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Electrophoresis deposition and field emission characteristics of planar-gate-type electron source with carbon nanotubes

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Abstract

An electrophoretic process was developed to selectively assemble carbon nanotubes (CNTs) onto the triode structure and a CNT-based planar-gate-type electron source panel of planar gate stripe was successfully fabricated with the special electrophoretic process. In this process, the CNTs were migrated on cathode electrode in the CNT suspension by an applied voltage between the gate electrode and cathode electrode. The applied voltage was also used to keep the CNTs off adsorbing on the gate electrode. The experiment results show that the CNTs are selectively defined onto cathode electrode and each cathode electrode has the same packing density. In addition, field emission characteristics of the planar-gate-type electron source panel were studied. The anode current densities could be modified from 0 to 216 μA/cm^2 by increasing the gate voltages from 0 to 150 V with anode bias of 1400 V for anode–cathode spacing was 500 μm.

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Keywords: Carbon nanotubes; Field emission; Electrophoresis

1. Introduction

Carbon nanotube [1] (CNT) was an ideal cold cathode material [2] because of its high geometric aspect ratio, small radius of curvature at the tip apex, high electrical conductivity, high mechanical strength, and chemical inertness. The advantages of CNTs as cold cathode material compared to the conventional cold cathode material are low-emission threshold fields, large-emission current density, emission stability and long lifetime. Therefore, it was not surprising that CNTs were considered to be ideal candidates for many practical vacuum micro-electron devices, such as field emission display (FED) [3], X-ray tubes [4], flat lamp as large area back-light unit of liquid crystal display (LCD-BLU) [5]. For these devices, triode-type field emission electron sources were more attractive for their lower driving voltage and excellent field emission characteristics. Several base on CNTs triode-type field emission electron source structures, such as normal gate [6], under gate [7], planar gate [8] were suggested by several groups. Up to now, one key challenge was to develop efficient deposition technique to assemble CNTs onto the triode structures. In recent years, electrophoresis method had been applied to assemble CNTs [9–11]. The process enables efficient deposition of homogeneous CNT coatings on conducting substrates with fine control of the film thickness and morphology. However, it was difficult to apply the process to make triode-type CNT cathode, because the CNTs were also easily adhered on the gate electrode in the electrophoresis besides the cathode electrode.

In this study, our aim was to develop the electrophoretic process to solve the difficulty to assemble CNTs onto the triode structure. In the new process, the CNTs were

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migrated on cathode electrode in the CNT suspension by an applied voltage between the gate electrode and cathode electrode. The applied voltage was also used to keep the CNTs off adsorbing on the gate electrode. A CNT-based planar-gate-type electron source panel was successfully fabricated with the special electrophoretic process. In addition, the field emission characteristics of the planar-gate-type electron source panel were also studied.

2. Experiment

The commercial CNTs were synthesized by CVD method. First, these raw CNTs were purified and shorted by refluxing in mixture of concentrated sulfuric and nitric acids (3:1; 98% and 70%, respectively) for 6 h at 60 °C. Then, the CNTs were washed with water and dried in air at 120 °C for 12 h. Thirdly, the processed CNTs were dispersed in isopropyl alcohol solution that had contained a little-dissolved $Mg(NO_3)_2 \cdot 6H_2O$. A little amount of dissolved ethyl cellulose was added to the suspension to disperse the CNTs. The CNTs suspension was ultrasonically dispersed for about a day, and then centrifuged for 20 min at 3000 rpm in order to remove the large-sized CNTs conglomerations. The top fraction of the suspension was used in the electrophoresis procedures.

The whole manufacture process of the planar-gate-type electron source panel was illustrated in Fig. 1. The indium tin oxide (ITO)-coated glass was cleaned in acetone for 10 min under ultrasonication. After rinsing the ITO by alcohol and deionized water, the ITO-coated glass was baked in a furnace at 60 °C for 20 min. Next, the substrate was coated by photoresist layer using spin coating method, and then, a photoresist pattern was formed by conventional photolithographic technology. Etching of the ITO layer on glass was carried out in an ITO etchant (mixture of hydrochloric acid and zinc powder). After ITO etching, the photoresist pattern was removed using acetone. Then, an interdigitated electrode of ITO was obtained as substrate for assembling CNTs. One of the two groups of interdigitated electrodes was used as cathode stripe for CNTs and the other one was used as the gate stripe, respectively. In final step, the processed substrate was immersed in the CNTs suspension and a direct current (DC) voltage of 30 V was applied between the two groups of interdigitated electrodes for 3 min. The CNTs were assembled only on cathode stripes. Then the planar-gate-type electron source panel was obtained.

To study the field emission characteristics of the planar-gate-type electron source panel, the sample was brought into the vacuum chamber, where the base pressure was 9×10^{-5} Pa. A quartz spacer of 500 μm thickness was placed on the substrate to isolate the cathode from the anode.

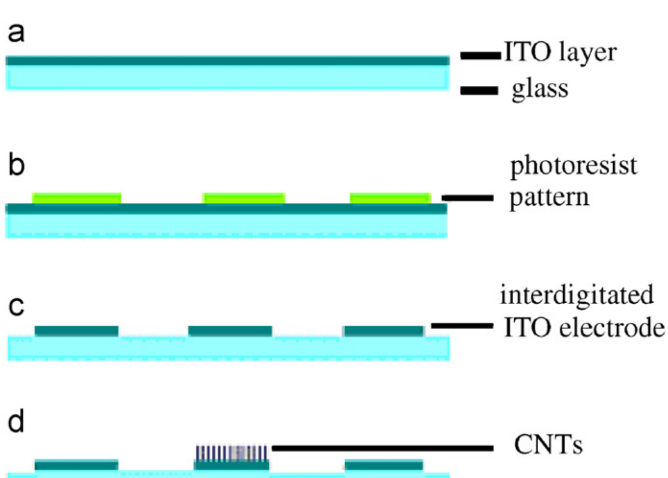

Fig. 1. Schematics of fabrication processes of the planar-gate-type electron source panel (cross section): (a) clean ITO glass, (b) spin-coated photoresist layer and formation of photoresist patterns, (c) etching of the ITO layer to form interdigitated electrodes of ITO, (d) removal of photoresist layer and electrophoretic deposition of the CNTs.

3. Result and discussion

Fig. 2 shows a typical image of the planar-gate-type electron source panel, observed by the optical microscopy. The cathode stripes and the gate stripes were interdigitated and paralleled on the same plane. The cathode stripe width, gate stripe width and the distance between gate and cathode were same, that is about 25 μm. The CNTs were selectively assembled on cathode stripes and the each cathode stripe has the same packing density. The CNTs were not adsorbed on the gate electrodes. In Fig. 2, inset is the cross-section scanning electron microscopy (SEM) image of CNTs. It clearly shows the morphology of CNTs. The CNTs are randomly oriented. Many CNTs vertically protrude the cathode stripe.

In the process of assembling the CNTs, when dc voltage was applied between the two groups of interdigitated

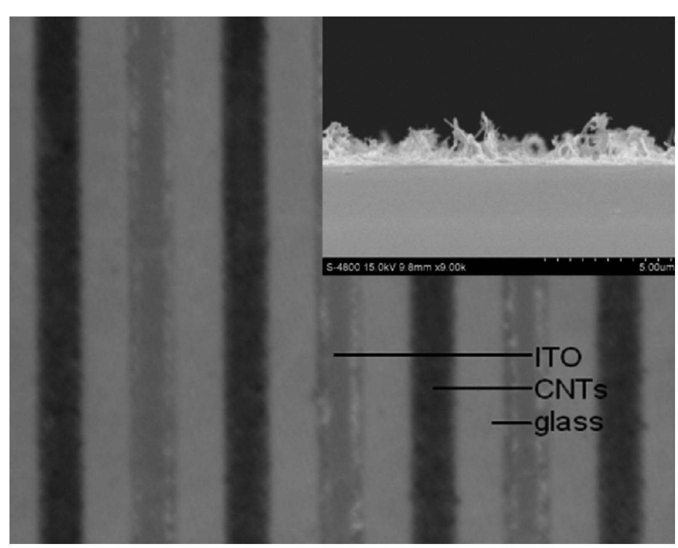

Fig. 2. Typical image of the planar-gate-type electron source panel, observed by the optical microscopy, inset is the cross-section SEM image of CNTs.

electrodes, the schematic electric field, shown in Fig. 3, would occur around substrate. The substrate was immersed in the suspension and the CNTs migrated towards the cathode stripes instead of the positive one under the electric field. This was because the Mg^{2+} ions were absorbable by suspending CNTs, and then the double electron layers around the CNTs in the suspension formed [12]. The CNTs adhered strongly on the cathode stripes. The good adhesion was attributed to from formation of metal hydroxide, which assists the interfacial bonding ([12], [13]). At the same time, the gate positive voltage can keep CNTs off adsorbing on the gate stripes. Moreover, the electric field was same around each cathode stripe, which will lead that each cathode stripe has the same packing density. Therefore, the process could be applied to fabrication of large area electron source.

Field emission characteristics of the planar-gate-type electron source panel were measured with triode mode. In measurements, the applied anode bias was fixed at less than 1400 V to avoid diode-type electron emission. The measurement results were shown in Fig. 4. It indicated that the emission current could be controlled effectively by the gate voltages. Fig. 4(a) shows field emission characteristics of the electron source with different anode bias. The anode currents increase with higher anode biases under the same gate voltages. This could be understood by a coupling of anode biases to gate voltages to enhance electrons emission. That suggested a triode mode of operation in this structure. The anode bias was fixed at the value, which just avoided the electron emission in the diode-like structure. Then, the emission current from the nanotubes was turned on and modified by increasing gate voltage. Fig. 4(b) shows field emission characteristics of the planar-gate-type electron source panel with different geometry structure parameter. When geometry structure parameter W (the cathode stripe width, gate stripe width and the distance between gate stripe and cathode stripe) was changed from 50 to 25 μm, the anode currents increased under same gate voltages and same anode bias. It was caused by the decrease of W, which enhanced the surface electric field of CNTs. In order to obtain higher current density at the same gate voltage, the decrease of W was needed. In our experiment, the optimal emission characteristic showed that the current densities could be modified from 0 to 216 μA/cm^2 by increasing the gate voltages from 0 to 150 V with anode bias of 1400 V for W was 25 μm and anode–cathode spacing was 500 μm.

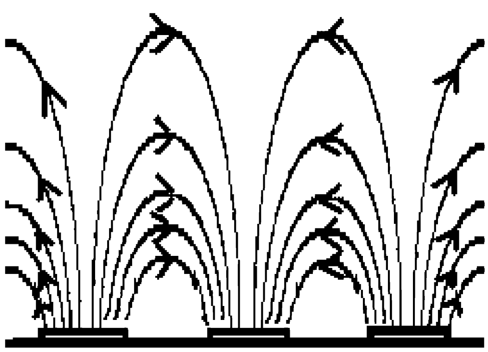

Fig. 3. Schematic electric field around the substrate when direct current (DC) voltage was applied between the two groups of interdigitated electrodes.

An emission stability of the planar-gate-type electron source panel was measured at constant gate voltage and constant anode voltage for initial emission current density of 200 μA/cm^2 for 60 min. The current variation was shown in Fig. 5 as a function of time. The electron source exhibited stable electron emission without degradation. The emission current fluctuation was less than 7.5%. The good stability of field emission (FE) current density with respect to time may be attributed to the CNTs, which adhered strongly on the cathode stripes. The emission stability also prefigured that the planar-gate-type electron source panel has repeatability of electron emission performance and long lifetime.

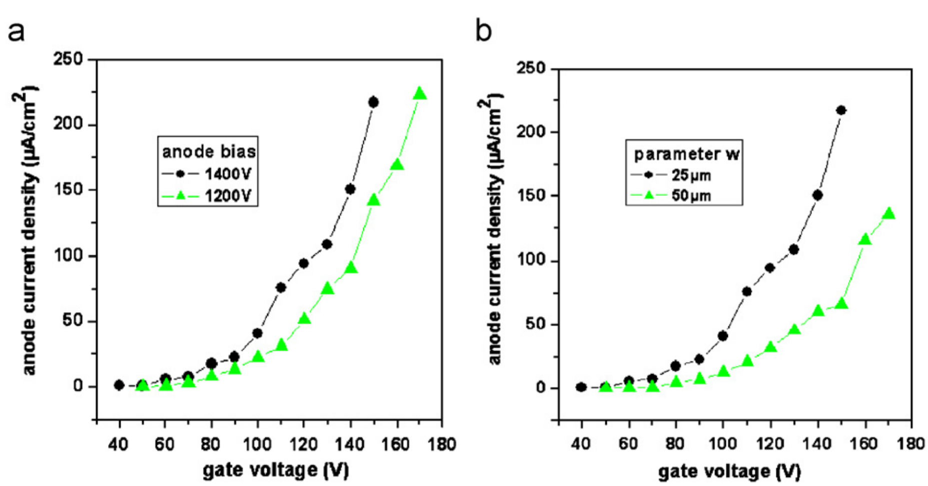

Fig. 4. Field emission properties of the planar-gate-type electron source panel: (a) different anode bias (1400 and 1200 V, $W = 25$ μm), (b) different geometry structure parameter ($W = 50$ and 25 μm, anode bias = 1400 V).

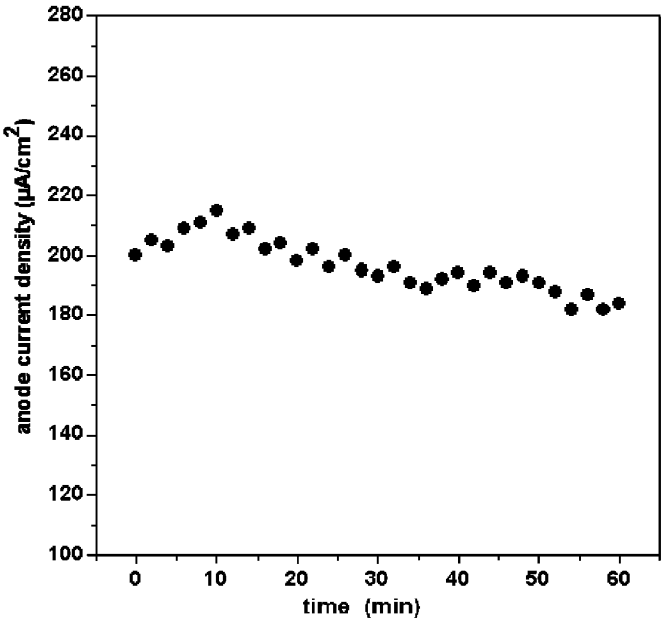

Fig. 5. The emission stability of the planar-gate-type electron source panel.

These results provided the way to fabricate the CNT-based planar-gate-type electron source with some advantages such as, simple structure (interdigitated electrode as substrate) and easy process (the special electrophoretic process to selectively assemble CNT). Moreover, field emission characteristic of the planar-gate-type electron source could be improved by structure parameter. So these cases may lead the planar-gate-type electron source applied in many practical vacuum microelectron devices. Furthermore, the experiment results suggested that the special electrophoretic process could be also used in fabrication of normal gate electron source and under gate electron source.

4. Conclusion

We have developed an electrophoretic process to selectively assemble CNTs onto the triode structure and a CNT-based planar-gate-type electron source panel of planar gate stripe was successfully fabricated with the special electrophoretic process. It was confirmed that the CNTs were selectively assembled cathode stripes and each cathode stripe had the same packing density. The optimal emission characteristic of the planar-gate-type electron source panel showed that the current densities could be modified from 0 to 216 $\mu A/cm^2$ by increasing the gate voltages from 0 to 150 V with anode bias of 1400 V for W was 25 μm and anode–cathode spacing was 500 μm. This efficient process could serve as a promising candidate for production of large-area CNT-based gate-type electron source, due to its easily process, low cost and easily scaling up.

Acknowledgments

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