Nano-emissive display technology for large-area HDTV

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Abstract — Using nano-emissive display (NED) technology, Motorola labs has successfully developed 5-in. full-color display prototypes. Carbon-nanotube-based field-emission displays with a pixel size of 0.726 mm for a 42-in. HDTV exhibit video image quality comparable to CRT displays and demonstrate a luminance of 350 cd/m^2. These novel low-drive-voltage NEDs take advantage of selective growth of CNTs to obtain the desired electron-emission performance while maintaining inexpensive manufacturing due to a simple self-focusing and self-regulating planar structure. Improved video image quality and color purity are achieved with very low power consumption and without the need for an expensive focusing grid.

Keywords — *FED, carbon nanotubes, hot-filament CVD growth, flat-panel displays.*

1 Introduction

1.1 Background

Nano-emissive display (NED) technology development at Motorola labs began as a R&D project in early 1999. The technical concept was rapidly demonstrated and performance potential and reliability were quickly established. To achieve the required performance and cost objectives, a solution involving the controlled integration of selectively grown CNTs by hot-filament chemical vapor deposition (HF-CVD) at low substrate temperature has been developed. To achieve low modulation voltage, high luminance, emission stability, spatial uniformity, and low manufacturing costs, an emissive cathode was designed, emissive material was developed, and the processes that improved the performance and reduced the cost of fabrication was established. Many of the problems which precluded the successful introduction of conventional microtip field-emission displays (FEDs) in the late 1990s have been solved through the development of NED technology.

1.2 Motivation

We believe that NED technology can revolutionize the high definition television (HDTV) display market by combining superior performance and low manufacturing cost. The allure of NED technology is clear: it encompasses the superior picture quality offered by color CRTs, and the lightweight and thin form factor offered by liquid-crystal display (LCD) and plasma-display-panel (PDP) technologies. Recent detailed cost-model analyses targeting the 40–50-in.-diagonal TV-panel market attribute the breakthrough in the projected NED commercial price to low manufacturing cost, the possibility to reuse a significant proportion of current flat-panel-display (FPD) production facilities, and the reduced cost of electronic drivers due to the low power consumption of NED. Consequently, NEDs have the potential to reduce the price point for large FPD TV to that of CRTs.[1]

Alternative FPD technologies are ready to enter the market and will pose a challenge to LCD and PDP products. Companies such as Canon and Toshiba,[2,3] are actively developing forms of FEDs compete in this marketplace. Other companies are working on nanotube FEDs which are based on paste-based application of CNTs. NED technology is different from these approaches in that aligned emitters are grown in place without any activation or forming step, thereby simplifying this crucial part of the manufacturing-process flow.

The use of CNT emitters offers a unique opportunity to overcome conventional FED limitations such as poor reliability of metallic micro-tips and the cost associated with scaling up to and beyond a 20-in.-diagonal display. CNTs represent the ultimate field emitters due to their high geometrical aspect ratio (their "sharpness"), their single molecule structure, and the intrinsic chemical stability afforded by their carbon in-plane σ bonds.

In the past 3 years, our NED technology has been successfully scaled up from initial 1-in. displays in 2002,[4,5] to 5-in.-diagonal monochrome displays in 2004,[6] and most recently to full-color video 5-in. displays in 2005.[1] In this paper, we present the state of the art in the development of Motorola NED FPD TVs.

2 Design and fabrication of NED technology

NED is essentially a thin, flat CRT. It has the CRT's advantages of high pixel luminance, large viewing angle, and higher luminous efficiency, without the CRT's bulky package and significant power dissipation disadvantages. NED and CRT technologies both employ an electron beam to strike a phosphor-covered plate creating electron-hole pairs which by radiative recombination produce light. However,

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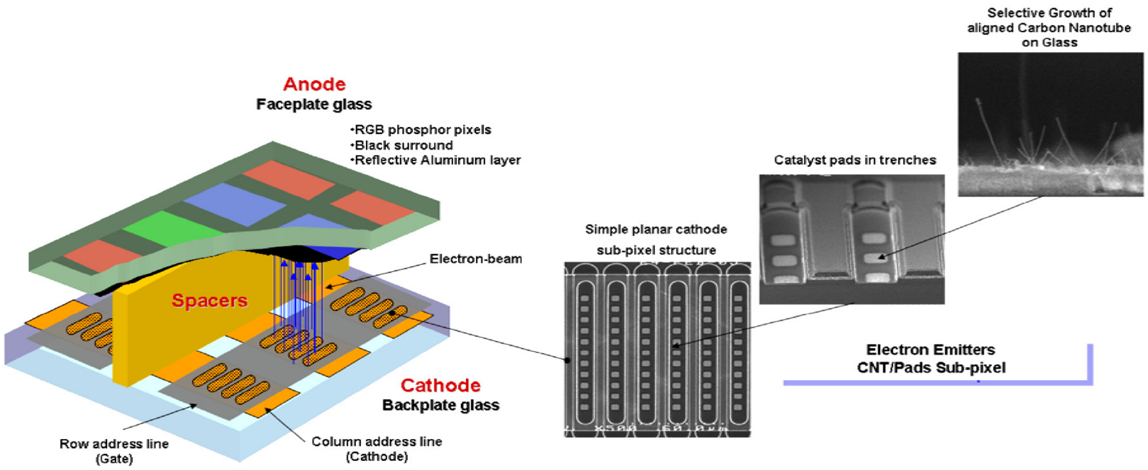

FIGURE 1 — Cut-away view of an NED structure (left) and emitter trenches, catalyst pads, and CNTs at increasing magnification (right).

there are also significant differences between CRT and NED technologies. A typical CRT uses three simultaneously operating electron beams to scan the phosphor plate pixel by pixel. NED generates images by controlling the emission of thousands of groups of CNT emitters positioned to strike the phosphor plate with their electrons. For NEDs there is no need to raster an electron beam across the display; thus, the separation between the cathode sources and the anode phosphor screen can be significantly reduced to design a thin, flat display.

The schematic diagram of a typical NED is shown in Fig. 1. NED is composed of a faceplate and a backplate, each made of transparent display glass. These two plates are separated by insulating spacers in a vacuum envelope. The interior surface of the face-plate is covered with RGB phosphor surrounded by a black matrix; the phosphor and matrix are both covered by a thin, conductive aluminum layer. This faceplate serves as the anode and the backplate as the cathode for the electron-emission circuit.

The backplate consists of a two-dimensional array of electron sources which are matrix-addressed by display driver ICs to form an image. The electron sources are created by growing CNTs selectively on catalyst pads which are patterned on the backplate. The catalyst pads, taken in column groups, are electrically connected through a ballast resistor to the metal line corresponding to that column group. In the current design a single subpixel is comprised of a population of 209 catalyst pads together with the corresponding phosphor area on the anode.

A second set of metal electrodes (gate electrodes) are placed above the catalyst pads and isolated from the pads and column lines by a dielectric layer. Patterned orthogonal to the column lines, these metal lines (row lines), together with the column lines, form the two-dimensional addressable matrix. To stimulate light emission from the phosphor of a subpixel (a given row and column address), a drive voltage is applied to the row while a lower voltage is applied to the column. The electrons tunnel from the CNTs in vacuum and are then accelerated towards the phosphor screen which is held at a high voltage (typically 4–10 kV). After acceleration in the high field created by the anode, their energetic impact at the anode phosphor generates light. In practice, the display is row-scanned, meaning that concurrently an entire row is activated and the data signal for each column electrode sent. If a data signal is in the low-voltage state, the subpixel is activated and light is emitted.

2.1 NED cathode design

2.1.1 Field-emission background

A basic requirement of a field emitter is to provide high current density at low applied field. A necessary condition for high emission current density is a very narrow tunneling barrier width and/or a very low barrier height. Since most materials of interest for field emission have a work function between 4 and 5 eV, the typical approach is to narrow the barrier height by applying a large electric field. For electrons to tunnel out of a flat metallic material, the magnitude of the local electric field must be around 5000 V/μm. Thus, in order to achieve such large local field values while applying only 50–100 V across a gap of a few micrometers, the field must be enhanced by a factor of 100 or more. This can be accomplished by using nanoscale high-aspect-ratio ("sharp") emitters. This multiplicative factor, due to the emitter geometry, is β, the field amplification factor. For a long cylindrical emitter such as a CNT, β is, to a good approximation, proportional to h/r, where h is the CNT height and r is the CNT radius. β can have values as high as 1000.[7] This means that the local field, $\mathbf{E}_{local}$, at the CNT tip surface can be expressed by $\mathbf{E}_{local} = \beta \cdot \mathbf{E}$, where $\mathbf{E} = V/d$ is the applied (diode) field. The large field enhancement afforded by CNTs allows the NED design to relax the typical spacing between the emitters and the gate electrodes can be relaxed up to about 5 μm.[4] This is fully ten times larger than the spacing needed for microtip-based FEDs. Consequently, it

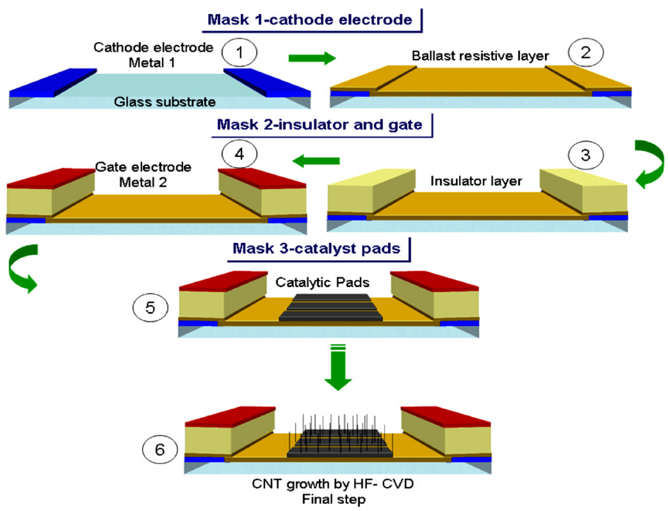

FIGURE 2 — NED technology has a simple structure, with few process and patterning steps.

resolves one of the major fabrication issues encountered during development of FED technology, economical implementation of micrometer photolithography on large-area substrates.

2.2 Fabrication of the cathode structure

A simple planar cathode structure has been designed to extract and modulate the electron emission by the gate electrode under constant anode voltage. As described in Fig. 2, the cathode structure is comprised of a first metal layer forming the display columns. This thin-film metallization is accomplished by standard physical-vapor-deposition (PVD) techniques such as sputtering or evaporation. The metal for the gate and cathode electrodes was chosen based on a suitable combination of electrical conductivity, adhesion to the underlying layer, compatibility with overlying layers, and thermal and electromigration stability. This electrode micro-fabrication stage comprises the first patterning step. Above this first layer, a highly resistive film is deposited. This resistive layer forms a series "ballast" resistor which limits the maximum current from individual nanotubes, thereby improving device stability. This ballast layer also plays an important role in image uniformity by providing a negative-feedback mechanism that reduces spatial variation of emission current resulting from short-range variations in CNT aspect ratio and areal density.

An insulator layer is subsequently deposited on the resistive layer. This dielectric is a dense SiO_2 film deposited by sputtering or PECVD to a thickness of nominally 1 µm. It exhibits a low dielectric constant to improve the capacitive time constant of the display, thereby improving response time and reducing power consumption. It has also good electrical insulating properties and high resistance to electrical breakdown. To create the gate structures, which correspond to the addressing rows of the display, a second metal layer is deposited on the insulator. Trench-shaped geometries are then etched in the gate metal and the insulator layers. Using a third mask step, 5 × 5 µm pads made of a material for catalyzing CNT growth are aligned in the center of these trenches. There are approximately 2×10^5 catalyst pads per square centimeter of display and the CNT/pad covered surface accounts for almost 4% of the cathode backplate surface. This emitter density or fill factor enables extraction of a peak current density ranging from 2 to 10 mA/cm^2. This extracted current depends on the spatial density and β factor of high-quality CNTs.

In short, this planar cathode device geometry allows critical dimensions on the order of 5 µm and can be fabricated with only three proximity lithography steps. This is the most promising design with which we have worked.[4,5]

2.3 CNT synthesis and integration in the planar cathode structure

2.3.1 Why CNTs as emitters?

The CNTs are at the heart of NED emitting sources because they are unusually strong carbon molecules with a high geometrical aspect ratio. CNT dimensions are exceptional: their diameters range from 0.7 to 1.8 nm for single-wall tubes and from 2 to 50 nm for multi-wall tubes, and they can attain several microns in length. The layered structure of graphite provides the perfect building blocks for high-aspect-ratio structures which in turn produce the high fields required to obtain a low threshold for electron emission. The electrical and physical similarities of CNTs to graphite offer further advantages. As a consequence of non-localized electrons, CNTs, like graphite, have high conductivity; CNTs have been reported to carry currents up to 10^9 A/cm^2. CNTs do not melt but rather sustain temperatures greater than 2000°C in high vacuum. That reduces the problem of emitter deformation experienced with metal emitters.[8,9] The graphene structure of CNTs renders them relatively inert; they are much less sensitive to environmental contamination such as the poisoning that affected the metal-surface work function of conventional microtip emitters.

2.3.2 Catalyst preparation

The catalyst used for CNT growth is a proprietary nano-supported material integrated in the structure in the form of square 25-μm^2 pads. As seen Fig. 3, the metal nanoparticles which catalyze the CNT growth are dispersed within an inert material which does not promote carbon nucleation. The areal density and the particle-size distribution of the catalytic particles influence the CNT film morphology, its field amplification distribution, and consequently, the field-emission properties.[10]

The optimum diameters and density of catalyst nanoparticles are <3 nm and $\sim 5 \times 10^{12}/m^2$, respectively. These values mainly depend on the composition of the catalyst film and its preparation prior to growth, and its growth

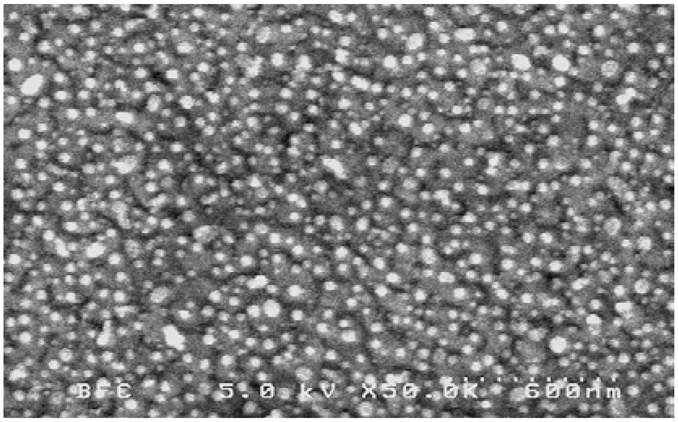

FIGURE 3 — Catalyst film morphology by AFM.

conditions. The catalyst nanoparticles are chemically reduced to their metallic state at the time of the growth process in the HF-CVD reactor. This reduction step is performed during the cathode temperature ramp-up and prior to the growth step.[4]

Along with CNT growth conditions, the control of nanoparticle density distribution is critical for tuning the CNT field-emission properties. If it is too low, there are not enough CNT emitters to generate the necessary current in a lasting stable emission mode. If it is too high then the neighboring CNTs effectively reduce the geometric aspect ratio and shield the electric field from each other resulting in a significant reduction in current per subpixel. The field amplification factor β of CNT emitters, which is approximately the ratio of the CNT height over its radius, is also strongly dependent on the catalyst particle diameter.[10]

2.3.3 Selective growth by HFCVD process

To fabricate a CNT-NED cathode with optimum control over the field-emission properties, we developed a technique for selective growth of CNTs on patterned catalyst pads by HF-CVD. However, it is a challenging endeavor to

FIGURE 4 — Array of filaments at growth temperature in an HF-CVD system.

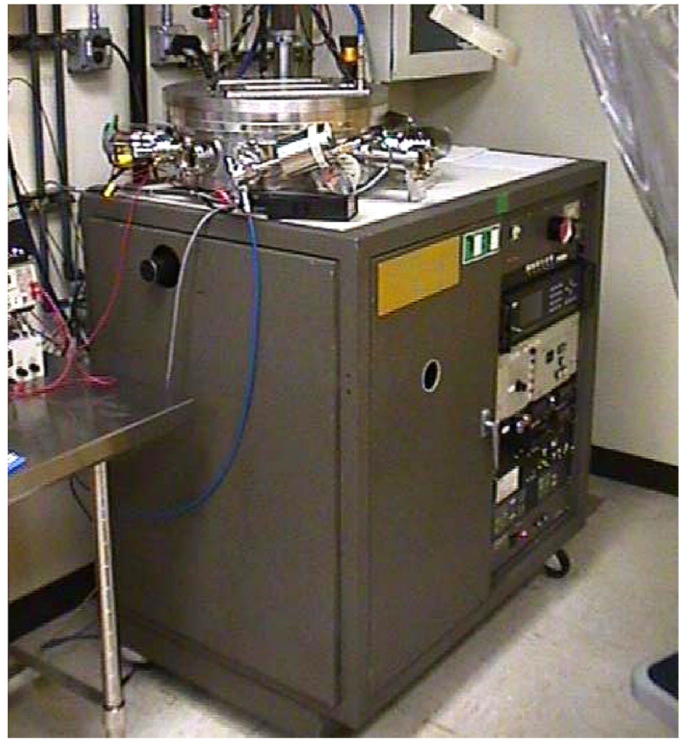

FIGURE 5 — The first HF-CVD system designed and built by Motorola's NED team.

grow CNTs for field emission on "low temperature" glass substrates because field emission requires small-diameter micrometer-long nanotubes. Thin CNTs are typically obtained at temperatures higher than the glass can withstand.

The CNTs are grown using a 20-in.-diameter HF-CVD reactor which was designed and built by the Motorola NED team (Figs. 4 and 5). The HF-CVD technique produces CNTs on glass. In addition, the HF-CVD technique recommended itself by virtue of its simplicity, its scalability, its low cost of operation, and its low cost of ownership. Indeed, HF-CVD growth is extremely selective, being localized to areas of exposed catalyst.[4,5]

The catalytic CNT growth is carried out using reactive CH_4/H_2 gas mixture as the carbon precursor. The average growth temperature of CNTs, as measured at the glass substrate, ranges from 480–550°C and is well below the transformation temperature of low alkali and borosilicate glasses used to fabricate LCDs and PDP displays. The CNT growth time is very short, typically a few minutes, which is favorable for process selectivity and thermal management of the cathode as well as for high-throughput/low-manufacturing cost. As seen in Fig. 6, the resulting growth produces a high density of very thin CNTs with free ends, oriented in the desired direction, perpendicular to the substrate. The long, thin nanotubes of interest for field emission will bend and re-orient in an electric field. As will be discussed in the next section, proper cathode design applies an electric field which aligns the free-ended nanotubes properly.

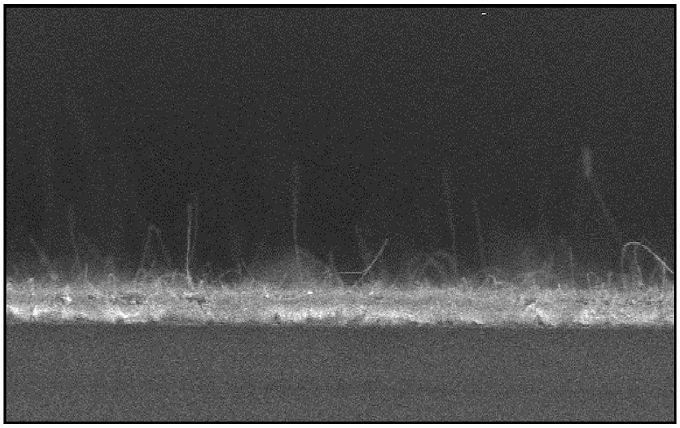

FIGURE 6 — HR-SEM photograph of disordered CNT film. As-grown, a significant proportion of the total CNT population is oriented normal to the cathode surface.

2.4 Field-emission device

2.4.1 Electrostatics of the pixel

Pixel emission is mainly controlled by the gate field. In order to model the electric field in the pixel, we employed the finite-element software tool, FEMLAB. Electrostatic simulations of the pixel structure show that the composite field above the CNT/pads is a linear combination of two fields; a field induced by the anode and a field component from the gate.[4,5]

$$E = E_a + E_g = \frac{V_a}{h} + \alpha \cdot \frac{V_g}{d}.$$

V_a is the anode voltage, h is the anode-to-cathode gap, V_g is the gate voltage, d is the distance between pad and gate, and α is a structure factor determined by electrostatic simulation.

Figure 7 illustrates one of the most important characteristics of the NED pixel design; namely, that the composite electric field as seen by the CNTs is essentially vertical. As the result of Coulomb forces, the flexible CNTs align themselves with this composite field, directed from cathode to anode, and emit a well-collimated electron beam in the direction of the phosphor screen. The relatively small divergence of the beam is a significant advantage for controlling spacer charging.

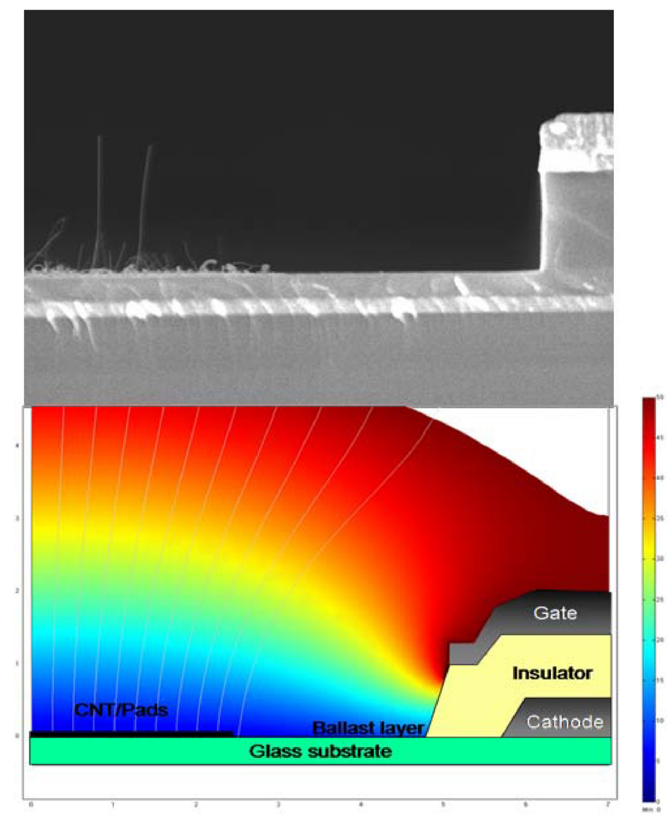

FIGURE 7 — (a) SEM cross-section illustrating the NED emitter structure and (b) finite-element electrostatic model of structure showing equipotential contours and resulting electron trajectories for V_{gate} = 90 V and E_{anode} = 4 V/µm.

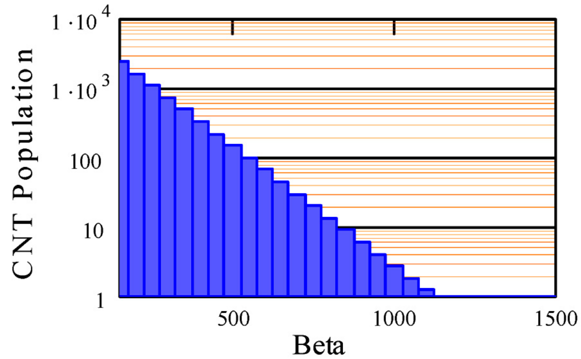

FIGURE 8 — Distribution of the field enhancement factor beta for CNTs HF-CVD film. The CNTs population, their length, and their radius to calculate the β factor were measured by HRSEM imaging

2.4.2 Collective emission of CNTs in a pixel

Nanotube films behave contrary to the emission of a single CNT that follows the basic Fowler–Nordheim (F–N) theory determined by the following current-field equation[11];

$$I(\beta) = aS\beta^2 E^2 \exp\left(-\frac{b}{\beta E}\right),$$

where β is the amplification as previously mentioned, S is the CNT emission area, and a and b are elliptic functions considered constant (assuming a CNT work function of 5 eV).[12] In reality, CNT films contain a population of emitters with a distribution of beta. Each pad contains a random sampling of emitters from the population. Each pad might contain from 1 to hundreds of nanotubes. In addition, each subpixel contains hundreds of such pads. Consequently, the pixel current cannot be determined from the single-emitter Fowler–Nordheim expression above; it must be computed with statistical analysis.

Typical films grown by thermal CVD and HF-CVD produce a distribution of β factor which is exponential.[5,12] We found that the distribution of our CNT film grown by

HF-CVD exhibits an exponential dependence upon the field-enhancement β expressed by

$$n(\beta) = \frac{N_o}{\beta_o} \exp\left(-\frac{\beta}{\beta_o}\right),$$

where N_0 is the CNT density and β_0 is the mean value of the distribution.

The quantitative distribution of the β factor of our CNTs film was characterized by SEM over a large number of pads. The result plotted in Fig. 8 exhibits the exponential distribution with a high population of CNT emitters in the low field-enhancement range ($\beta \sim 250$) and a low density with high field enhancement ($\beta > 750$).

We also found that the emission performance can be adjusted by tuning the CNT length or diameter and by increasing the CNT population of high β per pads to the limit of electrostatic shielding effects. Using FEMLAB simulation, we verified that optimum emission current density is obtained when the CNT separation distance is about 2 times their height.[12] For a CNT film with a vertical emitter height of 1 μm, this corresponds to an ideal density of around 2.5×10^{11} emitters/m^2, or just as six emitters of this length per 5×5-μm^2 pad. The CNTs density and their β factor distribution play a crucial role for the field-emission properties. A CNT density $N \sim 10^{11}$/m^2 and a $\beta_0 \sim 125$ are the values extracted from the distribution trend line exhibited in Fig. 8. This range of values for the mean distribution β_0 has also been reported.[13,14]

In principle, the pixel current and inter-pixel short-range uniformity can be calculated when the β factor distribution, nanotube density, and ballast resistor value are known. Interestingly, the population of nanotubes on any given 5 × 5 μm pad is only a small subset of the overall distribution, and the likelihood that two or more nanotubes have β factors that fall within 5% of each other is small. The result of this is, to a good approximation, that each pad behaves like the nanotube with the highest β factor on the pad. This is especially true for typical beta distributions that we observe and for cases where the number of nanotubes per pad is smaller than 30.

In order to compute the overall current per subpixel, the distribution of nanotubes must be used to calculate the distribution of pad currents. The pad current distribution must then be used to calculate the subpixel current distribution. With the above β factor distribution and number density of CNTs, it is clearly possible to obtain a bright and spatially uniform display.

In summary, CNT films of low density yield low currents because the emitter concentration and the β factor are low. For high-density CNT films, screening effects reduce the field enhancement and thus the emitted current. For films of medium CNT density, there is an ideal compromise between the emitter density and the CNT partition distance, which is sufficiently large to avoid screening effects.[15]

The catalytic HF-CVD growth technique produces a self-organized CNT films with superior density, field enhancement, and orientation characteristics. CNTs which initially provide negligible emission current, as a result of lower field enhancement factor or screening effects, provide a valuable "reserve" of emitters. In the event of the failure of the best emitter per pad, there is a supply of emitters available for a slight increase in gate voltage. Consequently, the NED cathode structure is less sensitive to emitter failure and enables very long display lifetimes.

FIGURE 9 — Packaged 4.6-in.-diagonal NED (0.726-mm pixel) showing a color video image of a parrot.

3 Display performance

Like most FPDs (PDPs, OLEDs, *etc.*), a NED is composed of a matrix of addressable pixels. The simple design of the display structure is capable of providing CRT-like performance, including high luminance and contrast, rapid video response, unrestricted viewing angle, and excellent color capability and image uniformity.

To demonstrate NED technology, the 4.6-in.-diagonal cathodes currently being developed have a pixel size of 0.726 mm which is equal to that required by a large-screen HDTV display (Fig. 9). This 4.6-in.-diagonal demo can be

FIGURE 10 — Two color images on NED demonstrators depicting the excellent color gamut representative of CRT (P22) phosphors.

regarded as a segment of a 42-in.-diagonal 16:9 HDTV (1280 × 720) or a 63-in.-diagonal HDTV (1920 × 1080).

3.1 Luminance

The NED uses conventional CRT phosphors (P22) which exhibit fast decay times (typically between 50 and 500 μsec). But, unlike a CRT, our drive scheme turns on an entire row at a time, substantially increasing the beam dwell time at each phosphor. Consequently, with longer excitation time and shorter decay time, the phosphor saturation efficiency is improved, even at 4000–8000 V on the anode (Fig. 10). For a given luminous efficacy of the RGB P22 phosphors,

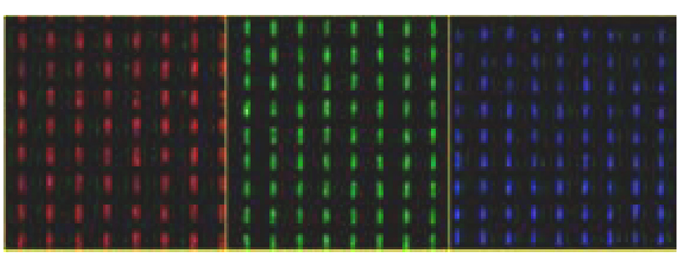

FIGURE 11 — R, G, and B subpixel pattern images showing the color selectivity of a NED at a 3000-V screen voltage and a 1.1-mm cathode-to-anode distance.

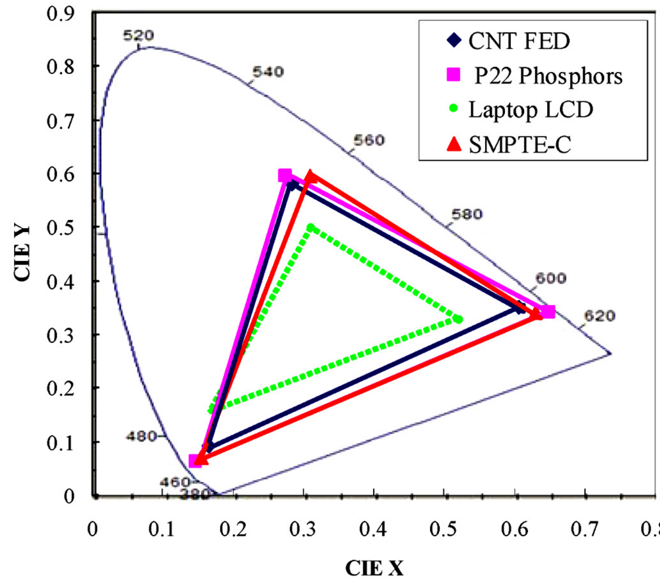

FIGURE 12 — Color coordinates of a NED plotted against the 1931 CIE Chromaticity Diagram. The measured points (◆) are close to the intrinsic phosphor color (■). The NED color gamut substantially exceeds that of a commercial laptop's LCD screen (▲).

the display luminance depends on the current density and on the electron energy impinging the phosphor dots. The typical operating conditions of a NED are as follows: an anode voltage of 4400 V, a total gate voltage of 90 V, and a switching voltage of 45 V and a 1/240 duty cycle (before the contrast-enhancement filter). The anode-to-cathode gap distance is 1.1 mm. Under these conditions, with an anode phosphor fill factor of 47%, the P22 phosphors deliver a white screen luminance of 350 cd/m^2 at 1.8-mA/cm^2 peak current density. Since NED cathodes are capable of delivering more current at the screen and the anode-voltage operating point can be substantially increased above 8000 V, we have a means of obtaining luminance in excess of 1000 cd/m^2 if desired. In fact, recent displays built with a 1.8-mm gap and operating at 6800 V have demonstrated >700 cd/m^2 at an equivalent 1/360 duty cycle.

3.2 Color selectivity and color purity

As shown in Fig. 11, the NED color selectivity is measured by addressing one color RGB image at a time and verifying the other non-selected color phosphor dots are not emitting light. In other CNT-based FEDs, the luminance of non-addressed color dots can be "non-zero" due to the electron beam divergence. NED achieves color selectivity by minimizing the divergence of the electron beam so that the beam strikes only the corresponding phosphor.[1]

As seen Fig. 12, the color coordinates of NED phosphors have been measured. The x, y values plotted for the NED are remarkably close to those of the phosphor screen measured with an electron gun in a vacuum system.

In view of these results, one can conclude that a NED exhibits excellent color purity and color saturation. The color is better than commercially available products. The color gamut of our display can be further enhanced by using starting P22 phosphors with better color points (especially green P22) and by optimizing the phosphor dot layout.

3.3 Artifacts and uniformity

3.3.1 Video artifacts

Unlike other FPDs (*i.e.,* LCDs, PDPs), NEDs do not show evidence of image artifacts associated with fast motion video, (*i.e.,* edge contouring or blurring). The sequential row scanning is fast enough and the decay times of the P22 phosphors are short enough to eliminate such a problem.

3.3.2 Short-range uniformity

In all matrix displays, the luminance of each color dot is determined by local operating conditions. Variation in these parameters causes short-range non-uniformity.

High-quality NEDs must maintain short-range uniformity variation below the eye's detection threshold. We define the short-range non-uniformity as the standard deviation of the brightness of a group of pixels over the mean. For a 42-in.-diagonal display with a 0.726-mm pixel pitch, the optimal viewing distance is 2–3 m, the contrast modulation threshold is thus approximately 5% using our metric.

As discussed in section 2.4.2, the β factor distribution directly affects the short-range uniformity. Clearly, control of the β factor distribution through growth controls the uniformity. In addition, there are two additional factors which act as low pass and high pass filters for the beta distribution, significantly tightening the β factor distribution beyond that of the growth. The first factor is the "pad rule" and the second is the ballast resistor.

The "pad rule" is simply the observation that the emission from a pad is statistically the same as that of the emitter with the best beta factor on the pad. The effect is to remove the contribution from all low β factor nanotubes in the distribution. The "pad rule" is a high-pass filter.

The ballast resistor acts as an active "electron valve" by limiting the overall current from each emitter group. The resistor limits the current from the small population of high β factor nanotubes, making these CNTs behave as if they have a much lower β factor. The ballast resistor acts as a low-pass filter for the β factor distribution.

As seen in the schematic in Fig. 1, each CNT-covered pad forms an individually ballasted emitter group, and there are many emitter groups behind each phosphor subpixel. In our current design, there are more than 200 individually ballasted pads (5×5 µm) per subpixel. These statistics, in combination with a ballast resistor of appropriate value (in the range of 10^8 Ω), deliver good short-range uniformity.

During the previous year of NED development, we halted the nanotube growth process in order to complete key stages of the structure development. With the existing design and process, we showed a short-range uniformity below 8% (standard deviation/mean) without optimization. We are now in the process of adjusting the nanotube growth process and structure to produce a short-range uniformity below 4%. Computations with the β factor distribution, the ballast resistor, and the structure factors show that obtaining this value is clearly feasible.

Finally, the distribution in β does not impact the gray-scale rendition because the NTE device uses time-domain-based pulse-width modulation, not amplitude modulation. The short-range uniformity for all gray-scale fields will be the same as for a full white screen.

4 Conclusions

In conclusion, we developed an NED based on a simple design structure made with a forgiving manufacturing process. The CNT-based FED is capable of providing CRT-like performance characteristics including high brightness and contrast, rapid video response, unrestricted viewing angle and excellent color capabilities. The demonstrator device, a 4.6-in.-sub-section of a 42-in.-diagonal HDTV display, operates at a low swing voltage of 45 V, enabling the use of low-cost driver electronics. Preliminary NED video-performance results demonstrate the potential of this technology as a new alternative for large-area HDTV display applications.

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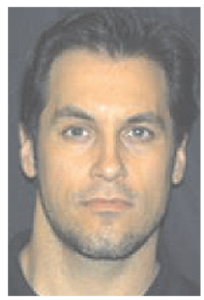

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