Quantum Dot Applications in LCD Displays

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ABSTRACT

Abstract: Quantum Dot (QD) technology offers the promise of efficient and relatively inexpensive liquid crystal displays (LCDs) with a large color gamut. Quantum dot displays now offer a variety of high color performance devices for applications ranging from 3" diagonal hand held smart phones to +85" diagonal TVs. Market research indicates that people clearly prefer these high color displays. Based on the ability to tune the emission wavelength and the narrow emission spectra, QDs are employed for use in LCD's to improve the color gamut. The QDs produce a white backlight with very narrow and well defined primary colors. The primary colors can then pass through the color filters and transmit saturated primaries generating large color gamut displays. In order to make a commercial LCD application possible, a delivery format that maintains an air free environment and is easy to handle is required. This review will explore the application and material properties required to bring this technology to commercial success.

Keywords: LCDs, quantum dots, QDEF, color, color gamut

1 OVERVIEW OF QUANTUM DOTS

Quantum dots (QDs) made from nano-semiconductor materials are highly efficient phosphor crystals. When pumped with blue light, they emit photons in a narrow spectral distribution with a peak wavelength (λ_{peak}) based on the size of the quantum dot. The narrow spectral distribution and tunable peak wavelength of the quantum dots make them ideal for producing large gamuts in LCD displays.[1][2]

The first QD enabled LCD products have now reached the market. QD displays that meet or exceed higher color gamut, such as DCI-P3 and Adobe RGB color space, are now available. Consumer research shows that people prefer displays with larger color gamut.[3] Larger color gamut translates into a richer color experience for the viewer.

Within the last few years, several quantum dot manufactures have developed or announced large scale production facilities. Moreover several partnerships have been announced between the QD suppliers and film/component manufacturers to produce quantum dots materials for consumer display products.

Quantum dots work by absorbing relatively short wavelength light and emitting a narrow spectrum of light at longer wavelengths. The emitted peak wavelength depends on the size of the quantum dot. For example, a 3 nm quantum dot will emit saturated green light (λ_{peak} of ~535 nm and FWHM of ~30 nm) while a 7 nm dot will produce saturated red light (λ_{peak} of ~630 nm and FWHM of ~35 nm). By tailoring the size of the dot, the emitted light can be closely tuned to the desired wavelength to within ~1nm.

When emitted light from green and red quantum dots are combined with the non-converted blue light, the result is white light with narrow spectral peaks corresponding to the three primary R, G, B colors. When this light passes through the color filters (CFs), the subpixels transmit saturated primaries that can be regulated and mixed to create a large color gamut.[2]

In conventional displays using white YAG (yttrium, aluminum and garnet) LEDs the light from the BLU has significant amounts of non-primary, intermediate wavelengths. This intermediate flux is, at best, absorbed and reduces system efficiency or, at worst, leaks through more than one color filter and reduces color gamut. In other words, the presence of these non-primary colors prevents the LCD from efficiently producing saturated reds and greens.

2 QUANTUM DOTS IN LCDs

In order to incorporate QDs into an LCD display, the QD need to have a carrier system. This systems needs to protect the QDs from air exposure (moisture and oxygen) and allow the QDs to absorb blue light and emit green and red light. Several different options including having the QDs on the LEDs, directly in front of the LEDs or in the recycling cavity have been utilized in display systems.

However, the optical and lifetime performance of the QDs is affected by exposure to heat and flux. Increased exposure to either high temperatures or high flux levels reduces the QD efficiency and lifetime. These sensitivities have helped to shape the strategies for integrating quantum dots into an LCD.

In one possible approach, quantum dots are incorporated directly on the LEDs. In this "on-die" approach the environmental conditions (temperatures and flux levels) to which the QDs are exposed is extreme, and the resulting reliability (lifetime) of the system is insufficient for most LCD applications.[4]

In a second approach, the quantum dots are encapsulated in a glass tube or "rail," which is positioned between the LEDs and the lightguide plate. This is termed the "on-edge" geometry. The disadvantage of this architecture is that the dots are still exposed to relatively high temperatures and flux from the LEDs, which can affect their efficiency and lifetime.[4] In addition, rails add another mechanical element that must be located along the edge of the display, which affects design flexibility and is not practically scalable to smaller display sizes with limited bezel area. Furthermore, this approach is not appropriate for direct-lit backlight systems.

3M Quantum Dot Enhancement Film (3M™ QDEF™) provides an alternative geometry for deploying quantum dots. This film approach further reduces exposure to high temperatures and flux conditions.[4] Additionally, a film approach offers several other advantages. First, having the QDs in the recycling cavity reduces the concentration of dots needed since light passes through the dots multiple times. The film architecture requires little to no structural change to a BLU architecture. Finally the system allows the flexibility of having several color gamut options using different films but with the same LCD system components.

QDEF has a film construction that can be generally seen as three layers consisting of an upper barrier film, a middle QD matrix material layer containing a small amount of quantum dots dispersed in polymer, and a lower barrier film. (See Figure 1) The amounts of quantum dots, and the ratio of green to red dots, are determined by the white point specifications of the display, the recycling efficiency of the back light unit, the color filter transmission, and the overall thickness of the film.

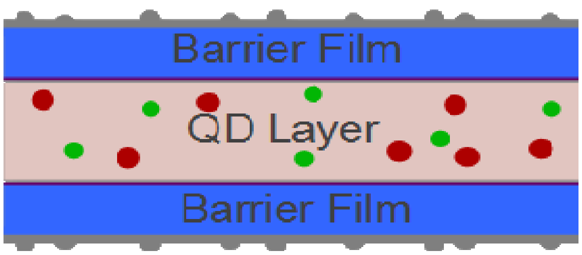

Figure 1. QDEF schematic: a layer of quantum dots dispersed in a polymer matrix between two barrier layers.

Integrating QDEF into the LCD architecture is straightforward. Currently, most LCDs have a bottom diffuser film in the BLU, positioned between the lightguide plate and the brightness enhancement films. Because QDEF has diffusive properties, it can be used in lieu of the diffuser sheet. The BLU's other components (i.e., the reflector, prism films and reflective polarizer) can stay the same.[1] (See Figure 2) Therefore, the only fundamental change is that the typical white LEDs in the BLU have to be replaced with blue LEDs.

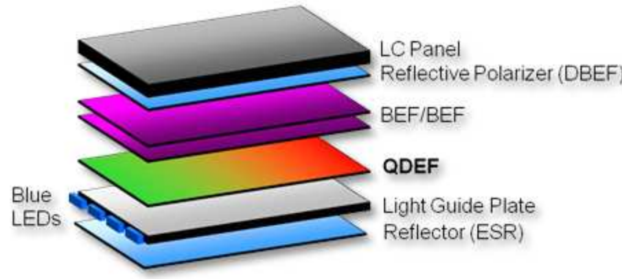

Figure 2. QDEF is minimally disruptive to a typical LCD architecture. QDEF can simply replace the current diffuser film. The only other significant change needed is to replace the white LEDs with blue LEDs.

3 QUANTUM DOT FILM CONSTRUCTION

3.1 Quantum Dot Protection

To make a long lasting QD film product, the QDs are sandwiched between 2 layers of barrier film. There are several demanding requirements for this protective film. First, the film must have excellent air barrier properties. Since QDs are susceptible to oxygen and water and need long term protection, the barrier layer needs to have good water (WVTR) and oxygen (OTR). This barrier also needs to be flexible and transparent. In order to make a robust product, the film construction needs to be flexible and tough.

Furthermore, the barrier film must have low absorption, especially in the blue wavelength range. Since the QDEF film is placed in the recycling cavity, any absorption is exaggerated by the multiple passes. When the blue light is absorbed it not only reduces the amount of green and red produced, but also effects the final white point. The film toughness is imparted from the PET substrate.

The QDEF product must also have an anti-wet out layer. In many cases, the film is placed directly above the light guide plate. The anti-wet layer eliminates optical coupling that can destroy the display uniformity. This is especially important for a light guide plate, but can also occur with other backlight films.

The sandwich construction (see Figure 1.) provides excellent protection to moisture and oxygen for the major surfaces. However in order to convert the part to fit the display, the edges of the construction are cut. This leaves the edges open to air ingress. Several methods have been used to eliminate or reduce this edge ingress.

3.2 Matrix Materials and Edge Ingress

Edge ingress is defined as water and/or oxygen exposure through an exposed edge causing a visual appearance change over a small area. As shown below (see Figure 3), the edge ingress can be seen in a small area along the edge of the film sample.

To make a robust product the edge ingress must be eliminated or minimized. Several methods to address this issue have been attempted, including edge sealing methods such as heat sealed polymers and foil tape. However, both of these methods require several millimeters for edge space to provide an effective seal.

As previous mentioned, the barrier film provides good protection to the major surface. Thin transparent barrier films with WVTRs less than 1 x 10^{-2} (g/m^2-day) are readily available. However, most polymer materials that could be used to support the QDs and adhere the barrier films together have much higher transmission rates. Typically, polymer materials are in the ~5-100 (g/m^2-day).

The other issue posed by the edge ingress is the lifetime concerns. In other words, will the edge ingress continue to grow during the product lifetime? We have found matrix materials that can support the QDs (excellent lifetime, External Quantum Efficiency, and mechanical stability), and provide minimal edge ingress.

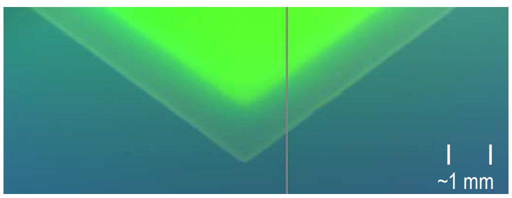

Figure 3. Quantum Dot film construction showing edge ingress after accelerated aging.

The edge ingress has been measured as a function of time and temperature. For our system, the edge ingress occurs rapidly in the beginning and then slows to a near asymptotic value. For our first generation QDEF product, the edge ingress appears to reach a maximum value of ~1.2 mm. As stated above, this is less than many of the edge sealing techniques.

The change in ingress rate and apparent stopping of the progress inward was determined to be related to a diffusion limited reaction model. The ingress distance slows greatly over time after the initial time. The darkening of the ingress resin (see Figure 3) is caused by the oxidation of the QDs due to oxygen diffusion from the open edges.

Physical aging experiments show that the ingress rate dramatically slows during aging. We believe the ingress stops at the edge due to diffusion limited oxidation (DLO) in the polymer matrix. The polymer thermally oxidizes causing oxygen diffusion to slow exponentially establishing a static oxygen concentration gradient. Ingress is a function of oxygen concentration gradient and oxidation rate of QDs.

The oxygen is consumed by the thermal oxidation of the polymer matrix in a continuous process. This forms a static oxygen concentration gradient with the maximum at the open edge and minimum where the ingress halts. The ingress versus time is a function of the oxidation rate of the polymer matrix, oxidation of the QDs and the local concentration level of oxygen in the polymer.

$$\frac{dC}{dt} = D\frac{\partial^2 C}{\partial x^2} - K_1 C \qquad (1)$$

D = oxygen diffusion coefficient
K_1 = oxidation rate constant

Equation 1, shown above, was used to model the edge ingress with time. As described above, the oxygen diffusion is balanced by oxidation of polymer (oxygen consumption). Polymer degradation involves many components and is usually solved using a closed loop oxidation mechanism where different products initiate, propagate and eventually terminate. Because QDEF ingress appears to reach steady-state, the model only includes one rate constant (K_1). Good agreement between the modeled data and measured data is shown (see Figure 4) in the figure below.

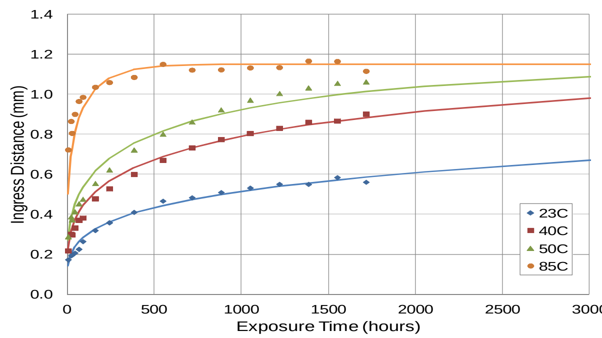

Figure 4. QDEF Edge Ingress data versus model predictions for several temperature conditions.

Eventual polymer loss due to oxidation will occur allowing further ingress. Polymer loss is expected to take greater than 30,000 hrs at 50C to affect ingress.[5] High temperature accelerated aging tests have shown ingress to essentially halt and the polymer loss effect to not be significant.

3.3 White Point Control

To reach the desired white point (WP) (x,y or u',v') in the LCD display, the relative amount of the primary R,G,B must be controlled. Several factors must be considered to have accurate control of the final product. Factors related to the QDs such as quantum yield, peak wavelength, full width half maximum, and QD reabsorption must be understood. Other aspects of the QDEF construction must also be considered, such as any absorption from the barrier films or the matrix materials, optical path length (thickness) and scattering. Finally, system features must be considered. The amount of recycling, the wavelength of the blue LEDs, and the color filter spectrum must be taken into account.

As shown below (see Figure 5), controlling the optical path length and/or the concentration of Green and Red QDs, the desired white point can be moved from the blue to the yellow. By adjusting the Green to Red QD ratio, the WP can be moved along the green/red access. This allows control to reach the desired WP.

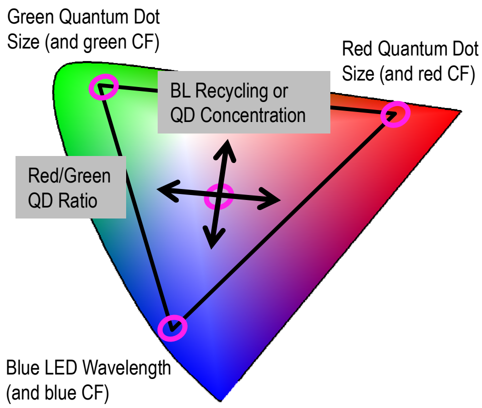

Figure 5. Control of White Point in QDEF.

During the manufacturing process for making QDEF, all the factors listed above must be controlled to make a constituent product that meets the specifications. With the purpose of having the ability to control the WP, the matrix, Green and Red QD are monitored and controlled independently. The film WP is monitored as the product is being produced. The schematic shown below (see Figure 6) details the WP control during the manufacturing process.

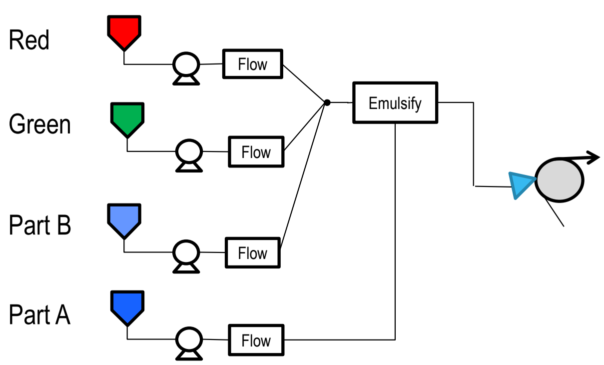

Figure 6. White Point Control Schematic

This control/processing scheme gives the ability to produce QDEF products that meet product specifications for many different applications. This allows high color gamut displays to be produced across the LCD display market space.

4 CONCLUSIONS

The use of quantum dots in LCD devices offers the opportunity for energy efficient, relatively inexpensive high color experiences for end users. Apart from pure esthetics (which alone may be sufficient) there are many good reasons why the display industry would want to offer high color gamut solutions to consumers. Quantum dot displays now offer a variety of high color performance devices for applications ranging from 3” diagonal hand held smart phones to +85” diagonal TVs. In order to make a commercial LCD application possible, a delivery format that maintains an air free environment and is easy to handle is required. A detailed QDEF product construction with barrier film, matrix material and manufacturing process has been presented. This construction and process provide a reliable product to provide high color gamut in LCD displays.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge all those not listed above who helped in the data collection and information gathering that went into this paper.

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