of the tip. The field emission properties ware indicated at the fig. 3(b) which shows good matched to the experiment data. The Br was 4.3×10^{11} A/m^{2}srV from the 2D simulation which also similar to our experiment.

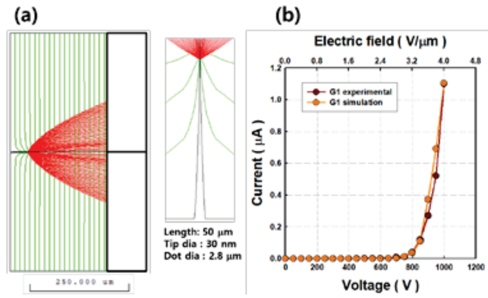

Fig. 3. 2D simulation of group 1 emitter and comparison of the I-V characteristics.

4 CONCLUSIONS

The source of electron was prepared with direct growing on the Si substrate with CNTs. The single CNT emitter shows micro scale of beam spot size in the diode configuration and the beam brightness depending on the β_{geo} of CNT emitter. The electron emission and beam brightness shows good matched with simulation data. Based on the simulation, we will design the electron beam column and optic system for microscope application.

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REFERENCES

[1] N. De Jonge and N. J. van Druten, "Field emission from individual multiwalled carbon nanotubes prepared in an electron microscope," Ultramicroscopy 95, 85-91 (2003)

[2] J. S. Kang, and K. C. Park, "Electron extraction electrode for a high-performance electron beam from carbon nanotube cold cathodes," J. Vac. Sci. Technol. B, 35, 02C109 (2017).

[3] H. R. Lee, H. H. Yang, and K. C. Park. "Fabrication of a high-resolution electron beam with a carbon nanotube cold-cathode," J. Vac. Sci. Technol. B, 35, 06G804 (2017).

[4] P. W. Hawkes and E. Kasper, Principles of Electron Optics II: Applied Geometrical Optics (Academic, London, 1996).

[5] N. d. Jonge, M. Allioux, J. T. Oostveen, K. B. K. Teo, and W. I. Milne, " Optical Performance of Carbon-Nanotube Electron Sources", Phys. Rev. Lett, 94, 186807 (2005)

[6] N. de. Jonege," Brightness of carbon nanotube electron sources", J. Appl. Phys, 95, 673 (2004)