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Carbon-Nanotube-Based Field Emission Devices with a Self-Focusing Gate Structure

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Field-emission devices with a novel self-focusing gate structure using carbon nanotubes as emitters have been fabricated. Without additional focusing electrodes, the self-focusing gate structure employed a pair of gate electrodes parallel with the vicinity of emitters, which resulted in an asymmetric emission area as compared with the conventional gate structure. Therefore, electrons emitted from the emitters gave rise to an overlapping region on the anode plate so that a reduction of spot size had been achieved. According to the simulation results and luminescent images, this self-focusing gate structure had good control of the trajectory of electrons and therefore showed a smaller luminescent spot size than the conventional one. This gate structure, which utilizes a simple fabrication process, has the advantages of low-cost manufacturing and large-area scalability, and therefore is promising for application in field emission displays.
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Carbon nanotubes (CNTs) have attracted much attention for application in field emission displays (FEDs) due to their high geometric aspect ratios, chemical inertness, and excellent emission capacity.[1-3] Two types of operation configurations have been demonstrated in recent years: diode and triode. The triode-type configuration seems to be a promising candidate because of its better driving ability in low-voltage operation.[4-6] Several triode-type device structures have been proposed, including normal gate, under gate, and side gate structures, and the normal gate structure seems to be more promising in terms of low operation voltages as well as device performance.[7-11] For application to FEDs, a high anode voltage is essential for high efficiency of the phosphor, high brightness, and color purity. The high anode voltage requires a large vacuum gap between the cathode and anode plates so as to avoid the problem of arcing. Accordingly, the large vacuum gap may give rise to an issue of electron-beam spreading, which would cause cross talk between adjacent pixels and would deteriorate the resolution of displays. Therefore, a focusing structure which could effectively control the trajectory of electrons and reduce the cross-talk noise is necessary. Several focusing structures of FEDs have been announced to overcome the issue of electron-beam spreading, such as the planar electrode,[12] double-gate,[13] and mesh-electrode structures.[14] Those structures have some drawbacks, however, such as manufacturing complexity and reduction in emission current due to the focusing electrodes.

In this work, CNT-based field emission devices with a self-focusing gate structure are proposed which do not require additional focusing electrodes as compared with other structures. The results of the simulation and luminescent images reveal good control of electron trajectory with this self-focusing structure, effectively reducing the spot size on the anode plate. Therefore, the focusing structure combined with simple processes is promising for application in FEDs.

Experimental

Figure 1 illustrates the schematic diagrams of the top and cross-sectional views of the CNT field emission devices with the conventional and self-focusing gate structures. The cross-sectional views are taken along section X-X′. The conventional gate structure shown in Fig. 1a has a square area of CNT emitters within the gate aperture, that is, the emitters are surrounded with the gate electrode, which is similar to the normal gate structure. On the contrary, the self-focusing structure has a pair of gate electrodes parallel to both the areas of CNT emitters, which results in an asymmetric emission periphery of each emission region (Fig. 1b). The fabrication processes were similar to previous work described in detail elsewhere,[5,6] and CNTs were grown with a multilayer catalyst at atmospheric pressure by thermal chemical vapor deposition. The multilayer catalyst (Co/Cr/Al) formed of Al (10 nm), Ti (3 nm), and Co (2 nm) was sequentially deposited by magnetron sputtering (Ion Tech Microvac 450CB) at the pressure of 7.6×10^{-2} Torr at room temperature. Samples with catalysts loaded into the quartz tube were heated to the designated temperature of 500°C in a nitrogen flow, followed by a pretreatment process with hydrogen gas

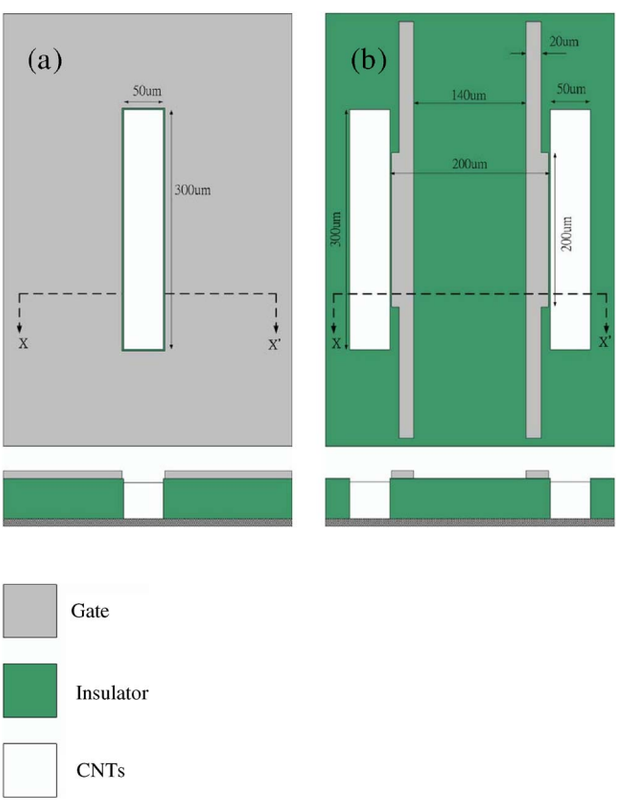

Figure 1. (Color online) Top and cross-sectional (taken along section X-X′) views of the CNT field emission devices with (a) the conventional structure and (b) the self-focusing gate structure.

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flow of 500 sccm. Then, nanotubes were synthesized with reaction gases, ethylene and hydrogen, at flow rates of 125 and 10 sccm, respectively, for 30 min.

The morphologies of the samples were characterized by scanning electron microscopy (SEM; Hitachi S-4700I). The fine internal structures of CNTs were determined by high-resolution transmission electron microscopy (HRTEM; JEOL JEM-2000EX), and Raman spectroscopy was used to exam the crystallinity of nanotubes. Field emission characteristics of devices were measured with a triode-type configuration in a high-vacuum chamber with a pressure of 5×10^{-6} Torr. A glass substrate coated with indium tin oxide and P22 phosphor (ZnS:Cu, Al) was used as the anode plate, and the gap between the cathode and the anode plates was set to be 550 μm. Gate voltages up to 80 V were applied at intervals of 1 V with a source measure unit (Keithley 237) for the verification of field emission characteristics while the cathode and anode were biased at 0 and 1000 V, respectively.

The simulations were carried out with a commercial software (SIMION-3D) using the finite element method to investigate the beam spreading of emission electrons. Meanwhile, the simulations were also performed by assuming the electron-beam divergence range and the energy of electrons emitted from CNTs to be −90 to +90° and 5 eV, respectively, which seemed to be a good assumption for good correlation of the simulation results and those of experimental observation in other work.[15,16]

Results and Discussion

The conventional device has a surrounding gate so that electrons are emitted from the peripheral area of the extraction gate. By contrast, the self-focusing gate structure has an asymmetric extraction gate area which consists of a pair of electrodes close to the emission region of CNTs. The SEM micrograph of the self-focusing gate structure is shown in Fig. 2a, which illustrates the top view of the device, while Fig. 2b is the cross-sectional view of the CNT emitters adjacent to the gate electrode according to the area squared in Fig. 2a.

Figure 3a shows an HRTEM image of nanotubes grown with the multilayer catalyst at 500°C, which reveals a closed tip filled with catalytic metal particles and a multiwalled structure consisting of wavy graphite sheets aligned parallel to the tube axis. The inner and outer diameters are about 10 and 25 nm, respectively. The correlative Raman spectrum of nanotubes shown in Fig. 3b indicates that the intensity of the D-band (1250–1450 cm^{-1}) is larger than that of the G-band (1550–1600 cm^{-1}). It is well known that the crystallinity of nanotubes synthesized at low temperatures is poorer than those grown at higher temperatures due to the formation of vacancies, grain boundaries, or other defects, and also the deposition of amorphous carbon in the outer walls.[17] The fine structure of nanotubes shown in Fig. 3a consists of an outer layer of amorphous carbon, which is conjectured to be the factor giving rise to a high D-band intensity.

Simulations were performed to investigate the beam spreading of emission electrons with commercial software (SIMION-3D) using the finite element method. The simulated equipotential lines and electron-beam trajectories of the conventional and self-focusing gate structures are shown in Fig. 4. The thicknesses of the insulator and gate were 1 and 0.2 μm, respectively, and the height of the CNTs was 0.8 μm. The distance between the gate electrode and the CNTs was 200 nm. The applied voltage between the cathode and anode plates was 0 V and 1 kV, respectively, and the spacing was set at 550 μm; the gate voltage was biased at 80 V. The efficient emission area (or length) of the CNTs is estimated to be about 25 μm away from the edge of the gate electrodes, which seems to be a reasonable assumption due to the turn-on field of CNTs (3–4 V/μm) in this work. Meanwhile, emission of electrons was assumed on a flat surface of CNT emitters. Simulation results show that the self-focusing structure had a spot size with a width of 232 μm in x direction on the anode plate, whereas the conventional one was 622 μm in width, which was much larger due to the serious beam divergence. Because the self-focusing structure has an asymmetric emission periphery caused by a pair of parallel gate electrodes, the emitted electrons travel through the spacing between the cathode and anode plates, bombarding into the anode plate, resulting in an overlapped spot. Oppositely, the conventional gate structure without focusing electrodes could not effectively confine the electron beams due to the divergence of electron trajectories so as to give rise to a large spot on the anode plate, which results in serious cross-talk noise between pixels. Moreover, the geometry of the focusing gate influences the beam collimation significantly because of the contour of electric potential near the emission area of the CNTs. In the self-focusing gate structure, the contour of electric potential between the two emission areas of CNTs has a convex curve which does not contribute a significant transverse of electric field close to the edge of the emission area as compared with a concave curve. Therefore, electrons emitted from CNTs follow a less divergent trajectory, that is, a smaller beam spot size on the anode plate. Consequently, the proposed simple self-focusing structure efficiently reduces the spot size on the anode plate, thus overcoming the issue of electron-beam divergence.

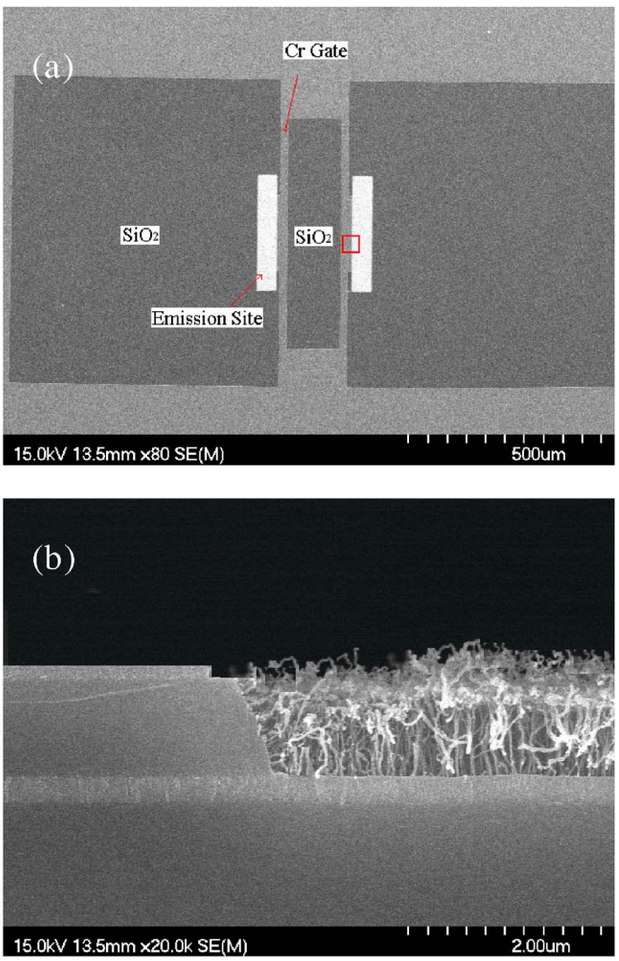

Figure 2. (Color online) SEM micrograph of the self-focusing gate structure: (a) top view of the device, and (b) cross-sectional view according to the squared area illustrated in (a).

The field emission characteristics of devices with conventional and self-focusing gate structures were measured in a high-vacuum chamber with a pressure of 5×10^{-6} Torr. The field emission curve of anode current (I_a) vs extraction gate voltage (V_g) is shown in Fig. 5, and the inset represents the corresponding Fowler–Nordheim plot.

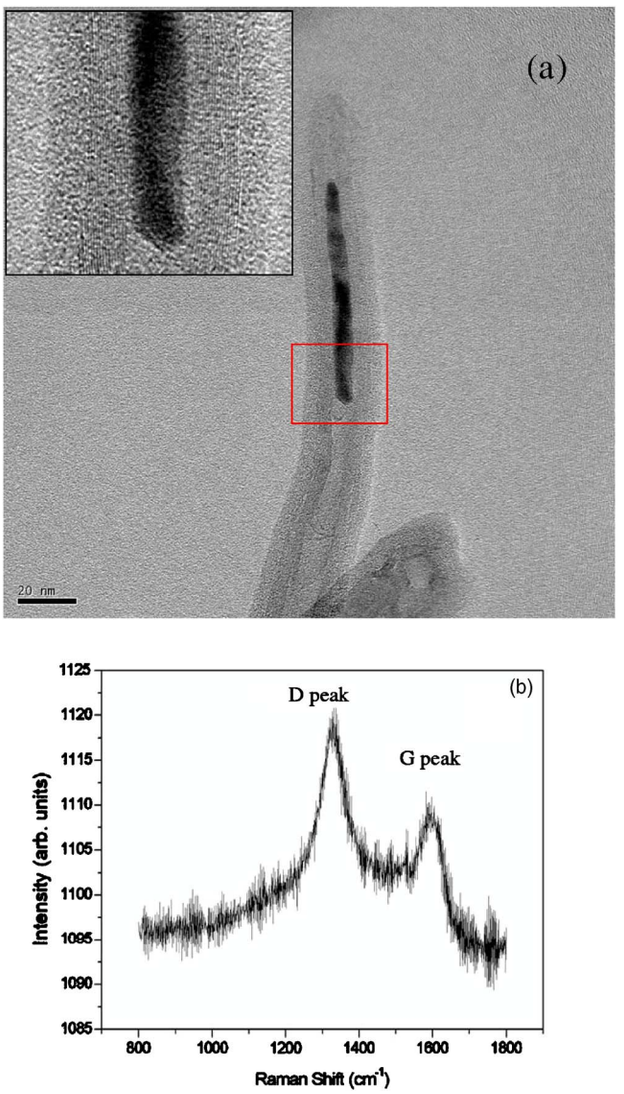

Figure 3. (Color online) (a) HRTEM image of nanotubes grown with the multilayer catalyst at 500°C, and the inset is an enlarged partial image of the square region. (b) The correlative Raman spectrum of nanotubes.

The distances between CNTs and gate electrodes in both structures were designed in the same configuration, i.e., nearly 200 nm, which is the simulation condition assigned in Fig. 4. Therefore, the higher emission current in the conventional gate structure is conjectured due to its larger extraction gate area as compared with that in the self-focusing one. Although the conventional structure has a higher emission current than the self-focusing one, there is no enormous difference between them. The photoluminescent images taken via charge-coupled device camera are shown in Fig. 6. The fact that the photoluminescent image for the self-focusing gate structure is a bit asymmetrical may be due to factors such as the misalignment of the gate electrodes in the *y*-axis direction with respect to the area of CNT emitters and the nonuniformity of CNTs. Because of the alignment error in the photolithography process, an asymmetry of electron-beam trajectory in the *y* axis takes place, thus resulting in an asymmetric photoluminescent image. In addition, as the morphology of CNTs in the emission region has a nonuniformity issue, the electrons emitted from CNTs governed by the electric field have different beam trajectories and therefore, the photoluminescent images are not symmetrical. Nevertheless, the spot sizes shown on the

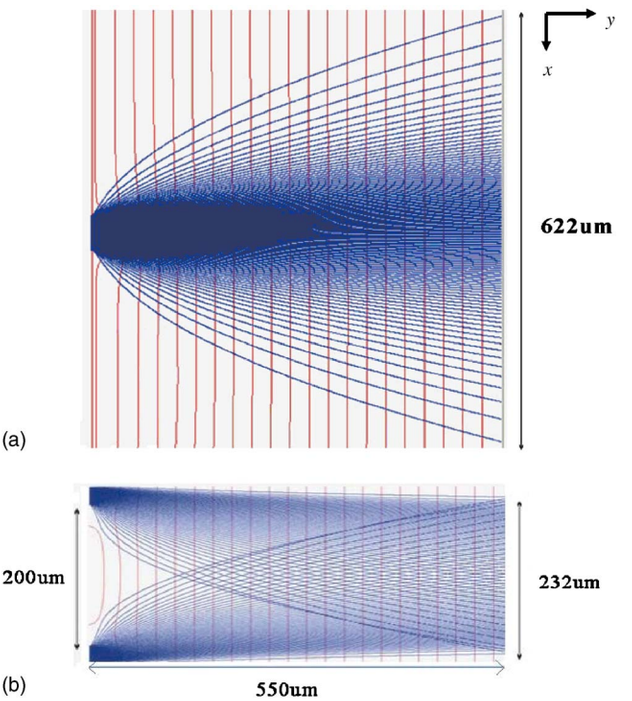

Figure 4. (Color online) Simulated equipotential lines and electron-beam trajectories of (a) the conventional structure and (b) the self-focusing gate structure.

anode plate along the *x* axis are qualitatively consistent with the simulation results, indicating that the self-focusing structure could alleviate the issue of beam divergence and has good functionality in controlling the electron beams as compared with the conventional structure.

Conclusions

Field emission devices with a self-focusing gate structure consisting of CNT emitters were successfully fabricated to show good control of luminescent spot size as compared to those with conventional structures. The results of simulations and luminescent images clearly indicate that the self-focusing gate structure employing a pair

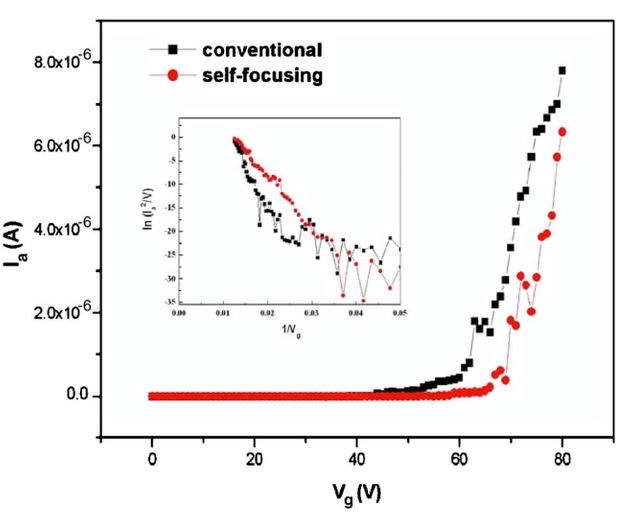

Figure 5. (Color online) Field emission characteristics of the conventional and self-focusing gate structures.

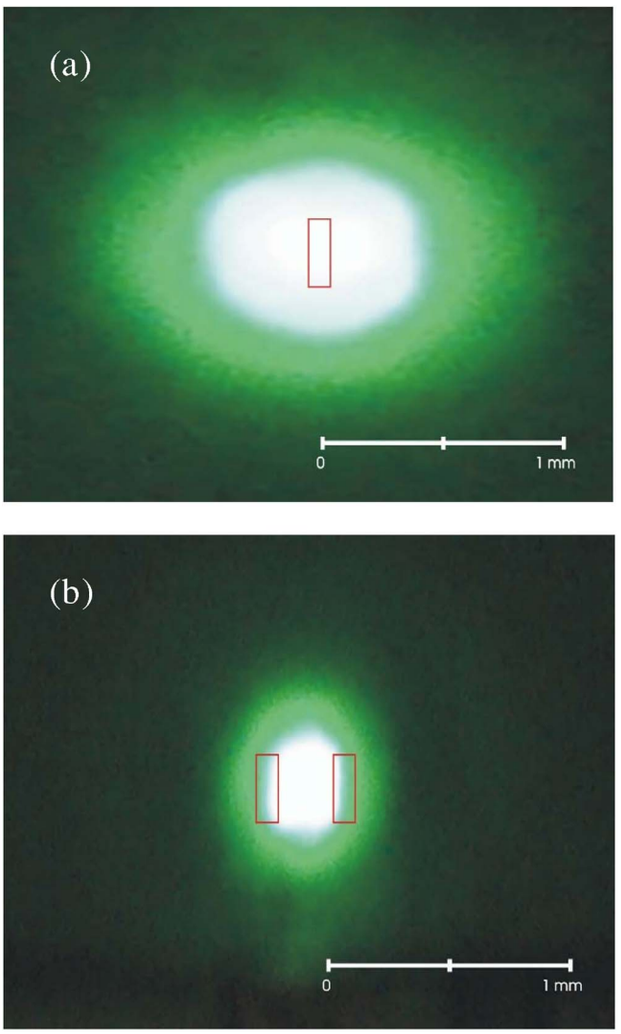

Figure 6. (Color online) Photoluminescent images of (a) the conventional structure and (b) the self-focusing gate structure. The squares shown in the images are the corresponding region of CNT emitters of the field emission devices.

of gate electrodes close to the emitters produced an asymmetric emission area, and the emitted electrons traveling through the spacing between the cathode and anode plates gave rise to an overlapping region on the anode plate. Because of the overlapping of electron beams, the luminescent spot sizes were remarkably reduced to 232 μm in the *x* direction, compared with 622 μm for the conventional gate structure, which has a serious issue of beam divergence. As a result, the self-focusing gate structure manufactured with a simple process can produce well-focused electron beams for application in FEDs.

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