Fabrication and Characterization of a 3D-Structured Field Emitter Using Carbon Nanotube

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Carbon nanotube has good electrical properties and a high aspect ratio, which enable it to obtain a high current at a low voltage due to its high field. Due to the life and uniformity of their emission tips, carbon nanotube field emitters are hard to commercialize. A field emitter with a three-dimensional (3D) structure was fabricated in this study to overcome such problems. In the 3D-structured field emitter, the field emission tips are located only at the vertical plane, where an enlarged field emission area can be attained. To fabricate the tip of the 3D-structured field emitter, carbon nanotube/silver nanocomposite powders were fabricated via molecular-level mixing and were sprayed at a substrate with good attachment and homogeneous dispersion between the CNT tips and the silver. The field emission properties of the 3D-structured field emitter were then determined and compared with those of a flat field emitter. The field emission area of the 3D-structured field emitter was found to be 4.5 times larger than that of the flat field emitter, with six times higher current density. Moreover, the 3D-structured field emitter had better stability than the flat field emitter. At a high gate field, the emission images of the 3D-structured field emitter showed light spots expanded towards the gate direction.

Keywords: Carbon Nanotube, Field Emission, 3D Structure, Life Time.

1. INTRODUCTION

Field emitters have various applications as electron emission sources. Especially in the case of field emission displays (FEDs), their predominant properties, such as their fast response time, low power consumption, wide viewing angle, and operating temperature, could make them advantageous over LCD and PDP. Metal−1,2 and silicon−type field emission tips are hard to commercialize, however, due to their low emission efficiency and short life. Hence, the discovery of the carbon nanotube was a breakthrough.

Carbon nanotubes have attractive properties as sources of field emitters, such as high aspect ratio, small radius of curvature, high mechanical strength, and chemical stability.5,6 Especially, their high aspect ratio enables them to obtain a high current at a low voltage due to their high field concentration, which could not be achieved by other materials. Many researchers have focused on the development of various methods of forming carbon nanotube tips, such as direct CVD growth,7−10 screen printing,11−13 spraying,14 electrophoresis deposition,15 and dip coating.16 Simply increasing the field emission tips, however, has a limitation in enhancing the field emission property. If the tips are too close to one another, the field emission efficiency will decrease through the interruption of the field concentration at each tip. This phenomenon is known as the “screen effect.”17 To prevent the screen effect, there has to be enough distance between the tips, approximately twice the height of the tip. Thus, there is a limit to the number of field emission tips on a flat surface. For a high current to flow through the field emission tips and to give such tips a long life, their degradation must be minimized, and the flowing current per emission tip must be reduced. As such, a field emitter that will increase the number of field emission tips while maintaining a sufficient distance between such tips should be developed.

In this study, a 3D-structured field emitter was fabricated (Fig. 1). In such field emitter, the field emission tips are not located on the flat surface but on a vertical plane due to the enlargement of the field emission area. This structure can increase the field emission tips while...
Fig. 1. Schematic diagram of the 3D-structured field emitter.

2. EXPERIMENTAL DETAILS

2.1. Fabrication of CNT Field Emitter Cathode

CNT/Ag nanocomposite powders were synthesized via molecular mixing, after which the CNTs were functionalized via acid treatment. 0.035 g of the functionalized CNTs was then dispersed in 300 ml ethylene glycol via ultrasonication, and 0.486 g silver nitrate was dissolved in 150 ml ethylene glycol. 5 ml hydrazine and 25 ml ethylene glycol were then added to the mixture of the CNT and silver nitrate solutions, after which the mixture was refluxed for 2 h at 60 °C. The CNT/Ag nanocomposite powders were washed with ethanol and were dried under vacuum at 80 °C.

A 5-mm-thick SUS 304 plate was used as a substrate. The shape of the 3D-structured substrate, which was made by wire cutting, is shown in Figure 2(a). A flat SUS plate was used as a substrate in a 2D structure.

The CNT/Ag nanocomposite powders were deposited on the substrate via spray coating.18 The powders on top of the 3D-structured substrate were removed by washing with ethanol. The substrate was then sintered for 30 min at 400 °C, under vacuum. To activate the emission tips, taping was carried out. The same process was applied to the 2D-structured substrate, except for the washing.

2.2. Characterization Techniques

The microstructures of the emission surface were measured using a scanning electron microscope (SEM, Hitachi S-4800).

The field emission properties of the 3D-structured field emitter were measured using a triode-type system, as shown in Figure 2(b), and those of the 2D-structured field emitter were measured using a common-diode-type system. The field emission properties were measured in a high-vacuum chamber with a base pressure of $5 \times 10^{-6}$ torr. High-voltage DC power supply was applied, and the current was measured. The obtained data were recorded in a PC using GPIB.

3. RESULTS AND DISCUSSION

3.1. Microstructure of 3D-Structured Field Emitter

The whole surface of the substrate was uniformly coated with the CNT/Ag nanocomposite powders via spray coating. It was not necessary to make emission tips for the 3D-structured field emitters located on top of the structure. To remove the powders on top of the structure, the top surface of the structure was wiped with ethanol. The CNT/Ag nanocomposite powders were then removed from the cleaned top surface (Fig. 3(a)). The other surfaces, however, such as the sides of the structure, were still coated with CNT/Ag nanocomposite powders (Fig. 3(b)).

![Fig. 3. SEM images of the 3D-structured field emitter’s surface (a) top area; (b) side area; (c) after sintering; and (d) high magnification image after sintering.](image-url)
Figure 3(c) shows the surface of the 3D-structured field emitter after sintering. Ag nanoparticles were not detected, as opposed to Figure 3(b). The sintering temperature was lower than the melting temperature of Ag, but the Ag particles were small enough to be melted. During the sintering, the melted Ag particles flowed to the interface between the CNT and the substrate and then formed a metal layer. The metal layer increased the bonding strength between the CNT and the substrate, which can help increase the life of the field emitter. Figure 3(d) shows a high-resolution image of the surface. The density of the CNT tip was about $5.6 \times 10^{10} / \text{cm}^2$, and the transferred plane density was about $2.5 \times 10^{10} / \text{cm}^2$. The increase in the density of the CNT tip is expected to increase its life and current density.

3.2. Field Emission Properties of 3D-Structured Field Emitter

The 3D-structured field emitter’s emission properties were measured using diode and triode systems. Power supply was applied to the voltage from the cathode to the gate. Through this experiment, the emission area was detected. The 3D-structured field emitter was found to have a larger current density than the 2D-structured field emitter (Fig. 4(a)). Figure 4(b) shows that the current density ratio of the 3D-structured field emitter to the 2D-structured field emitter was 6 in the range of 2.1–2.6 V/μm. Theoretically, the emission area of the 3D-structured field emitter is 4.5 times larger than that of the 2D-structured field emitter. As the residual CNT/Ag nanoparticle powders on the top surface of the substrate were emitted electrons, however, the real emission area value is larger than the theoretical value.

Figures 5(a)–(d) show the emission properties of the 3D-structured field emitter, determined using a triode system. The anode current density increased when the gate field increased (Fig. 5(a)). As the gate field helps electrons emit easily, the anode current density is thus higher at a high gate field. On the other hand, the increment of the anode current density decreases because the gate electrodes also receive electrons. This phenomenon is revealed by the emission images. The higher the gate field that is applied, the more the light expands (Figs. 5(b)–(d)). To solve this problem, a bigger distance with a higher voltage between the cathode and anode is essential.

The field emission stability over 6 h was measured under a limited anode current density and applied field. Figure 6 shows that the 3D-structured field emitter is more stable than the 2D-structured field emitter. The limitation of the applied fields was confirmed by the $I-V$ curve. The 3D-structured field emitter’s applied field was set at 4.8 V/μm, and that of the 2D-structured field emitter was set at 6 V/μm, to reach an anode current density of 250 mA/cm². The 2D-structured field emitter’s anode...
current density decreased by 15%, but in the case of the 3D-structured field emitter, it was its applied field that decreased rather than its current density. This phenomenon has two meanings. First, the 3D-structured field emitter is more stable than the 2D-structured field emitter because of the former’s large emission area. The mechanism for current degradation is related with a high current on each CNT tip. The current on each CNT tip can be reduced by increasing the CNT tips, but too dense CNTs decrease the field concentration, which will require a large emission area. Second, it is expected that the direction of the 3D-structured field emitter’s emission tips was changed from the gate to the anode. The emission tips were also affected by the anode and gate field, after which they were automatically optimized.

4. CONCLUSIONS

In conclusion, a 3D-structured field emitter was successfully fabricated and was uniformly coated with CNT/Ag nanocomposite powders via spray coating. The use of CNT/Ag nanocomposite powders is expected to increase the bonding strength. Through a field emission test, it was verified that the 3D-structured field emitter had a larger emission area and better stability compared to the 2D-structured field emitter.

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References and Notes


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