

Triode-Type Field Emission Displays with Carbon Nanotube Emitters

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Abstract

Carbon nanotube emitters, prepared by screen printing, have demonstrated a great potential towards low-cost, large-area field emission displays. Carbon nanotube paste, essential to the screen printing technology, was formulated to exhibit low threshold electric fields as well as an emission uniformity over a large area. Two different types of triode structures, normal gate and undergate, have been investigated, leading us to the optimal structure designing. These carbon nanotube FEDs demonstrated color separation and high brightness over 300 cd/m^2 at a video-speed operation of moving images. Our recent developments are discussed in details.

Keywords : field emission display, carbon nanotubes, triode-type structure

1. Introduction

A field emission display (FED) is generally described as a device to have CRT-like image qualities as well as flat-panel-like exterior volume such as fast response time, wide viewing angles, wide operation temperature, cathode ray tube (CRT)-like colors, ultra-slim features, and low-power consumption.[1)] For the last decade, FED had been recognized as a powerful flat panel display and also expected to have been successfully introduced in to the market. Many frontier companies and institutes have accordingly involved themselves in researches and developments of this device. Most activities have focused to achieve technical or business goals by means of microtip-type, called Spindt-type FEDs. In consequence, microtip FED prototype samples from Candescent Technologies worked with SONY Co. shown in the last year proved enough that such devices are technically ready to be moved up to a commercial level. However, no one has built up a mass production line for FED yet and so started the FED business except a small amount of monochrome products for special applications. Unfortunately, the circumstances, these days, compared are very different to that 5 years ago. A recent thin film transistor liquid crystal display (TFT-LCD) industry's cost driven tendency based on stiff technical and business competitions between TFT-LCD companies has enlarged their market size and shall move up to bigger and profitable display markets, such as monitors and even TVs in the near future. Plasma display panel (PDP) is now in the mass production stage, and active matrix organic electroluminescent display (AM-OLED) based on TFTs is generally accepted as a strong candidate for future display of which characters are almost the same as

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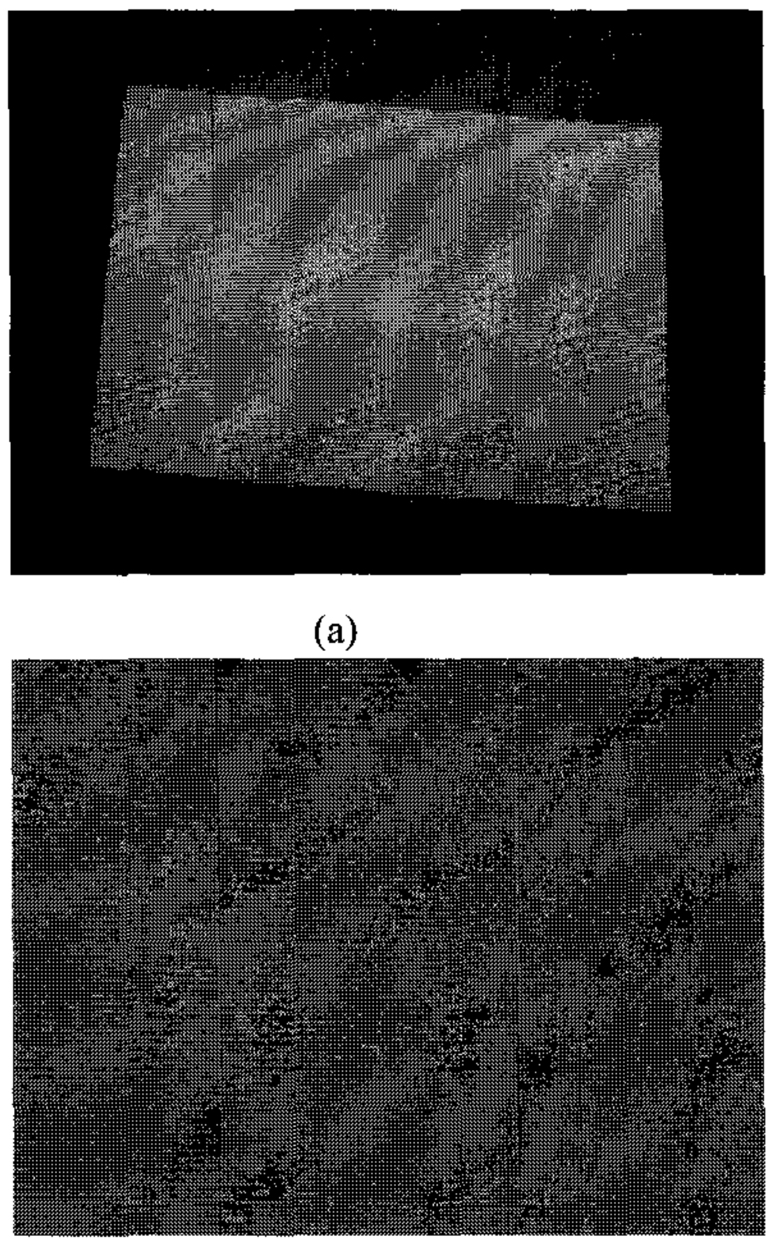
those of FED. Although FED still retains the original potential as good as others, the important subject in a FED society will therefore be to find the most cost-effective way to produce FED panels with large screen size and so do other competitors.

For this purpose, we have been developing c-FEDs utilizing carbon nanotubes (CNTs) with excellent field emission characteristics through simple fabrication technologies.[2-4] Our studies have then focused on the refinements of low-cost, simple, and scalable fabrication technologies for cathode plates with CNT emitters such as improvements of CNT paste's emission strength and uniformity over a large area, decreases of operating voltages by means of cathode structure modifications, and reductions of cathode preparation steps. This paper presents formulation technologies of CNT pastes for screen printing and several triode structures of c-FEDs with a high potential of practical applications.

2. CNT Paste

The CNT powder prepared was mixed with frit, other inorganic and organic vehicles to be a printable paste. Those materials were well mixed together using ball mill and/or 3-roll mill and appropriate vehicles or solvents were added to control viscosity that played a very important role in screen printing process. The CNT paste was then filtered through a high mesh to remove large particles. The paste therefore, generally speaking, consists of materials, CNTs for electron emission, frits for concrete cohesion between several solid particles in the paste, vehicles for good printing quality, fillers for better printing shape, and etc. The CNT paste critically influences the emission capability of cathode and also the display characteristics of c-FED device. Selections of ingredients and their quantities in the paste are therefore the most important key factors. In the other hand, the processes and structures of cathode also affect the choice of such pastes, for example, non-photosensitive paste or photosensitive paste, low temperature processing paste or higher temperature processing paste, high or low viscosity paste, etc. These two subjects, the material and the cathode structure have a very close relation with each other to be optimized.

From the view point of the cathode structure, CNT pastes must have enough emission efficiencies as well as enough strength during the cathode fabrication processes.



(a)

(b)

Fig. 1. Uniform emission images from (a) non-photosensitive CNT paste with brightness of 450 cd/m^2, operated at an anode voltage of 2 kV and (b) photosensitive CNT paste with brightness of 360 cd/m^2, obtained at an anode voltage of 1.5 kV. Images were observed with 20 μs pulse duration and 100 Hz frequency for the cathode to anode gap of 200 μm.

After printing, most CNTs themselves are laid or imbedded inside the remaining paste on cathode electrodes or insulator, thus they are not actual electron emitting sites. Only CNTs erect on the paste surface contribute to the real electron emission. It has also been known that CNTs are oxidized or damaged in an ambient of air during firing and so lose their emission capabilities. Current drying & firing processes described in this paper may severely reduce the number of erect CNTs on the surface, depending upon the process temperatures and ambient. Additional treatments of the CNT paste surfaces printed are sometimes necessary on purpose. Inappropriate processes for cathode plate inevitably result in non-uniformity and poor electron emissions from CNTs. In such cases, the paste surfaces show few CNTs or highly non-uniform distribution of CNTs. Fig. 1(a) shows a uniform emission image from non-photosensitive CNT paste operated at 2 kV anode voltage with 20 μs pulse duration, 100 Hz frequency, 200 μm gap between cathode and anode plates, after finishing all fabrication processes of cathode plates. Here,

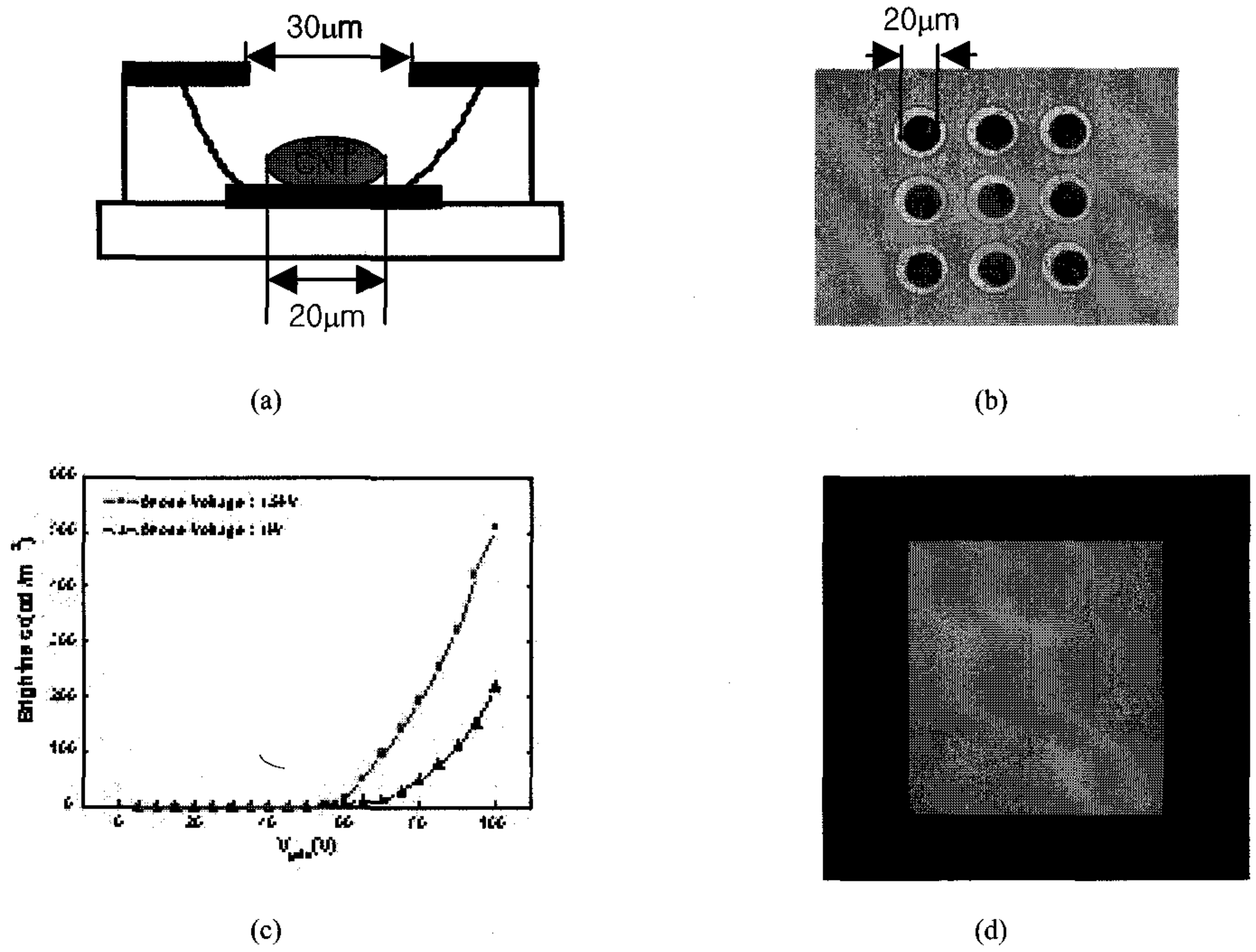


Fig. 2. 5.2" diagonal Type I normal-gate structure c-FED with a gate hole diameter of 30 μm and a diameter of CNT paste dots of 20 μm : (a) a schematic structure, (b) a plan view observed by optical microscopy, (c) anode current-gate voltage curves for the anode biases of 1 and 1.5 kV, and (d) an emission image with the resolution of 360 lines x 129 lines, obtained with a gate bias of 100 V (duty: 1/120, 130 Hz) and the anode voltage of 1.5 kV.

diode structures are normally used for testing CNT pastes because of its easy fabrication. The brightness through the green phosphor screen was measured as 450 cd/m^2. For the case of photosensitive pastes, in addition to the emission and printing qualities, patterning capabilities are also required. The example is shown in Fig. 1(b), prepared through several steps such as printing, drying at 90 °C for 10 min, imaging with 310 nm main peak and about 2000 mJ/cm^2, firing at 450 °C, and developing with Na_2CO_3 developer in distilled water. Our photosensitive CNT paste normally produces 20 μm dot patterns that are applicable to cathode structures with gate holes of 30 μm in diameter. To make higher resolution displays, the photosensitive paste with precise patterning and high emission capabilities is a fundamental prerequisite in cases of using screen printing technologies. The image shown in Fig. 1(b) was obtained at anode voltage of 1.5 kV, 20 μs pulse duration, 100Hz frequency and the measured brightness was 360 cd/m^2. However, our new photosensitive paste under development exhibits even 2300 cd/m^2 at 2.6 kV. This subject is still a major research part in our c-FED development.

CNT pastes sometimes require additional treatment for higher brightness and more stable, uniform emission. A key issue of the additional treatment of pastes is to increase the densities of emission site. Various methods have been developed depending on pastes, device structures, fabrication processes, etc. Regarding the mass production case of c-FED, the best way is to engage in additional treatments as few as possible, which means the CNT paste itself has enough emission density survived during the whole display preparation processes. If the treatment is absolutely necessary, it should be applicable to large area uniformly. This technology will be discussed in detail.

3. c-FED Devices

Even feasibility studies of c-FEDs were carried out with diode geometry,[2-4] a triode structure has to be realized for practical applications of c-FEDs. We have investigated several different types of triode structures for c-FEDs. Here, in this study, normal-gate and under-gate type c-FEDs are described. The normal-gate triode

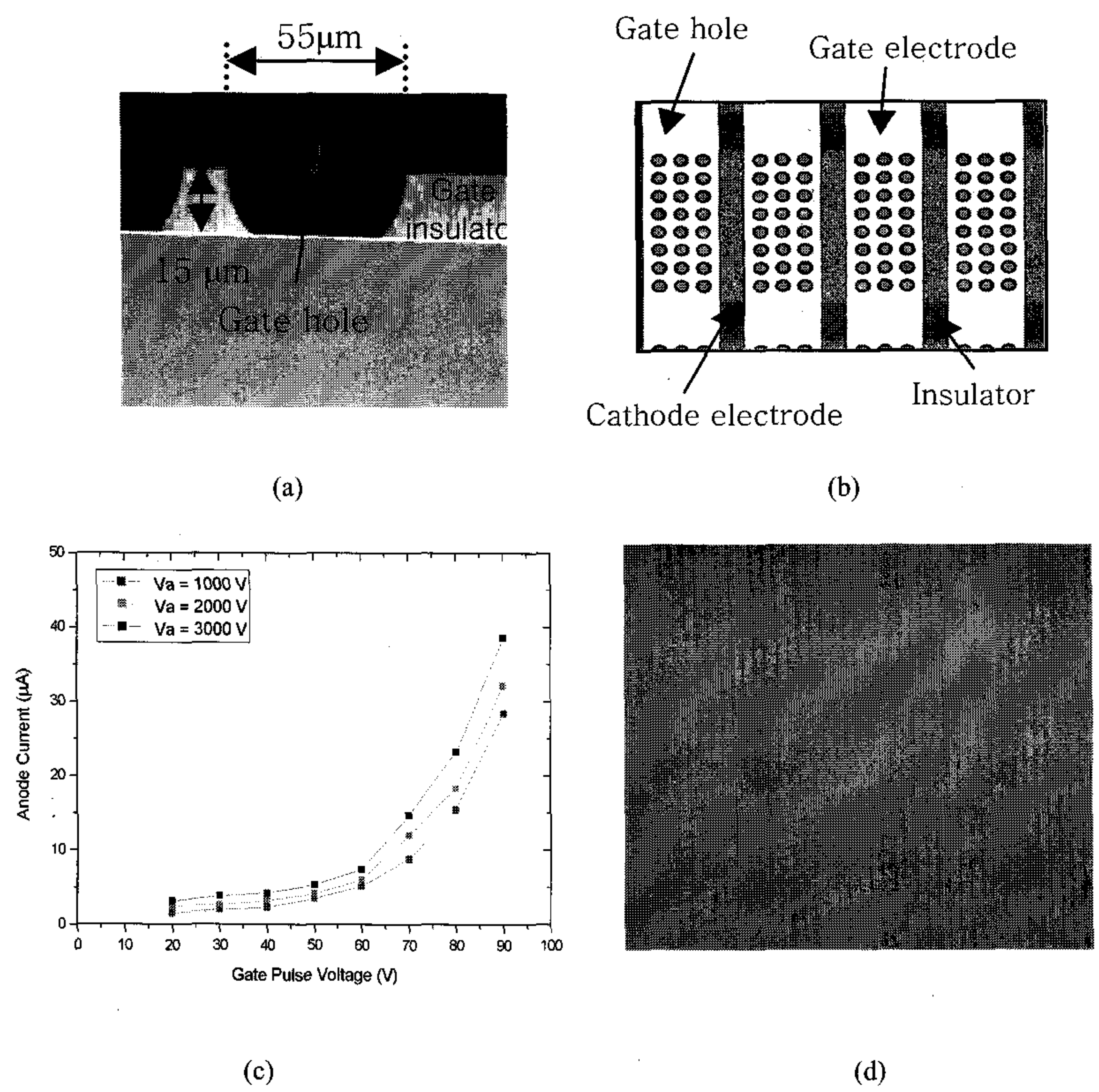


Fig. 3. 5.2" diagonal type II normal-gate structure c-FED with the gate hole diameter of 55 μm and an insulator thickness of 15 μm: (a) a cross-sectional view before forming CNT paste dots inside gate holes, (b) a plan view of field emitter arrays, observed optical microscopy, (c) anode current-gate voltage curves for the anode biases of 1, 2, and 3 kV, and (d) an emission image obtained with the gate voltage of 100 V (duty: 1/500, 100 Hz) and the anode voltage of 3 kV.

structure resembles the most common Spindt-type FED structure but larger gate holes and CNT emitters instead of microtips. This structure can be realized using several different processing methods, depending upon the insulating layer thickness between cathode and gate electrodes. Two ways are introduced here. The type I normal-gate structure, represented in Fig. 2(a), shows an insulator thickness of several μm, gate hole diameter of 30 μm, and CNT dot diameter of 20 μm. CNT paste dots are defined inside the gate holes by photo-lithography, following screen-printing of the photosensitive CNT paste. For optimization, computer simulations were performed using Opera 2-d (Vector Field) on this structure for a fixed gate hole diameter of 30 μm and different diameters of CNT paste dots, ranging between 3-20 μm. The results showed that a smaller diameter of CNT paste dots had a stronger electric field and more converging trajectories of emitted electrons. Thus, a smaller diameter of dots should be recommended. However, an experimentally realistic approach considering current screen printing and CNT paste technologies is to define dots with a diameter of 20 μm. Such CNT paste dots were well formed inside the gate holes as shown in Fig. 2(b). Emission characteristics were given in Fig. 2(c). The threshold gate voltages were as low as approximately 60 V for the anode voltages of 1-1.5 kV when a resistive layer was engaged in this structure to make more uniform emission, otherwise the threshold gate voltage reduced to 20-25 V. Fig. 2(d) presents a uniform emission over a large area of 5 inch diagonal with the resolution of 360 lines x 129 lines, which was observed with the gate voltage of 100 V and the anode voltage of 1.5 kV, finally resulting in brightness as high as 500 cd/m^2.

The same structure is applicable to the type II normal-gate c-FED but a larger gate hole of 55 μm and an insulator thickness of 15 μm. Its cross-sectional structure is given in Fig. 3(a). A thick insulating layer was formed by screen print. Electrical potentials and electron beam trajectories were computer-simulated for

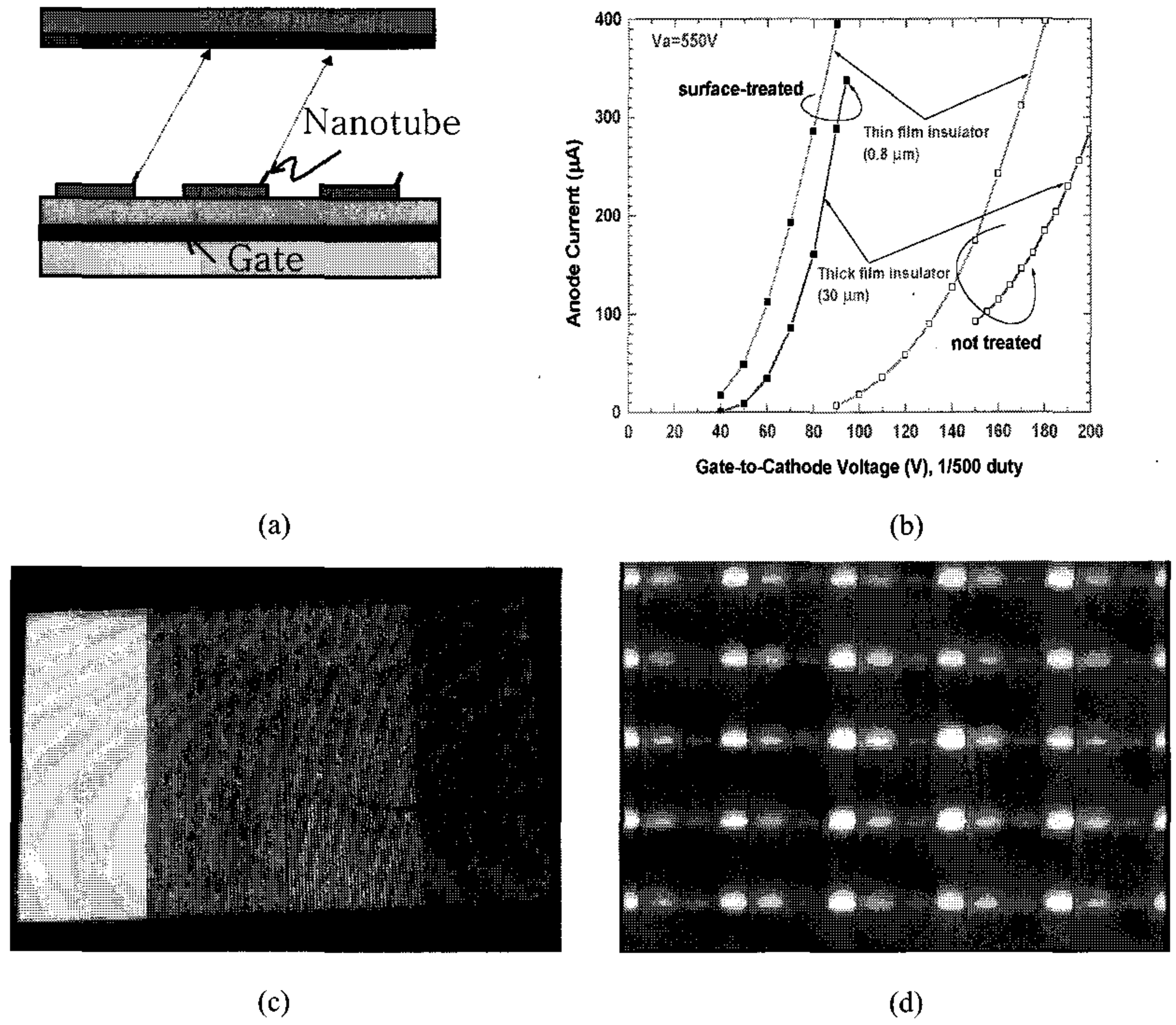


Fig. 4. Structure and emission characteristics of the 7" diagonal undergate type c-FED with a resolution of 120 lines x 160 lines x 3(R,G,B): (a) a schematic structure, (b) dependency of anode currents upon gate voltages, (c) a moving image of red, green, blue, and white color bars operated at the gate of 70 V (1/500 duty, 100 Hz) for the anode bias of 4 kV, and (d) a magnified emission image of the white color region.

different diameters and thickness of CNT dots at a fixed gate hole diameter. It was observed that that smaller diameters and lower thickness of dots resulted in stronger electric fields and better convergences of electron beams. Fig. 3(b) shows a top-view of the type II normal-gate cathode plate where CNT paste dots were successfully defined inside the gate holes. Emission measurements were shown in Fig. 3(c). Threshold gate voltages were approximately 50-60 V for the anode voltages of 1-3 kV. The gate biases were applied with a duty ratio of 1/500 at a frequency of 100 Hz. An emission image given in Fig. 3(d) was taken at the gate and anode voltages of 100 V and 3 kV, respectively, revealing a uniform 300 cd/m^2 emission all over the 5 inch diagonal sample with resolution of 360 lines x 3(R,G,B) x 129 lines.

The other triode c-FED is an under-gate type triode structure. For this case, gate electrodes are located underneath cathode electrodes with an in-between insulator layer. The simple structure and easy fabrication processes enable the under-gate triode structure to possess higher potential for practical applications. A schematic of this structure is given in Fig. 4(a). In computer simulations, electric field strength was concentrated at the edges of the CNTs on cathode electrodes. Electrons, therefore, seemed to be emitted from the edges rather than the central areas. An increase in gate voltages enhanced the electric field strength around the cathode electrodes, leading to the electron emissions. Thus, CNT emitters should be laid out to form only on one edge of the cathode electrodes, by screen print. The non-photosensitive pastes were used in most cases. The device was controlled by the gate voltage modulation. A dependency of anode currents upon gate voltages is presented in Fig. 4(b), for different thickness of an insulator layer, 0.8 and 30 μm, and post-treatment of CNT paste emitters. The thin layer of insulator leads to higher currents at the same level of gate voltages, but an improvement of emission characteristics is more prominent for the post-treatment. The treatment reduces more than half of the gate bias required to produce the same current level irrespective of the insulator thickness. It is implied that the post-treatment is so effective as to enhance the emission characteristics such as operating voltages, emission uniformity, etc. Fig. 4(c) represents a moving image of our 7" diagonal under-gate triode c-FED with a resolution of 120 lines x 3(R,G,B) x 160 lines. Uniform and stable bars of red, green, blue, and white colors controlled by scan and data circuitry, are obtained with the gate voltage of 70 V, the duty ratio of 1/500, frequency of 100 Hz, and anode bias of 4 kV. Colors are successfully separated with little cross-talk between adjacent pixels. The white color region exhibits the brightness of 270 cd/m^2. A magnified emission image of the white color region was observed as given in Fig. 4(d). Red, green, blue color dots are well defined pixel by pixel with an excellent uniformity.

Our study suggests that the triode structure c-FEDs can be a promising candidate for a new type of flat panel displays with low-cost, large-area applications. During an operation of the triode structure c-FEDs, there are still two problems to be solved in order to meet the display performances. One is to suppress a diode emission from the CNT emitters which occurs by anode voltages. For the CNTs with extremely low threshold electric fields, electrons can be emitted only by anode voltages exceeding a certain level. If high anode voltages beyond this level are required for sufficient luminance, such a diode emission phenomenon cannot be avoided. The other is to focus electron beams onto their designated phosphor subpixels. These problems have been tried to be solved in several ways. One of such efforts is to engage an electroplated Ni wall structure (NWS) just above the gate electrodes to modify electrical potential distribution inside the gate holes towards decreasing the electric field strengths of anode voltages as well as reducing the divergence of electron beams.[5)] Considering such issues, our efforts will be continued to develop c-FEDs to meet the display performances required for products to be marketed.

4. Conclusion

An emerging electron emission material, CNT, was successfully applied to large area and full color field emission displays, c-FEDs. We have developed the low-cost fabrication process of screen printing to produce field emitter arrays. As a prerequisite for good field emission, two different types of CNT pastes, photo-imageable and non-photo imageable, were formulated. All triode structures introduced here suggested certain feasibility of CNT-FEDs as a new flat panel display this moment. With high electron emission efficiency, low gate voltage, and simple processes based on screen printing, the c-FED may be considered as the next generation FED which is suitable for flat panel displays in TV application market with large screens.

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