Carbon Nanotube-Based Triode Field Emission Lamps Using Metal Meshes With Spacers

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***Abstract*—We fabricated a carbon nanotube (CNT)-based triode field emission flat lamp with a gated emitter structure, which is composed of a metal grid with a spacer as a gate, a cathode electrode layer, and a CNT layer. The metal mesh was designed with trenches and numerous holes to make a gap between gate and cathode electrodes and to provide electrons with a highly efficient passage. We observed that this metal mesh decreased the vibration and leakage current owing to high electric field generated from anode. As a result, the uniformity and stability of this field emission lamp was improved.**

***Index Terms*—Carbon nanotube (CNT), field emission flat lamp, leakage current, metal mesh, triode.**

I. Introduction

CARBON nanotubes (CNTs) have emerged as potential candidates for replacing microtip field emitters [1]–[4]. These CNT field emitters show comparable performance to microtip field emitters. These emitters can be made without the expensive thin-film deposition and photolithography tools used in the process of fabricating microtip field emitters. In fact, they can be deposited with low-cost large-area scalable techniques such as screen printing [5] or simple chemical vapor deposition [6]. Use of these low-cost techniques opens up the possibility of producing field emission displays (FEDs) and flat field emission lamps (FELs) with diagonal sizes between 25 and 40 in.

The lamp application requires high brightness and efficiency. To achieve both properties, a high anode voltage has to be applied. The emitted electrons need to be sufficiently focused. Therefore, the construction of a reliable triode emitter structure has been one of the critical issues in applying the CNT-based FED [5], [7].

In a normal triode structure, the gate electrode can be fabricated with screen-printing methods. However, the process is somewhat complicated because a few different masks should be used. This letter attempts to use a metal mesh as a gate electrode. The metal mesh can be easily made and has been used in color cathode-ray tubes [8]. It protects the cathode from damage resulting from high-voltage penetration. It also prevents uncontrollable electron emission by the anode voltage.

However, it is difficult to control the electron emission uniformity of the CNT-based triode FEL when designed for use in a large-area panel because the tension of metal mesh and applied electric field lead to the vibration in the metal mesh. Its vibration has a bad influence on the FEL, such as a variation of gap between gate and cathode, arcing, and more leakage current. Particularly, the uniform spacing between three electrodes [cathode, gate (metal mesh), and anode] plays an important role in the fabrication of a large-area panel [9], [10]. To solve those problems, we suggest the metal mesh integrated with trenches and numerous gate holes, as shown in Fig. 1.

This letter reports on the fabrication of the triode FEL, which is composed of a cathode plate with an electrode, CNT emitters, the suggested metal mesh, and an anode plate with an electrode and a phosphor layer to improve uniformity and stability characteristics.

II. Fabrication

The fabrication process of a CNT-based triode FEL is divided into three steps. The first step is to fabricate metal mesh by a conventional etching process. The second step is to format CNT emitters, cathode electrodes, and phosphors by a screen-printing process [5]. The final step is to assemble a fabricated anode, cathode, and metal mesh.

Fig. 2 shows the fabrication process. The metal mesh, as a gate, was made of SUS 304 stainless steel plate, and its size was 8 cm × 8 cm × 150 μm. The trenches were formatted on a SUS plate, and the gate holes were formatted on a backside of a SUS plate by a conventional wet etching process. The SiO_2 layer was deposited on the fabricated metal mesh to decrease its leakage current by plasma-enhanced chemical vapor deposition. The size of a trench and the distance between trenches were 3.25 mm × 80 mm × 0.05 mm and 60 μm, respectively. The diameter of a gate hole was 170 μm, and the number of gate holes was 26 334.

The substrate was a soda-lime glass (SLG), and its size was 12 cm × 10 cm × 1.1 mm. A paste of a Ag cathode electrode was screen printed on an SLG substrate with an active area of $8 \times 8\ cm^2$, and its linewidth was about 3.1 mm. Then, the sample was dried at 120 °C for 30 min in a conventional oven and was fired at ∼ 500 °C for 30 min under ambient N_2.

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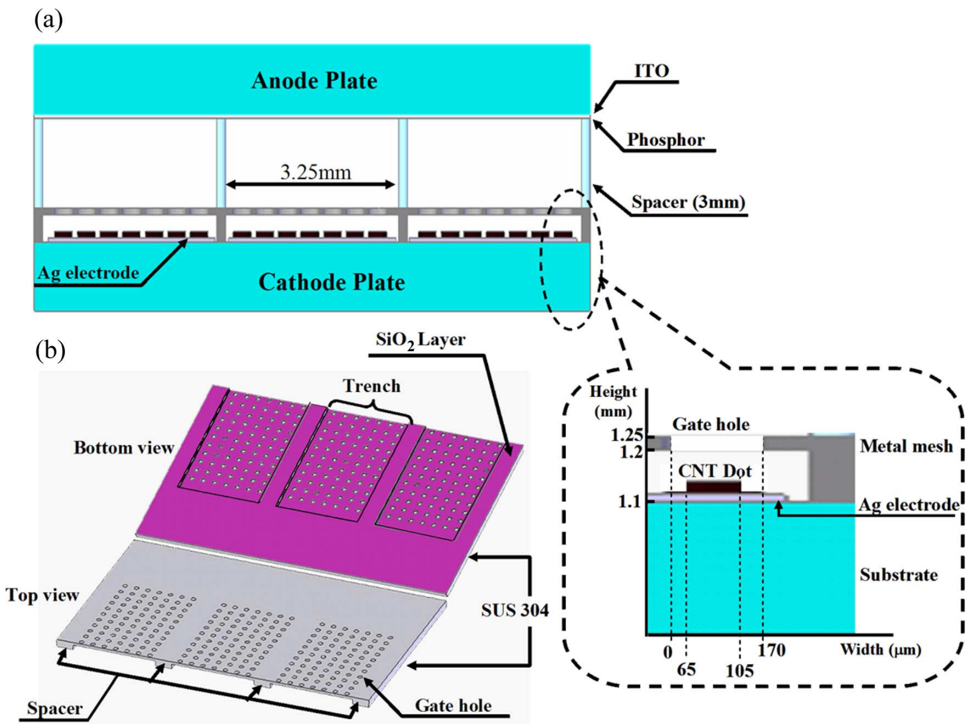

Fig. 1. Schematic of a triode FEL. (a) Cross-sectional view of a CNT-based triode FEL. (b) Structure of metal mesh with spacers.

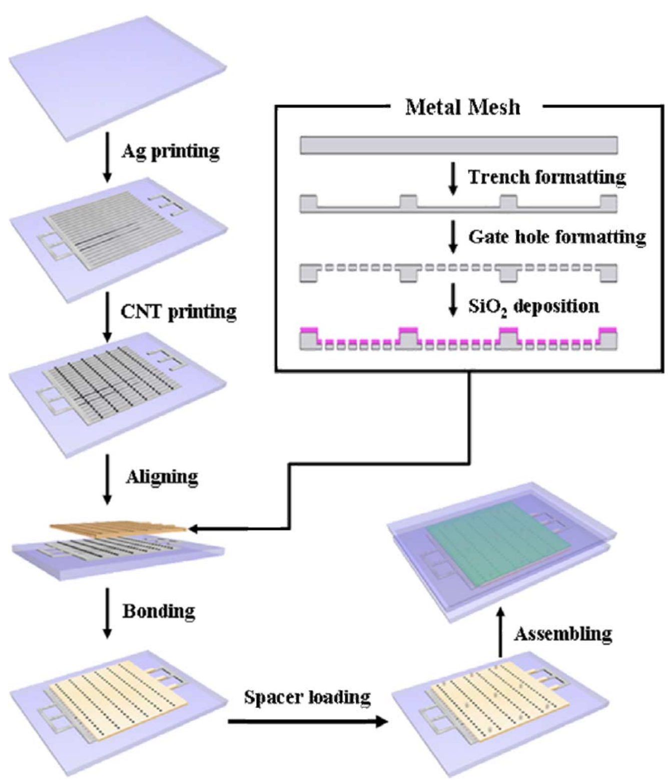

Fig. 2. Fabrication process of a metal mesh and CNT-based triode FEL by using a metal mesh.

The CNTs used were multiwalled CNTs (MWCNTs) synthesized by thermal–chemical vapor deposition [11]. The CNT pastes were mixed with MWCNTs, an organic binder (ethyl cellulose), and a glass frit in a solvent. CNT dots were printed at a thickness of 6–8 μm and a diameter of 40 μm on the Ag screen-printed SLG substrate. The sample was then dried at 120 °C for 1 h in a conventional oven. To remove the organic binders, the sample was fired at $\sim$ 380 °C for 20 min under ambient N_2. It was then naturally cooled down to room temperature.

The surface treatment method of the CNT dots was the adhesive taping method [12]. A phosphor layer was screen printed on an indium-tin-oxide-coated SLG substrate as an anode plate. The firing process was identical to the printed CNT dot process.

To fix the metal mesh, the bonding glue line was printed on the prepared cathode plate. The prepared metal mesh was aligned and bonded on a cathode plate by a screen printer, which has two microscopes and the moving worktable. The distance between the gate hole and cathode plate was 100 μm. Finally, the spacers were loaded on the metal mesh, and the cathode and anode plates were combined. The two glass plates were separated by a distance of 3.15 mm.

III. Results and Discussion

Field emission experiments were performed in a vacuum chamber with a 5×10^{-7} torr vacuum level at room temperature. The applied voltage between the anode and cathode was dc voltage. To prevent the degradation of the device, the applied voltage between the gate and cathode was dc pulse voltage [13]. The emission current was measured by a Keithley source measurement Model 2400. The pieces of equipment were controlled by a PC system with a general-purpose interface bus interface card.

Fig. 3 shows the anode current as a function of applied gate voltage in a pulse mode of 20% duty ratio and 400 Hz. During the measurement, an anode voltage was fixed at 4.5

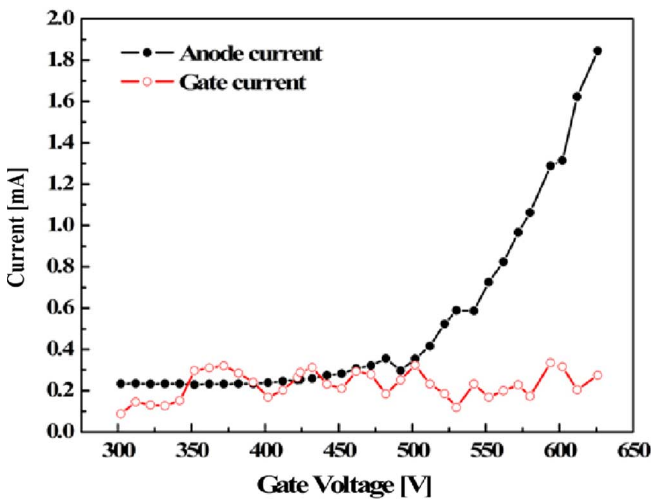

Fig. 3. Emission characteristics of CNT emitters as a function of applied gate voltage.

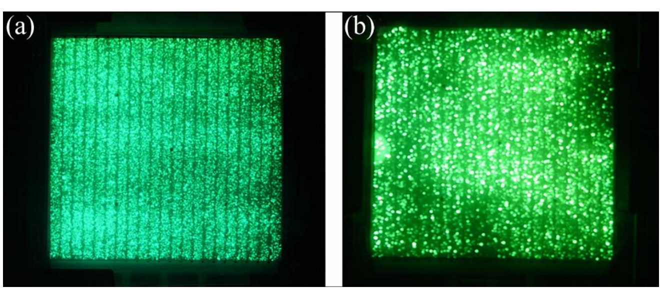

Fig. 4. Emission images of the green phosphor anode plate for the triode structure (a) with and (b) without bonding process using the same metal mesh.

kV, whereas the gate voltage was changed. The turn-on voltage is defined as the voltage required to produce detectable field emission in our device [9]. The turn-on voltage was 160 V. An anode current of 1.68 mA and a gate current of 0.2 mA were extracted at a gate voltage of 640 V. When the gate voltage was increased, the measured gate current was $\sim$8 times lower than the anode current. This phenomenon resulted from the definite gap between CNT dots and gate holes owing to a decrease in the vibration of a metal mesh.

The CNT-based FEL with the suggested metal mesh shows a very stable performance without any damage when the anode voltage was applied over 4.5 kV. In addition, arcing between the metal mesh and anode plate did not have an effect on the CNT emitters because of the perfect shielding of the metal mesh from electrical arcing. This meant that the suggested metal mesh had a very strong immunity to the high anode voltage. This immunity enabled us to apply a high anode voltage of over 4.5 kV along with an electron beam focusing effect.

Fig. 4 shows the emission images of a CNT-based FEL from the active area at a gate voltage of 640 V in a pulse mode of 20% duty ratio and 400 Hz using a green phosphor anode plate. To confirm the improved uniformity, two devices were fabricated with and without bonding processes using the same metal mesh [Fig. 4(a) and (b)]. The devices with and without bonding processes are designated as samples 1 and 2, respectively. The uniformity of sample 1 was better than that of sample 2 because the vibration of the metal mesh was significantly decreased. Samples 1 and 2 exhibited a brightness of 6000 and 4800 cd/m^2, respectively.

From these results, we found that the vibration of the metal mesh was significantly decreased. As the vibration was decreased, arcing between the metal mesh and CNT dots was also decreased. Our metal mesh can be a good candidate for a high-voltage FEL because high-voltage architecture is indispensable to a FEL.

IV. Conclusion

CNT-based FEL by using a screen-printing method, with a metal mesh as a gate electrode, has been successfully fabricated. To fix the metal mesh onto the cathode plate, the metal mesh was designed with trenches and numerous gate holes. As the metal mesh was fixed in between the cathode and anode under high anode voltage, the vibration of the metal mesh was dramatically decreased, and the distances between three electrodes were uniformly sustained. In addition, the charging phenomena of spacer and gate current were decreased. Use of a suggested metal mesh in the triode FEL improved the uniformity and stability properties.

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