Low Voltage-Driven CNT Cathode and It's Applications

Chun Gyoo Lee, Sang Jo Lee, Sung Hee Cho, Eung Joon Chi, Byung Gon Lee,

Sang Ho Jeon, Sang Hyuck Ahn, Su Bong Hong, and Deok Hyeon Choe

Corporate R&D Center, Samsung SDI, 428-5 Gongse-Ri, Kiheung-Eup,

Yongin-City 442-731, Korea

Abstract

By approaching the counter electrode to the CNT emitter, remarkable reduction of the cathode operating voltage has been accomplished in the under-gate CNT cathode structure. The peak emission current density of 2.5 mA/cm², which is sufficient for high brightness CNT field emission display, was obtained at the cathode-to-gate voltage of 57 V when the CNT-to-counter electrode gap was 2.2 μm. The gate current was less than 10 % of the anode current. The CNT cathode with low driving voltage can help the cost-effective field emission display implemented.

1. Introduction

Field emission displays(FEDs) are generally described as devices having CRT-like image qualities and low power consumption and expected to be a candidate for large-size flat panel display. However, the micro-tip technology as the first generation of FED didn't appeal to the society for the commercialization due to the high cost in manufacturing and difficulties in fabricating the large size panels. Therefore, it is important to find the most cost-effective way to produce FED panels with large screen size.

Carbon nanotubes discovered by Iijima in 1991 have attracted much attention due to their excellent electronic and structural properties[1]. Carbon nanotube material has been tried to be used as electron emitting sources in the large-area field emission displays[2,3,4]. In order for CNT-based FED to be a candidate for the large screen HDTV market, it should be manufactured at a price that consumers can afford. To realize the low cost objective, low voltage driven CNT cathode structure, which can use the low-cost column driver IC's, should be implemented. In our previous study, the large-size under-gate cathode structure has been developed and introduced in the literature[3]. The peak anode current density of 2.5 mA/cm^2 was obtained at the cathode-to-gate voltage of about 130 V. During the feasibility study, it was observed that the CNT-to-counter electrode gap(d_G) is very critical to the operation voltage. Therefore, it was concluded that d_G should be reduced as small as possible.

In this work, the under-gate cathodes with the CNT-to-counter electrode gap of a few micrometers are characterized and compared with the cathode of 30 μm gap.

2. Device Structure and Fabrication

Figure 1 shows the schematic view of the under-gate cathode structure. The under-gate electrodes are located underneath the cathode electrode with an in-between insulating layer. The CNT emitters are formed at the edges of the cathode electrodes. In this study, the photosensitive CNT paste, which consists of the CNT powder, frit, and photo-imageable resin, was used for the CNT emitters. The counter electrodes are in front of the CNT layers. The under-gate electrode and the counter electrode play a role of the electron extraction gate. The CNT-to-CNT distance is 233 μm in pitch, and the CNT pattern length is 120 μm. Theoretically, electric field strength is concentrated at the edges of the CNT layer. Electrons therefore are emitted from the edge of the CNT layer rather than from the central area. The typical fabrication processes have been introduced in the literature[3]. In order to fabricate the cathode with micron-sized d_G, some modifications are needed during the fabrication processes. To make micron-sized d_G, the back-side ultra-violet(UV) over-exposure technique through the metal masking window is utilized. UV-exposed narrow area forbidden by the metal masking is ultimately transformed to the CNT-to-counter electrode gap.

Figure 2 shows the process sequence of the cathode with micron-sized d_G. Some preceding steps are not shown in the figure. Photoresist was coated and UV-exposed excessively from the backside of the substrate(a). The top layer of thin film metal electrode is wet etched selectively(b). Once again, photoresist is coated and patterned so that only the edge of the cathode electrode is exposed. The protruded bottom layer of the cathode electrode is wet etched with the masking of the top layer(c). The CNT paste is screen-printed, baked, UV-exposed from the backside, and developed for the CNT emitter(d). By etching the protruded bottom layer of the counter electrode selectively, the micron-sized gap between the CNT edge and the counter electrode is formed(e). Very recently, 38"-diagonal large cathodes with micron-sized gaps have been implemented with the conventional 1x aligner. Whereas the process technique can easily be applied to the large area cathode fabrication, it requires the additional photolithography steps.

The fabricated cathode substrate is 4.8"-diagonal in size, and the pixel number is 128*3*128. Figure 2 illustrates the scanning electron microscopic image of the fabricated cathode with a gap of about 1 μm. It can be seen that d_G is clearly defined. The CNTs used in this study were made by arc-discharge. Observation by transmission electron microscopy (TEM) revealed that as-grown single-wall CNTs (SWNTs) existed as bundles in which the individual nanotube has a diameter of around 1.4 ~ 2 nm. Many nanotubes shorter than 1 μm in length are protruded and partially oriented.

3. I-V Characteristics

The required emission current density from the cathode can be expressed as Eq. (1)[5].

$$Jav = \frac{B \cdot \pi}{Va \cdot \eta} \times 10^2 \qquad (1)$$

where, Jav is the average anode current density($\mu A/cm^2$), B is the brightness(cd/m^2), Va is the anode voltage(V), and η is the phosphor screen efficiency(lm/W). For a 1000-line field emission display with luminance of four hundred candelas per square meter and assumptions for the phosphor screen efficiency of 8.5 lm/W and anode potential of 6 kV, the anode current density required for fully on pixels is estimated to be about 2.5 $\mu A/cm^2$ at the duty driving of 1/1000. It corresponds to the peak current density of 2.5 mA/cm^2.

Figure 3 shows the I-V characteristics of five cathodes. Table 1 illustrates the differences of the five cathodes. Electrical measurements were made in a vacuum chamber at the pressure of 3×10^{-5} torr. During testing, the gates were grounded, the anode was biased to +700 V, and the cathodes were connected with the scan driver IC's which operated at the duty ratio of 1/1000. The gap between the anode and the gate was maintained to be 1 mm. Comparing the cathodes B, C, D, and E, it is seen that the cathode-to-gate voltage decreases as d_G decreases. When d_G decreases from 30 μm to 1.6 μm, the cathode-to-gate voltage for the anode current density of 2.5 $\mu A/cm^2$ remarkably decreases from 130 V to 73 V. Furthermore, by using the high purity CNT powder for the CNT paste, the cathode-to-gate voltage was noticeably reduced from 77 V to 57 V at the same CNT-to-counter gap of 2.2 μm. The reduction in cathode-to-gate voltage could not only be the result of the higher CNT population density, but also from better CNT distribution in the CNT paste. Further investigation is needed for elucidating the dominant factor. For cathode A, the emission current density of 0.025 $\mu A/cm^2$, which is for fully off pixels, would be obtained at the cathode-to-gate voltage of about 27 V by the extrapolation. Therefore, the data switching voltage of cathode A would be about 30 V, which means that low-cost data drivers are available for the cathode structure. It is expected that the driving voltage could be reduced further by increasing the number of CNT patterns per sub-pixel area.

Figure 4 shows the anode and gate currents as a function of the cathode-to-gate voltage in cathode A. It was thought that the gate current would become larger as d_G decreased. However, the gate current was as high as about 10 % of the anode current, unexpectedly. All the measured cathodes with micron-sized d_G showed the similar gate current level. Since the Ig-Vcg curve shows linear behavior, it appears that the gate current could not be the result of electron emission toward the counter electrode, but rather the effect of leakage due to cathode-to-gate electrical short. Conclusively, the gate leakage current level is acceptable, and it is not needed to use driver IC's with high current drivability. In terms of the emission uniformity, the emission current deviation was less than ±5 % on the 4.8" whole area. However, the pixel-to-pixel uniformity is not so good yet, it should be caused by the geometrical randomness of the CNT emitters. It is expected that the short-range emission uniformity could be much improved by adopting the ballast layer in the cathode structure.

4. Conclusion

The under-gate cathode structure with micron-sized CNT-to-counter electrode gap has been implemented and characterized. By adopting high purity CNT powder in the cathode with d_G of 2.2 μm, it is shown that the data swing voltage of 30 V could be accomplished. The low-voltage driven CNT cathodes are expected to be used to implement the low-cost large area CNT field emission displays.

Acknowledgements

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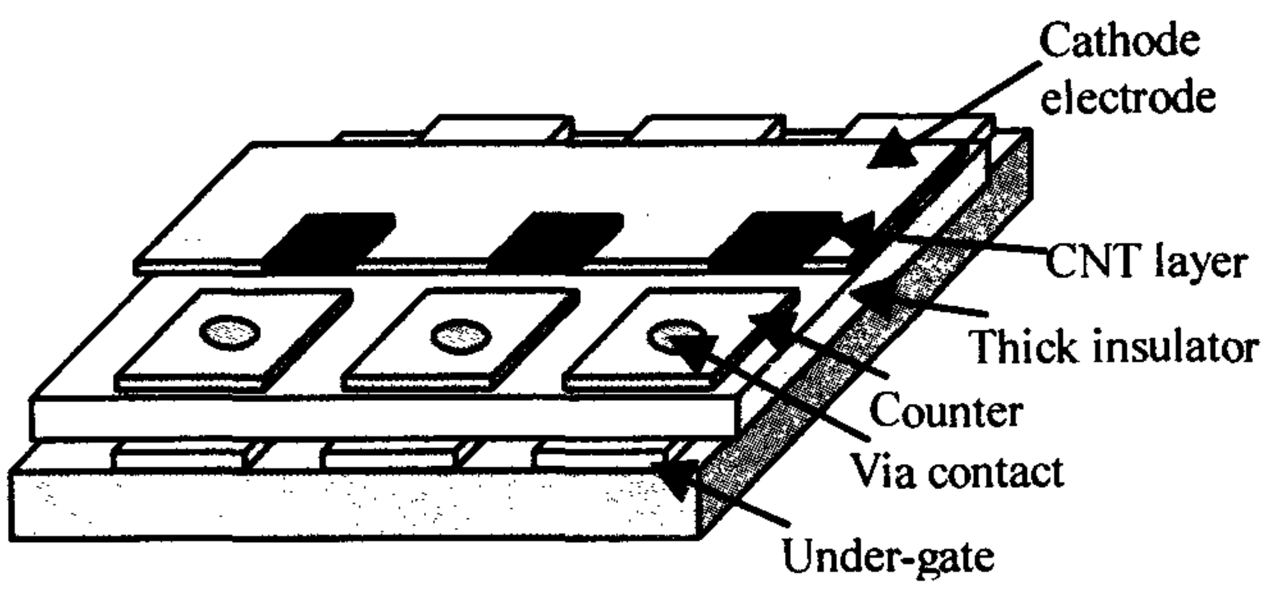

Figure 1. The typical under-gate CNT cathode structure.

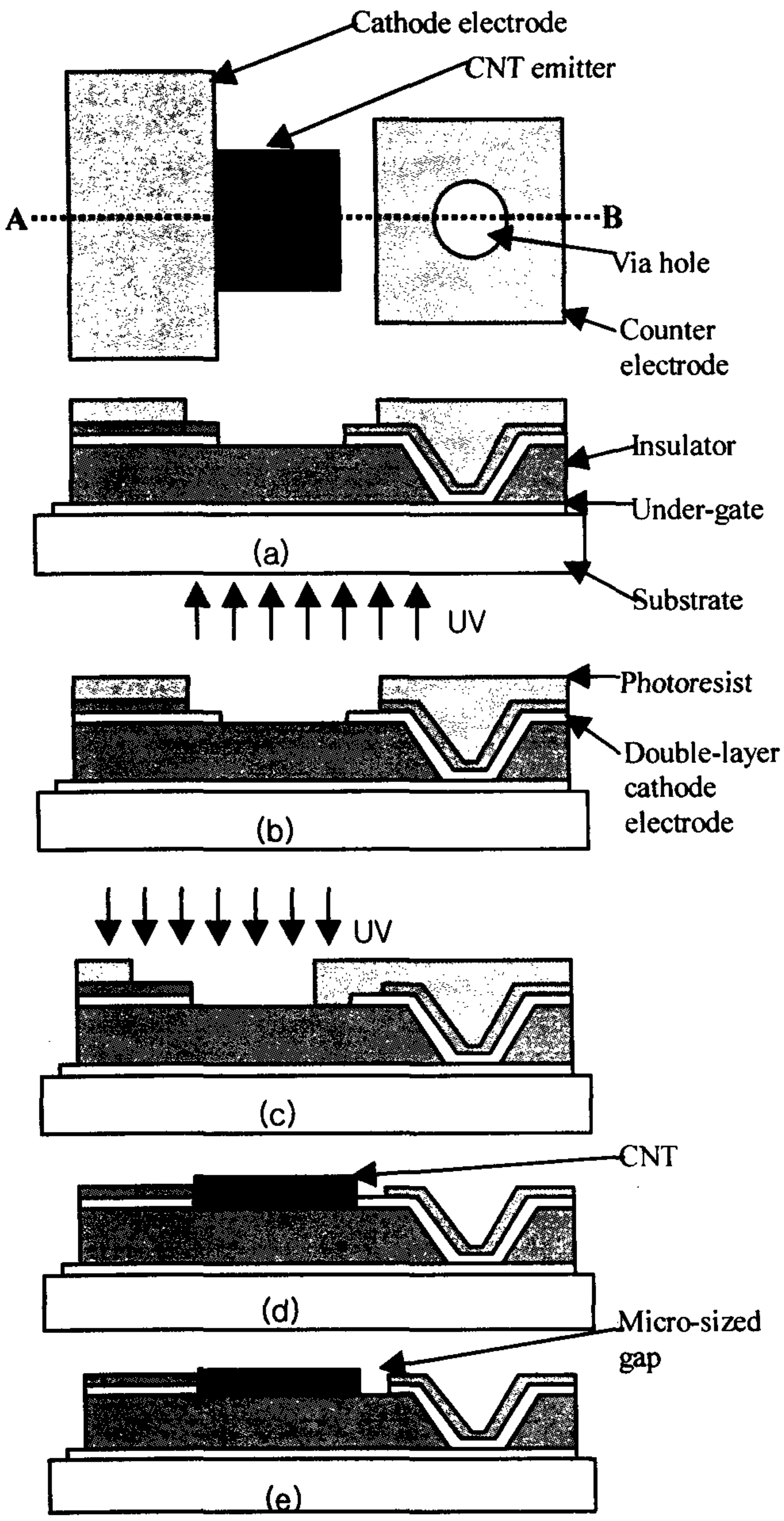

Figure 2. The fabrication processes of the under-gate cathode with a micron-sized gap.

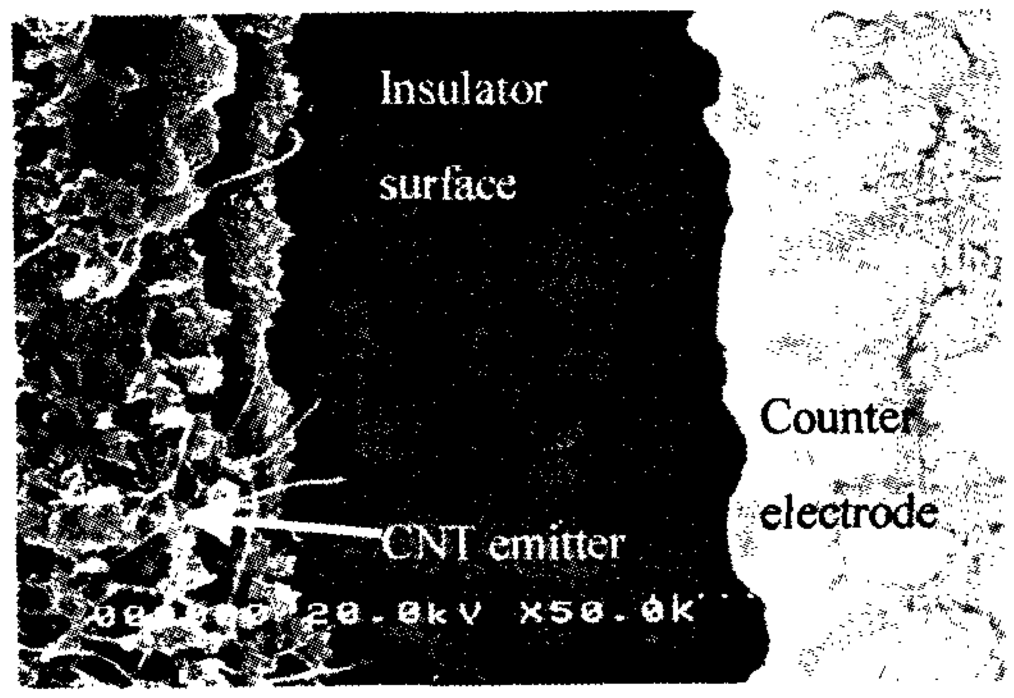

Figure 3. The top-view of CNT cathode with the micron-sized CNT-to-counter gap. The gap is about 1 μm.

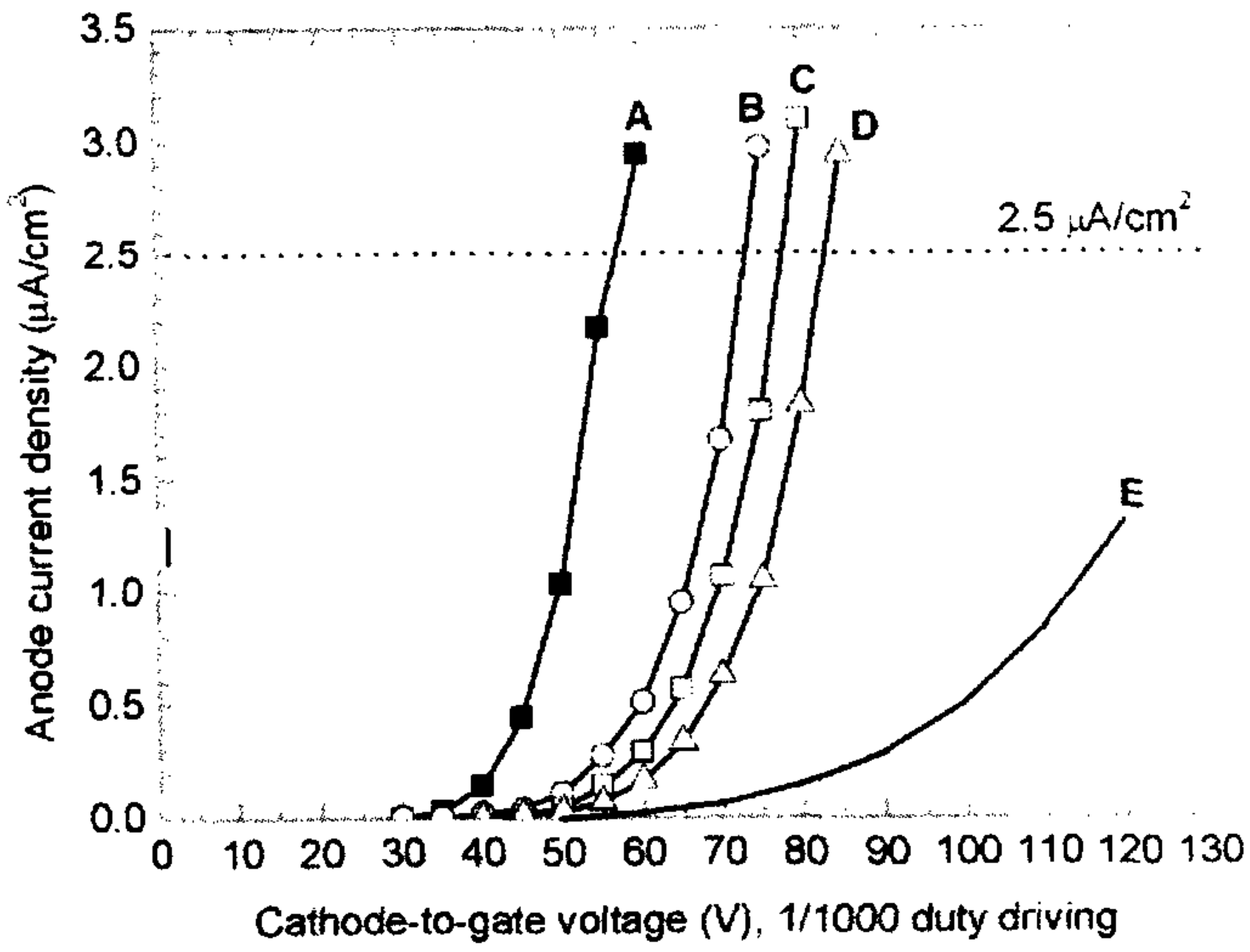

Figure 4. I-V characteristics of the fabricated cathodes.

Table 1. Illustration of the differences of five cathodes.

Cathode ID.	CNT-to-counter gap (d_G, μm)	CNT powder purity (%)
A	2.2	> 95
B	1.6	< 10
C	2.2	< 10
D	3.5	< 10
E	30.0	< 10

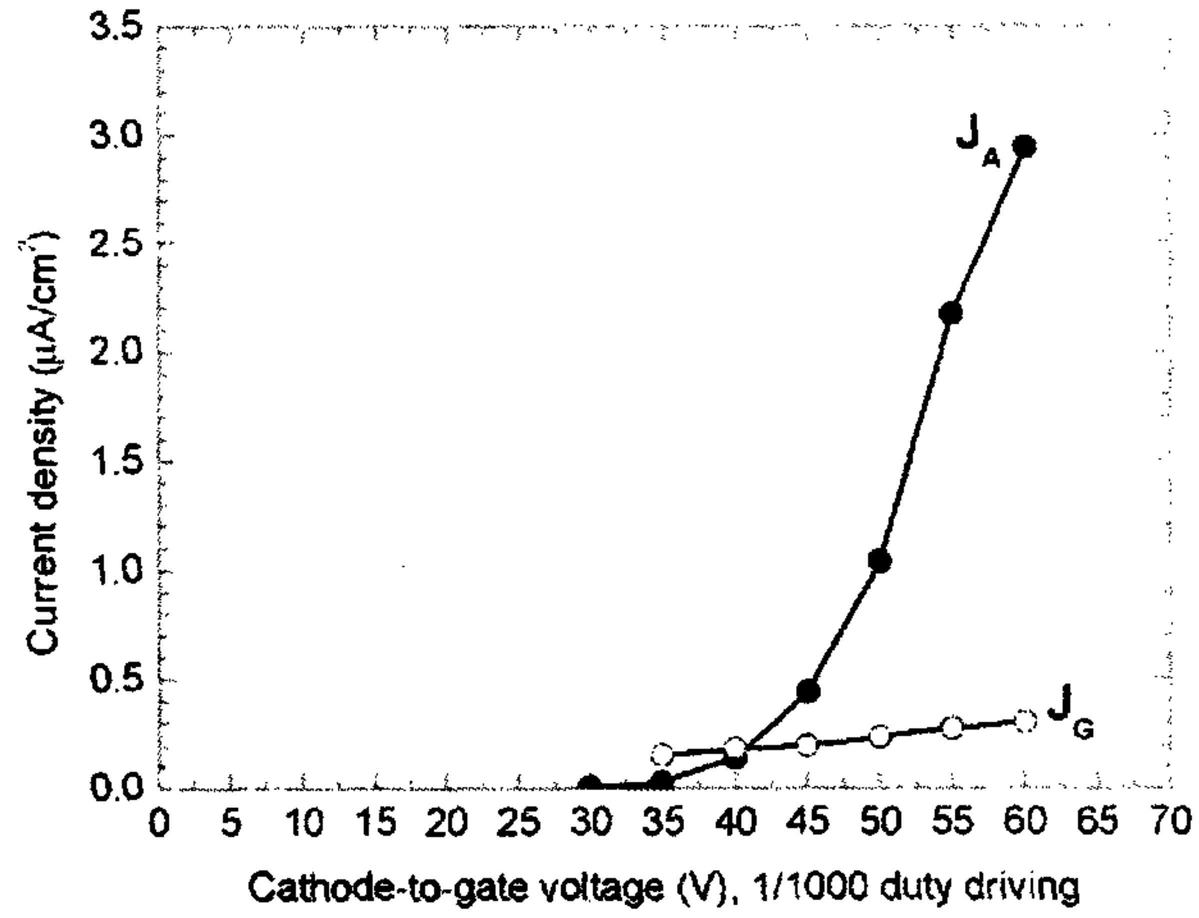

Figure 5. The anode and gate current as a function of the cathode-to-gate voltage. The gate current was about 10 % of the anode current.