Color Nanotube Field Emission Displays for HDTV

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Abstract
We demonstrate color video displays driven by carbon nanotube electron field emitters. These nanotubes are incorporated into the device by selective growth using low temperature chemical vapor deposition. The device structure is simple and inexpensive to fabricate, and a 45 V switching voltage enables the use of low cost driver electronics. The prototype units are sealed 4.6" diagonal displays with 726 um pixels. They represent a piece of a 42" diagonal 1280x720 high definition television. The carbon nanotube growth process is performed as the last processing step and creates nanotubes ready for field emission. No activation post-processing steps are required, so chemical and particulate contamination is not introduced. Control of the nanotube dimension, orientation, and spatial distribution during growth enables uniform, high-quality, color video performance.

1. Introduction

Field emission displays produce light in the same way as a cathode ray tube, yet they can be built as thin as 1 cm while maintaining comparable image quality. Many companies believe that field emission displays can be built inexpensively enough take market share from plasma displays panels(PDPs), liquid crystal displays(LCDs), and projection displays in the large area (> 40" diagonal) flat panel display marketplace. Canon[1,2], Toshiba[1], Samsung[2], Sony[3], Noritake[5], Mitsubishi[6], and others[7,8] are actively developing field emission display technology based on carbon or carbon nanotube emitters.

At Motorola, we have focused on creating a low cost, large area display technology with the goal of being substantially less expensive than PDPs or LCDs. Our cost model analysis indicates that the key contributors to the overall display manufacturing cost are the panel fabrication steps and the display electronics. We find that the lowest cost is not obtained by using the least inexpensive thick film printing techniques to form the cathode layers. The least expensive types of direct print patterned thick films have a resolution limit on the order of 50 μm. This is much too large to produce a device geometry that can operate at low voltages using low voltage driver electronics. Our approach uses proximity lithography to define our critical geometry. This increases the cost of the panel, but significantly reduces the cost of the driver electronics, resulting in lower overall display cost. Using the guidance of the cost model, we have designed a display technology incorporating a reasonably low cost cathode, a low cost anode, and low cost driver electronics so that the total display cost is minimized.

We demonstrate Motorola's low cost display technology using a 4.6" display with the pixel size of a 42" 1280x 720 high definition television (HDTV) (or a 63" 1920 x 1080 HDTV). Carbon nanotubes are grown directly and selectively into the structure as the last processing step. Control of the nanotube distribution, placement, and dimensions allows the use larger features, enabling proximity lithography to define the critical device dimension. We show full motion video with luminance above 100 cd/m^2 and good color purity, using a switching voltage below 45 V.

2.0 Building a device

2.1 Device Structure

The device structure contains an electron-emitting plate, and phosphor coated anode plate (Fig 1). The anode plate is fabricated with standard thick film techniques used to deposit the black surround and the phosphors in plasma display panels. A thin reflective aluminum layer is coated on the anode with the techniques used by commercial cathode ray tube manufactures to make the reflective aluminum layer in their displays.

We designed the electron-emitting plate so that it can be fabricated using low cost proximity

lithography. A schematic cross-section of the cathode plate is shown in Figure 2. First, we start with substrate glass. Currently we use OA10 borosilicate glass from Nippon Electric Glass, but all our processes, including chemical vapor deposition (CVD) growth of carbon nanotubes, are compatible with PD200 glass from Asahi Glass Company. We then sputter deposit the first metal layer (column electrodes) and pattern it. In our process line, we currently use sputtered Mo for this layer, but the sputtered Cr/Cu/Cr layer used in PDP manufacture could be used in a production situation, as could a photo-definable paste.

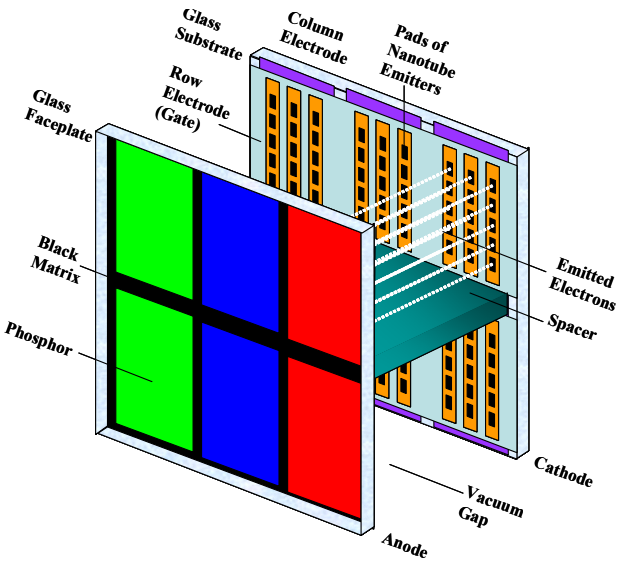

Figure 1. Schematic of a nanotube-based field emission display.

Next, we deposit a ballast resistor material which is based on amorphous silicon. The ballast layer prevents individual nanotubes from emitting excessive levels of emission current. This improves the short-range pixel uniformity and it eliminates the most significant emitter degradation mechanisms. The role of the ballast material in achieving lifetimes in excess of 9000 hours in nanotube displays has been reported previously [9]. The ballast material can be deposited by chemical vapor deposition (similar to the amorphous transistor deposition in LCD manufacture) or by sputtering. This ballast layer is restricted to the active area with gross patterning so that the input-output (I/O) lines are uncoated. The layer is continuous (unpatterned) through each subpixel in the active area. Next, we deposit a dielectric layer based on SiO_2 by chemical vapor deposition, similar to the dielectric layer in an LCD. We then deposit the second metal layer (gate and row I/O). We pattern and the second metal layer and the oxide layer in the same lithography step. We use the same material for the second metal layer as for the first metal layer.

Finally, we deposit and pattern a catalyst material which acts as a seed for the growth of nanotubes. The size of the pad is approximately 25 μm^2 and the pad to gate spacing is on the order of 5 μm. The pads are defined by proximity lithography. The catalyst material, while proprietary, is simple to make. It has been deposited by sputtering, evaporation, screen-printing and stamping.

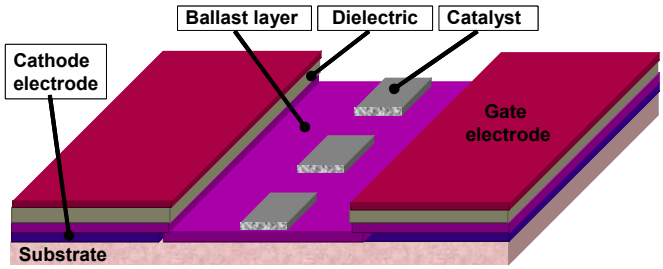

Figure 2. Cross-section schematic of the layers deposited on the cathode plate.

Through careful design of the electrodes on the device, we achieve good control of our electron beams without the need for an independent focusing electrode [10]. This eliminates a significant level of complexity which is reflected in reduced display cost.

The electron-emitting plate and the anode plate use processes and materials currently available in PDP and LCD manufacturing lines. The cathode is fabricated with three proximity photomasks and another large feature mask for the ballast layer. This results in a simple, low cost, scalable panel fabrication technology. Moreover, this structure could be fabricated in a retrofitted PDP or LCD line.

2.2 Carbon Nanotube Growth

The catalyst material that we deposit directs the nanotube growth. It is a nanocomposite material in which metallic nanoparticles are embedded in a matrix. Since the diameter of the nanoparticles determines the diameter of the nanotubes, we can control the nanotube diameter via the catalyst.

In other technologies, nanotube catalyst materials create nanometer-sized particles by coalescence from a thin metal film (< 5 nm). The

diameter of the particles is a function of the metal thickness and the growth temperature. These dependencies make it extremely difficult to grow nanotubes of the appropriate size and density at the low growth temperatures required by glass substrates. In addition, nanotube growth is highly sensitive to sub- nanometer variations in catalyst thickness, so it is clearly not scalable for deposition over a large area panel.

In contrast, Motorola's catalyst lies in an embedded matrix which maintains the catalyst particle size, independent of temperature. Moreover, the catalyst material is a bulk nanocomposite, not a surface layer. For any thickness of catalyst, the surface always contains embedded nanoparticles. Consequently, the particle size and growth properties are independent of catalyst layer thickness. We have used catalyst ranging in thickness from 20 nm to 300 nm to 5000 nm with similar results. Clearly, this process is scalable over any size since the growth properties are insensitive to the catalyst thickness.

Nanotube growth is performed in a hot filament chemical vapor deposition (HFCVD) tool using hydrogen and methane source gases. The tool heats the substrate to the desired temperature while the hot filament enables the appropriate gas phase chemical reactions to occur, and nanotubes grow from the catalyst. The growth technique is highly selective; nanotubes can only grow from the catalyst below the filament grid, and no carbon is deposited anywhere else in the system. All that is required to scale the HFCVD process to large areas is a platen which keeps the substrate temperature uniform, and a filament grid that covers the substrate area. The platen technology is already used in LCD factories. HFCVD systems with filament grids 20 times the area of our 4.6" display are commercially available, demonstrating scalability.

Nanotubes grow up from the substrate with one anchored end and one free end. They emit as grown. This contrasts sharply with thick-film or paste methods of depositing nanotubes where the nanotubes are embedded in a matrix. In a paste process, the nanotubes must be released from the paste via an 'activation' process which involves peeling, tearing, or ablating the paste. As a result, a paste process cannot control the distribution or orientation of the nanotubes. In addition, particles generated in the activation process cause electrical defects in the device. Exposure to materials that would remove particles, such as a rinse step, is highly detrimental to nanotube field emission. Once created, these particles cannot be removed easily. In the case of Motorola's CVD process, well-oriented emitting nanotubes are produced without additional steps and without adding particles to the device.

Nanotube growth is performed as the last processing step before sealing the device. This is highly desirable in vacuum displays because oxidizing gases and materials can degrade the emitters and cause lifetime problems. The high temperature reducing atmosphere of the nanotube growth processes also outgasses the glass and the device layers. It eliminates oxygen in general. LETI has measured the lifetime of displays formed with nanotube CVD as the last process step prior to sealing. They reported an emitter lifetime in excess of 9000 hours without optimization [9].

3.0 Device Properties

3.1 Video

To demonstrate the feasibility of our technology for building a display, we built a 4.6" diagonal technology demonstrator unit. The 4.6" display has a 726 mm pixel size and represents a 4.6" sub-section of a 42" diagonal HDTV (1280 x 720) or a 63" HDTV (1920 x 1280). Images from a sealed display are shown in Figure 3. Typical operating conditions are an anode voltage of 4400 V, a total gate voltage of 90 V and a switching voltage of 45 V. The anode to cathode gap is 1.1 mm. Under these conditions, the display luminance is 100 cd/m^2. Recently we reported improvements to our device current and anode voltage operating point [10]. These advances will soon enable the display luminance to exceed 800 cd/m^2.

The demonstrator display shows full motion color video. We used a computer to scale a motion picture from a digital video disk (DVD), so that the entire movie plays on the display, rather than just a small subsection of the movie. The display uses P22 phosphors, just like a CRT. The motion response time, often a problem for liquid crystal displays, is set by the P22 phosphors in our field emission technology. Consequently, the motion response is the same as that of a CRT. The longest phosphor decay time (red) is less than < 1 millisecond. This is ideal for showing motion without artifacts.

Figure 3. A sealed nanotube-based field emission display showing color images of a tiger, top-down (a) and at an angle (b). Images were produced with a 45 V column swing, 90 V total on the gate electrode, 4400 V on the anode, using a 1.1 mm anode-to-cathode gap. The anodes were fabricated by TECO Nanotech Company.

The display image is produced using integrated driver electronics designed and built at Motorola. During operation, the row driver sequentially scans each row at a high state. This state is the sum of a D.C. offset voltage and a driver switching voltage. A pixel is turned on when the row is scanned high and the column switches from approximately 45 V to ground. This is the switching voltage that determines the cost of the driver electronics. Motorola fabricated driver chips for both row and column drivers and they consist of a flip-chip die attached to a flexible polyimide carrier with an epoxy under fill. The driver electronics are connected to the display using the tape automated bonding (TAB) process. The column drivers are Motorola designed integrated circuits with 192 outputs. These drivers control the grayscale through pulse width modulation. They are capable of providing 8 bits of gray scale at HDTV scan rates. In addition, analog amplitude modulation capability is provided for in the driver architecture for color correction and for additional gray scale resolution.

3.2 Color Purity

The color purity of the panel is determined by the colors of the phosphors, the alignment of the anode plate to the cathode plate, and the bleed-over of a subpixel's electron beam into a neighboring subpixel's color. We have primarily been concerned with constraining the electron beam to its color, with no significant bleed-over. Our design goal is to achieve excellent color purity without employing an additional focusing layer and its associated costs. In previous work, we demonstrated very low beam bleed-over without extra focusing layers [10]. Here we present the color coordinates of the display operating in video mode. In fact, at this time, our primary color impurity is due to misalignment of the anode and cathode plates. Our alignment is currently done with a primitive manual system, and with it, we have produced displays with the color coordinates in Fig. 4. The misalignment is evident in the rotation of the color triangle with respect to the phosphor colors. Using a computer model, we computed the color coordinates that would result from perfect alignment and plotted this result in Fig. 4 as well. In any case, our color coordinates are very close to the intrinsic phosphor color, and are substantially better than the LCD screen on the laptop computer in our lab (a commercially available consumer product).

4. Conclusions

In conclusion, we demonstrate nanotube field emission display technology showing full motion color video images. The demonstrator device, a 4.6" sub-section of a 42" diagonal HDTV display, operates at a low swing voltage of 45 V, enabling the use of low cost driver electronics. The video image, the luminance and the color purity demonstrate the potential of this technology for large area HDTV display applications. This display is built by selectively growing carbon nanotubes on pre-defined catalyst pads via HFCVD. The control of the nanotube growth provides for a well-controlled emission properties. In contrast to the nanotubes-in-paste approach, CVD-grown nanotubes provide for a clean, defect-free device.

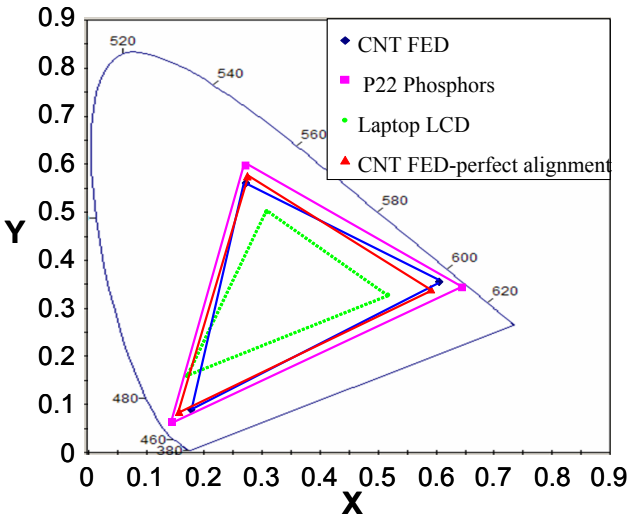

Figure 4. Color coordinates of a carbon nanotube field emission display plotted against the 1931 CIE Chromaticity Diagram. The measured points (♦) are close to the intrinsic phosphor color (■), even though the anode to cathode alignment has a significant error. The color coordinates with perfect alignment were computed from the data set and show no rotation (▲). The color gamut of our NED display substantially exceeds that of our laboratory laptop's LCD display (●).

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