High brightness vertically aligned carbon nanotube (CNT) cold cathode for electron microscope

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ABSTRACT

We developed a high-brightness carbon nanotube (CNT) cold cathode and its studied structural analysis and electron emission characteristics. Based on structural properties, there is a difference in electron emission characteristics, which in turn affects the brightness of the beam. The correlation between the CNT cold cathode structure and its brightness was established, and an optimized electron beam module was designed for secondary electron microscopic imaging.

1 INTRODUCTION

An electron source for high-resolution imaging requires several important parameters such as angular current density and beam brightness. These parameters will ultimately affect the performance of the electron microscope depending on the characteristics of the electron source. A representative criterion for evaluation and determining performance with a microscope is the resolution or resolving power. The smaller the probe size, the smaller the edge of the sample is clearly visible, and the electron beam can now be focused at the nanoscale. The formation of the probe size is made in the form of a fine electron beam using an electromagnetic lens, and the minimum size is determined according to the size of the original electron source.

The vertically aligned (VA) CNT has a radius of nanomenter-sized tip apex has a unique electron emission characteristic. Due to its high aspect ratio structural characteristics, it can reliably drive currents up to several microamperes. [1] We figured out the structure of three types of electron emission sources and grouped them differently according to the trend of the electron beam trajectory. Finally, we successfully demonstrated scanning electron image according to the structural properties of VA-CNT cold cathode.

2 EXPERIMENT

The location of CNT emitters grown on a Si substrate is one of the important parameters in device applications. For this reason, we used a photolithography process to pattern the catalytic nickel (Ni) metal for growing CNTs. The CNT emitters were grown using the triode type direct current plasma enhanced chemical vapor deposition (DC-PECVD) system to control the density and shape the vertically aligned grown CNTs on the substrate. [2]

The basic field emission properties were measured in diode mode and anode phosphors coated on ITO glass were used to analyses the emission pattern. [3] The distance between the anode and the cathode electrode was maintained at 250 μm, and the CNT cold cathode was fixed on the cathode electrode using Ag paste. An electrons emitted from the cold cathode by applying positive voltage excite the phosphor in vacuum of 10-7 Torr. At this time, the emission pattern is observed with an optical microscope and its analyzed using by the commercialized image analysis program.

3 RESULTS and DISCUSSION

Fig. 1 shows a graph comparing the field emission characteristics of each group of CNT cold cathodes. Based on the emission current of 1 μA, G1 (red circle) was obtained at 700 V, G2 (blue rectangle) at 900 V, and G3 (green triangle) at 2,200 V. Fig. 1 (b) indicated that the FN plot of the three groups. The reason for the difference in field emission properties of the emitter is that the edge of the emitter tip, the lower the threshold voltage. This means that even if the same electric field is applied, the thinner the tip portion, the more effective the electric field can be induced. Besides, the shape of the tip is important, but the height of the emitter itself is also important parameter. therefore, many studies refer to the high aspect ratio (geometrical factor) as a very important variable.

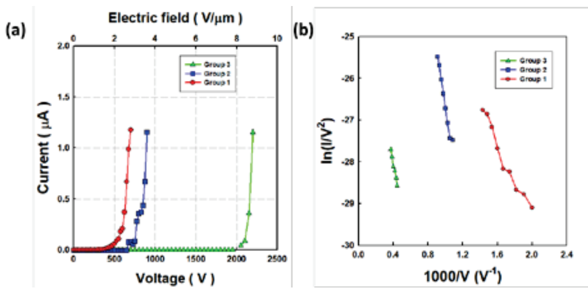

Fig. 1 Comparison of field emission properties. (a) Field emission properties of Group 1, 2, 3, (b) F-N plot.

An important parameter for the resolution of high resolution electron beam mechanism is reduced brightness (B_r). The B_r measures the spot size of a

particular size and the amount of current that can be concentrated at a particular solid angle. It is a function of the radius of the virtual source (r_v), the brightest part of the emitted electron beam and the respective current densities (J) corresponding to the beam potential U (Hainfeld 1977; Hawkes & Kasper 1996) [4].
The brightness is a measure of the amount of emission current that can be focused on a specific point in a solid angle. In addition, the electrons are decelerated or accelerated by the applied voltage, the B_r plays an important role in obtaining a high-resolution image. The function of B_r consists of r_v, angular current density (J_Ω), and the applied voltage (V). [5]

$$B_r = \frac{J\Omega}{\pi {r_v}^2 V} \qquad (1)$$

Using this calculation method, we were able to obtain the theoretical B_r of the G1 CNT cold cathode (9.26×10^{10} A/sr m^2 V). The theoretical reduced brightness was calculated based on the trajectory of the beam in the diode structure, and there will be a difference in the electron beam module of the triode structure. However, the tendency of reduced brightness according to the structure of the electron source will be an important indicator for obtaining electron microscope images in the future.
Fig. 2 show the modeling of the SOURCE 2D simulation of G1. In case of VA-CNT cold cathodes, the tip has a spherical shape. The height of the CNT cold cathode is 40~50 μm, and based on this, we modeled it, as shown in Fig. 2 (a). The G1 CNT cold cathode, which has 17.5 nm of the tip radius and distance of anode to source plane was 200 μm. Fig 2 (b) indicates that the effective beam divergence of G1, G2 CNT cold cathode from the computed trajectory coordinates in binary code. [6] The G1 CNT cold cathode shows 9.6 μm of beam diameter at 200 μm of distance from cathode and G2 was 108 μm.

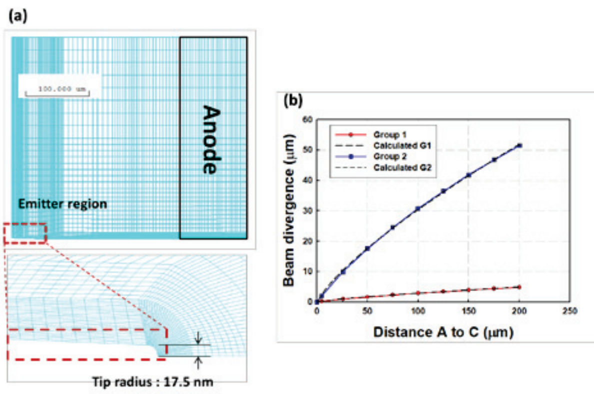

Fig. 2 Simulation results. (a) Modeling of SOURC 2D simulation in diode mode, (b) electron beam trajectory prediction by distance.

The first scanning secondary electron imaging experiment using a CNT cold cathode is shown in Fig.3. With condenser 1 and 2 turned off, the TEM grid mesh (2000) was imaged using an objective lens and a scanning system.

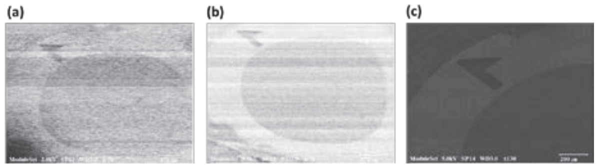

Fig. 3 Scanning secondary electron images according to the condition of electron emission. (a) First image at 0.04 μA of emission current, (b) image at 0.08 μA of emission current, (c) image at 0.08 μA of emission current after aging process.

The Fig. 3 shows secondary electron images according to electron emission conditions. The electron emission was measured at 10^{-8} Torr vacuum condition with an acceleration voltage of 5 kV and Fig. 3 (a) was the first image when the emission current was 0.04 μA. Secondary electron images appear in alternating light and dark areas, because the emission current is unstable. First, to obtain a brighter image, the emission current was increased 2 times more (Fig. 3 (b)), and the electrical aging process was performed for 2 hours. After the aging process, despite the electronic emission conditions such as Fig. 3 (b), we obtained a more stable image, as shown in Fig. 3 (c).

4 CONCLUSIONS

We conducted experiments and characteristics analysis for electron microscope imaging using a high-brightness electron source. There is a difference in brightness depending on the structural characteristics (geometrical factor) of the electron source, which in turn affects the trajectory of the electron beam. We have also confirmed that there is a difference in resolution of secondary electron images depending on the structure of the VA-CNT cold cathode.

5 ACKNOWLEGMENT

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