The high contrast ratio and fast response time of a liquid crystal display lit by a carbon nanotube field emission backlight unit

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Abstract

We report on the fabrication of a carbon nanotube field emission backlight unit (CNT-BLU) and its application for liquid crystal displays (LCD). The CNT-BLU was operated with locally controllable luminance and impulse-type scanning. The local luminance control, which is based on a very small block size of 1 cm², consisted of local dimming and local brightening. This resulted in the contrast ratio of the LCD-TV to be as high as 300 000:1. A fast response time of ~5.7 ms was also achieved from the LCD-TV lit by CNT-BLU, originating from the impulse-type scanning. In addition, the CNT-BLU showed long-term emission stability and high luminance uniformity.

1. Introduction

Carbon nanotube (CNT) based field emitters have been reported to exhibit high emission current with long-term stability, resulting from their high aspect ratio with small tip radius of curvature and high chemical inertness [1–3]. Thus a large amount of research is being carried out to utilize their excellent properties in practical applications, such as field emission displays (FED) [4, 5] and x-ray sources [6, 7]. Another fascinating application of CNT emitters is a field emission backlight unit (FE-BLU) for liquid crystal displays (LCD) [8]. Although various types of lamps are being used as backlights for LCD, a cold cathode fluorescent lamp (CCFL) is by far the most widely used backlight for commercial LCD- TVs and monitors [9]. However, the LCD lit by a CCFL has suffered from a couple of serious problems: one is low contrast ratio and the other is the motion blur phenomenon.

When an LCD is representing black color, the liquid crystal should completely block the transmission of light generated by the BLU; however, there is always a small amount of transmitted light. Since a CCFL illuminates the whole display area including the black image area, it is not possible to represent the black image with a very low grayscale. This is due to the small amount of light leakage, causing the poor contrast ratio of the LCD (~1500:1). To represent true black with an improved contrast ratio, the BLU should be operated with local dimming. Recently, a light emitting diode (LED)-BLU with local dimming has been developed for improving the contrast ratio of the LCD [10, 11]. However, the size of the dimming block in the LED-BLU (a few tens of cm²) is not small enough to represent fine luminance control, causing light leakage in some black areas close to a bright image. In addition to the dimming, local brightening is also required to increase the contrast ratio further. However, it is very difficult for the LED-BLU to increase the luminance locally.

Another critical limit of the LCD panels lit by a CCFL is the motion blur phenomenon. It is caused by their sample-and-hold nature, i.e. the liquid crystal remains in the same state after addressing during a whole frame. When displayed objects move as is the case of TV images, it causes a blurred image of
the objects on the retina of a viewer [12]. To overcome this limitation, the operation of a BLU with impulse-type scanning has been suggested as one of the best solutions [13].

Hence, a new type of advanced BLU, which has the functions of both locally controllable luminance (dimming and brightening) and impulse-type scanning, should be developed. This can provide a high contrast ratio and motion blur-free image for next-generation LCDs. These functions could easily be accomplished using an FE-BLU since the operation of an FE device is locally addressable and based on impulse-type scanning. Here, we describe the fabrication and properties of an FE-BLU with CNT emitters, abbreviated to CNT-BLU hereafter, and its application to LCD-TV. The LCD-TV lit by a CNT-BLU demonstrated excellent image characteristics, including higher contrast ratio and faster response time, compared with a conventional LCD-TV lit by a CCFL.

2. Experimental details

A top-gated cathode structure with CNT emitters was fabricated using the following procedure. An insulator (~20 μm) was prepared on the indium tin oxide (ITO)-coated glass plate by screen printing of the glass (PbO-SiO2–B2O3) paste, followed by firing at 560 °C. Then, the Mo thin film (~400 nm) was deposited on the insulator by DC magnetron sputtering which was used as a gate electrode. Later, photolithography was carried out to make gate holes with the exposure of the ITO surface. Then, a UV-blocking layer was formed inside the gate holes using photoresist to define the size (diameter: ~20 μm) of CNT emitters at the desired positions [14], followed by screen printing of the CNT paste which was prepared by mixing 1 wt% of thin multi-walled (MW) CNTs (diameter: ~2–4.5 nm) with an organic binder (methyl methacrylate-methacrylic acid), negative-type photo-imageable resin (polyester acrylate), inorganic powders (In2O3) and solvent (terpineol), followed by three-roll milling. Since the negative-type photo-imageable CNT paste was printed onto the transparent ITO electrode, the back side of the cathode was exposed to UV. The following development process formed one paste dot per gate hole. The cathode was fired at 420 °C in N2 ambient. Finally, physical surface treatment was executed using a liquid elastomer to form CNT emitters with vertical alignment. The red (Y2O3:Eu), green (ZnS:Cu,Al) and blue (ZnS:Ag,Al) phosphors were mixed in appropriate proportions to produce white color. Later the mixture was blended with organic binder to make phosphor paste, which was screen-printed onto the ITO-coated glass plate. In the next step, an Al reflection layer was formed on the phosphor by thermal evaporation to increase the luminance by reflecting light. The cathode and the anode plates were then hermetically sealed with posting spacers (1 cm in height). The evaporable getter was also loaded inside the panel to preserve the high vacuum state after packaging. Finally, the panel was pumped down to 1 × 10−6 Torr through an exhausting tube connected to a turbo-molecular pump, followed by tip-off and getter activation processes.

Figure 1(a) shows the arrangement of gate holes in a local dimming/brightening block. An array of 40 μm gate holes, 120 × 120 holes per block (1 cm2), were fabricated with a pitch of 70 μm. The inset in figure 1(a) illustrates the morphology of CNT tips formed inside a gate hole. It can be observed from the image that the physical surface treatment using liquid elastomer [15] efficiently forms vertically aligned CNT emitters. Only one weight percent of CNTs resulted in a large number of emitting tips since we used thin-MWCNTs with high purity (98 wt% CNTs with 2 wt% catalyst particles). In the case of such a high CNT concentration, the transport of electrons through the paste is believed to be by tunneling between CNTs which are closely spaced together [16]. In addition, the aligned CNTs were observed to be well distributed although the raw CNTs were bundled and entangled tightly (not shown here). It confirms that the CNT paste was well prepared, resulting in effective dispersion of nanotubes. Our cathode structure is similar to the conventional Spindt-type field emission cathode [17], except multiple CNT emitters per aperture were present in this case. Structurally, the optimal configuration in the Spindt cathode has been proposed to have an equal height of tip apex to the gate position [17]. However, in our cathode, the gate electrode was prepared on a thick (20 μm) insulator, resulting in a higher gate position than the CNT tip heights (~4 μm). This leads to the suppressing of uncontrollable field emission caused by high anode bias (15 kV). The dimensions of cathode structure including emitter dot, gate hole and hole-to-hole pitch are still being optimized.

The anode current (Ia) versus gate voltage (Vg) characteristic of the fully sealed 32 inch diagonal CNT-BLU panel is represented in figure 1(c). Since the LCD panel absorbs ~95% of light output from the backlight, the BLU is, in general, required to be ~20 times brighter than the desired luminance of the LCD. The electron penetration depth into the phosphors is known to be proportional to Vg/ΔV, where Vg is the anode voltage and n is a material constant, for example, n for ZnS is 2.4 [18]. Therefore, higher Vg is preferred for higher luminous efficiency. However, we found that a Vg of higher than 15 kV causes the device to generate large amount
of harmful x-rays. Hence, the CNT-BLU was designed to be operated at $V_g = 15$ kV. $V_g$ was applied with 0.72% (~1/139) duty ratio at 60 Hz. The electron emission was turned on at $V_g = 40$ V and then increased steeply to 19.02 mA with increasing $V_g$ to 70 V. It was found that $I_a = 11.3$ mA was high enough for the operation of the 32 inch diagonal CNT-BLU with sufficient luminance (6000 cd m$^{-2}$). We could extract an anode current of $I_a = 11.3$ mA by applying $V_g = 66$ V with a duty ratio of 0.72%. Since the emission was turned on at $V_g = 40$ V, the difference between $V_g$ for turn on and $V_g$ for sufficient luminance, defined as the swing voltage, was 26 V. Such relatively small swing voltage might be a result of the emitter’s high field enhancement factor ($\beta$). To analyze the Fowler–Nordheim (FN) plot (not shown here) obtained from the $I_a$ versus $V_g$ curve, we used the modified FN equation for gate-driven cathodes: $I_a = aV_g^2 \exp(-b/V_g)$ [19], where the duty factor $f = 139$, $a = 6 \times 10^{-5}$ A V$^{-2}$ and the linear slope $b = 375$ V. By using the relation $b = 6.44 \times 10^9 \phi^{3/2}/\beta$ where $\phi$ is the work function, and by assuming the $\phi$ of MWCNTs to be 4.9 eV [20], the $\beta$ of the emitter was determined to be as high as $1.86 \times 10^6$ m$^{-1}$ (186 $\mu$m$^{-1}$). Such a high $\beta$ value in this work can be attributed to the gated cathode structure and high aspect ratio of thin MWCNTs. The relatively smaller swing voltage obtained in this work is expected to result in less power consumption and lower the cost of driver electronics.

The inset in figure 1(c) represents $I_a$ versus operation time with the initial current of 11.3 mA. As shown in the figure, the CNT-BLU panel shows long-term emission stability, from which no emission decay for $\sim$120 h was observed after an initial decay for $\sim$20 h. Such stable emission for long time was the result of three aspects. First, the emitter current density $\sim$90 $\mu$A cm$^{-2}$ is much smaller than that of CNT-FEDs which is the order of a few hundred $\mu$A cm$^{-2}$ [5, 21, 22]. In the case of FED, the diameter of the gate hole should be narrower to prevent the electron beam being spread. This results in the smaller dimension of emitter dots. However, the BLU does not require focusing of an electron beam, making it possible to have larger emitter size, in other words smaller current density. The smaller current density induces less Joule heating, which is beneficial for long-term emission stability of a field emission device. Second, through heating ($\sim$470 °C) during the exhausting process, we have tried to remove the water vapor adsorbed on various components of the inner panel. This is expected to improve the emission stability of CNT emitters. Third, the Al layer formed on the phosphor layer efficiently protects the CNT emitters from the emission-induced degassing of phosphor elements which takes place in the phosphors without an Al layer [23].

Figure 1(d) demonstrates the uniform emission pattern of a 32 inch diagonal CNT-BLU having 2800 blocks (70 × 40). A luminance of 6000 cd m$^{-2}$ was obtained at $V_g = 15$ kV and $I_a = 11.3$ mA with a corresponding anode current density ($J_a$) of 4 $\mu$A cm$^{-2}$. In order to evaluate the luminance uniformity quantitatively, nine groups on the panel were chosen to be measured. Each group was composed of nine adjacent blocks (3 × 3): hence, a total of 81 blocks were used for the evaluation. The luminance of all selected blocks was measured individually, and then the block-to-block uniformity (BU) was calculated using the definition of BU (%) = $(1 - \sigma/x) \times$
100, where \( \sigma \) and \( \mu \) are standard deviation and mean value, respectively \[5\]. The uniformity of the CNT-BLU shown in figure 1(d) was determined to be as high as \( \sim 90\%\). Repeated measurements of 10 samples showed that the BU ranged from 88 to 91\%. By the assistance of a light diffuser generally utilized to improve the uniformity of the LCD, the BU was increased to \( \sim 97\%\), which is comparable to that of an LCD-TV with a CCFL.

The brightness of each block was independently controlled with 256 (8 bits) grayscales, which was accomplished by varying the duty ratio. Therefore, by decreasing the on-time (pulse width) selectively, local dimming was easily achieved in an LCD-TV lit by a CNT-BLU. In addition to the dimming, we also developed a novel local brightening technique by simply increasing the duty ratio on desired blocks. The local luminance was designed to increase on decreasing the load ratio of image size (the relative area, which is representing the image, over the whole display area). \( V_g \) of 66 V with a duty ratio of 0.72% was applied with a load ratio of 100%, so-called full white, to obtain a luminance of 6000 cd m\(^{-2}\), as shown in figure 1(d). On decreasing the load ratio from 100% to 30%, the duty ratio is designed to be increased from 0.72% to 2.06% while the frequency was kept constant at 60 Hz. In the load ratio ranging from 30% to 0%, the duty ratio was designed to be kept constant at 2.06%. Figure 2(a) represents the designed (blue solid line) and experimentally observed (blue open circles) luminance in our CNT-BLU as a function of load ratio. Also included in the figure is the corresponding variation of power consumption. The experimentally observed data was found to be in good agreement with the designed values.

The luminance almost linearly increased with duty ratio, and the power consumption decreased with decreasing load ratio at constant duty ratio (see the load ratio range of 0–30%).

As a result, for a load ratio of 10% (2.06% duty ratio), three times higher luminance was achieved with only 30% power consumption, compared to a full white case (100% load ratio, 0.72% duty ratio). Figure 2(b) shows the photographs of an LCD-TV lit by a CNT-BLU taken at three different load ratios. It can be clearly observed that the luminance indeed increases with decreasing load ratio. The luminance of 10, 50 and 100% load ratio images was measured to be 845, 560 and 280 cd m\(^{-2}\) with a relative power consumption of 35, 95 and 100%, respectively. Luminance decreased by 95.3% from the original values represented in figure 2(a) since the transmittance of the LCD panel used in this study was 4.7%. The luminance of an LCD-TV with a CCFL is \( \sim 400 \) cd m\(^{-2}\). From the above results, it can be noticed that the CNT-BLU results in a brighter LCD-TV than a CCFL which is attained for a load ratio of smaller than 70%.

The luminance at the position of black in the image with the load ratio of 10% was measured to be 0.003 cd m\(^{-2}\), which is the lower limit of our measurement system. This indicates that the contrast ratio of the LCD-TV lit by our CNT-BLU is at least 300000:1. We believe that the real luminance of the black image is much lower than the limited value obtained from our measurement system (0.003 cd m\(^{-2}\)) since there is no illumination. It is therefore expected that the real contrast ratio of the LCD-TV lit by our CNT-BLU is even higher than 300000:1. Since the contrast ratio of a conventional LCD-TV lit by a CCFL is \( \sim 1500:1\), the CNT-BLUN was found to improve the contrast ratio of the LCD-TV by at least 200 times, compared with a CCFL.

Figures 3(a) and (b) show the images of LCD-TVs lit by CNT-BLUs with different load ratios of \( \sim 40\%\) and \( \sim 85\%\), respectively. The corresponding backlight images with light diffuser operated with local luminance control are shown in figures 3(c) and (d), respectively. It indicates that synchronized BLU images with the final LCD images were achieved with our CNT-BLU. Furthermore, since the block size for dimming/brightening is as small as 1 cm\(^2\), fine control of local luminance is realized by simple matrix addressing.
local dimming [9], in contrast to our 2800 blocks with the same panel size. It can be therefore said that our CNT-BLU demonstrates better local luminance control than an LED-BLU does, which is attributed to smaller block size with the additional function of brightening. Note that, since the load ratio of figure 3(c) (∼40%) is smaller than that of figure 3(d) (∼85%), figure 3(c) looks brighter than figure 3(d) does, due to the local brightening with small load ratio.

We have also observed much enhanced sharp moving images using the CNT-BLU, since the backlight is operated with impulse-type scanning. Figure 4 shows two response time data of LCD-TVs lit by a CNT-BLU and a CCFL. In the case of a CNT-BLU, the transient time for the variation of relative luminance from 90% to 10% was as fast as 5.7 ms. This is almost three times faster than that observed from a CCFL (16.4 ms). The enhanced image sharpness is ascribed to the impulsively generated light output from the CNT-BLU. It was indeed found that the motion blur did not occur even in fast moving images. However, we could not include those images due to the limited resolution of our camera.

4. Conclusion

We have developed an FE-BLU using a CNT emitter (CNT-BLU), and then analyzed its field emission characteristics including emission current, stability and uniformity. Well-distributed CNTs were precisely integrated into gate holes through simple photolithography and a surface treatment process. The CNT-BLU generated high emission current with long-term stability and the observed emission uniformity was high enough to be used for an LCD-TV. The image characteristics of an LCD-TV lit by the CNT-BLU were evaluated and compared with those by a CCFL. Compared with a CCFL backlight, at least 200 times enhanced contrast ratios and three times improved response times were demonstrated by using the CNT-BLU. These were achieved by fine local luminance control and impulse-type scanning, respectively. Achieving these technologies using CNT emitters is believed to be very promising for the next-generation LCDs with excellent image characteristics.

References