Quantum-Dot-Based Color Filter Array for Reflective Displays

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Abstract

Fabrication process and testing results are reported for reflective color filter arrays incorporating quantum dot ink layers. Approximately 1.35x higher total reflectivity and 2.5x higher on-axis luminance in respect to conventional absorptive color filters are demonstrated. The components can be used in reflective or transflective liquid crystal or electrowetting displays.

Author Keywords

Reflective display; color filter; quantum dots; LCD; electrowetting.

1. Introduction

It is of no surprise that reflective displays remain a topic of active interest both in the industry and in the technical community. They are easier on the eyes than emissive displays and allow for much longer battery life, which is especially important for portable devices. Currently, an undisputed champion in the field is the electrophoretic displays. There are an estimated one billion E-ink devices in use in the world today, including 130 million e-readers. While the technology started its life as black-and-white only, full-color devices were recently introduced [1], and the performance keeps steadily improving [2], although the colors still look washed out. However, the most significant shortcoming of the E-ink displays is the slow refresh rate, which is approximately one second for the latest generation full-color panels, making displaying video impractical.

At present, there are only two known display technologies capable of live video refresh rates – liquid crystal (LCD) and electrowetting (EW) displays, and they struggle with their own challenges. EW displays have the advantage of higher reflectivity due to not using polarizers, but making small enough pixels to achieve a good resolution is very difficult [3]. LCD technology is very advanced, and the resolution can be very high, enough for near-eye displays, but even the best reported devices [4] have a reflectivity of only ~ 10%. A major source of loss, roughly 2/3, in RGB side-by-side display designs is due to the absorptive color filters (CF). As was suggested in [5], this loss can be partially negated by introducing luminescent materials, or phosphors, in the green and red sub-pixels, which allows to "recycle" the blue and red ambient light. One of the best currently available phosphor materials, with high quantum efficiency and narrow spectral lines, are polymer inks filled with colloidal quantum dots (QD), which are already widely used in the industry, both in LCD backlights and in novel types of displays such as QD-OLED.

In this work, we report on the fabrication and testing of the reflective CF arrays incorporating QD layers. About 1.35x increase in effective total reflectivity and a 2.5x increase in on-axis luminance are observed, compared with the conventional CF array without QD.

2. Sample fabrication

The process for fabricating the reflective CF arrays with QD layers is as described below.

To serve as a back reflector, the enhanced aluminum (thin Al layer followed by a single TiO_2/SiO_2 pair) mirror coating with an average 94% reflectivity in the visible spectral range is deposited on a 6-inch glass substrate. The substrate is rinsed with deionized (DI) water. The metal alignment keys are fabricated using a photolithography process. The red (R), green (G), and blue (B) CF are fabricated using the following process. Hexamethyldisilazane (HMDS) treatment is applied to improve the photoresist adhesion to the substrate. The R CF photoresist is spin-coated and pre-baked at 110 °C. An exposure process is done using an i-line (365 nm) stepper, and a development process is using a potassium hydroxide (KOH) spray gun. A post-bake at 230 °C completes the fabrication of the R CF, and the same process is repeated to fabricate the G and B CF. The black pixel-defining layer (PDL) fabrication process begins with spin-coating the black PDL material and pre-baking it at 100 °C. The exposure process is performed using an i-line stepper, and the development process uses the tetramethylammonium hydroxide (TMAH) spray gun. Post-baking at 100 °C is the last step in fabrication of the black PDL. The fabrication of the conventional absorptive CF array is thus completed, and one sample is set aside to serve as a reference.

The additional performance-enhancing layers are fabricated using inkjet printing. R and G inks are used for the R and G subpixels, and TiO2 particle-filled ink is for the B subpixels. The inks were filled into the subpixel areas via an industrial inkjet print head and cured using 395nm UV light. The QD ink for green and red pixels, TiO2 ink for blue pixels, and CF are industrial materials synthesized by CHEME Co Ltd of Korea. The black PDL photoresist for QD pixels is an industrial material synthesized by DUKSAN Neolux Co Ltd, South Korea.

Figure 1 shows a schematic of the plane view and cross-section of one pixel. The overall pixel size is 370 µm × 370 µm, and the sub-pixel size is 175 µm × 175 µm. After singulation, each individual sample has a 67 × 67-pixel array on a 30 mm × 30 mm substrate with an active area of 24.79 mm × 24.79 mm.

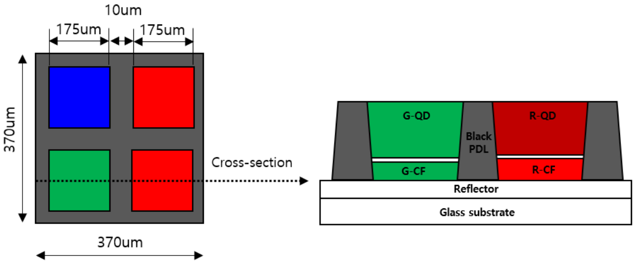

Figure 1. Schematic diagram of QD pixel structure.

The sub-pixels are arranged in a BRGR pattern. The black PDL with the inter-sub pixel width of 10 µm is used to prevent color mixing between subpixels.

Figure 2 shows the measured transmission spectra of the CFs. The thicknesses of the red, green, and blue CF films are approximately 1.78 µm, 1.82 µm, and 2.05 µm, respectively. As is evident from the graph, the filters have high transmittance at 460 nm, 530 nm, and 650 nm regions, as intended. Figure 2(b) is an optical microscope image of CF and black PDL patterned using the photolithography process.

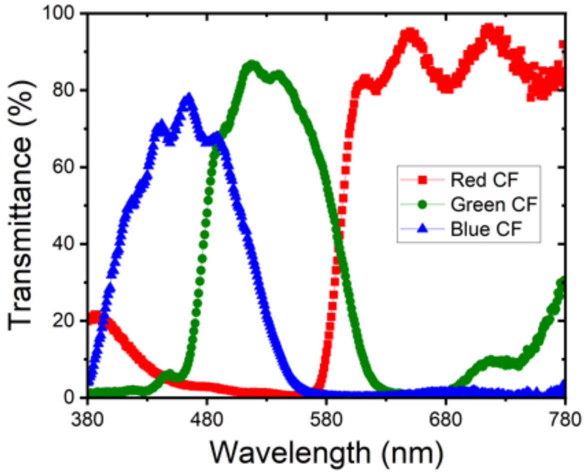

Figure 2. Transmission spectra of the CF.

Figures 3(a) and 3(b) are optical microscope images of the R, G, and B CFs and black PDL, taken at different magnifications. They confirm the high quality of the patterning with a sub-pixel width of 175 µm and a black PDL width of 10 µm. Figure 3(c) is a photograph of a sample that completed the CF and black PDL processes on a 6-inch glass substrate.

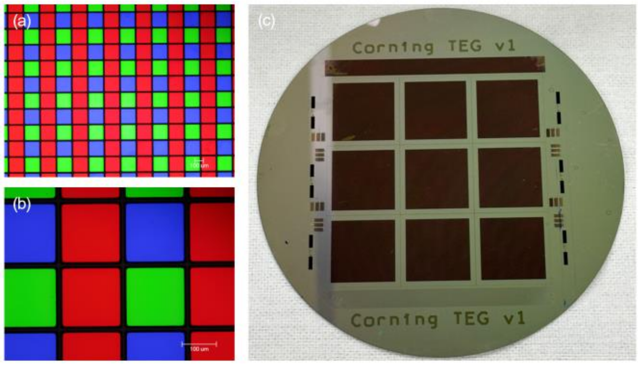

Figure 3. Low (a) and high (b) magnification optical microscope images and a photograph (c) of 9 completed CF arrays defined by the black PDL on a 6-inch substrate.

Figure 4 shows SEM images taken after forming the additional performance-enhancing layers on top of the CFs. As can be seen from the cross-sectional image of Figure 4 (a), the thickness of the TiO2-filled ink layer in the blue sub-pixel is 8.5 µm. The image in Figure 4 (b) confirms that the thickness is uniform over the area of the sub-pixel. Figure 4(c), taken after filling in the green and red sub-pixels with the QD ink, shows that the thickness is uniform throughout the entire array.

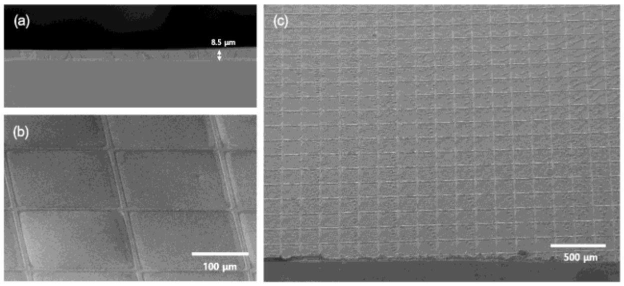

Figure 4. SEM images of pixel arrays filled with (a), (b) TiO_2 ink, and (c) QD ink.

Figure 5 is an image of the fabricated QD pixel array taken by a confocal laser scanning microscope at an excitation wavelength of 405 nm. The green and red QD emission images in the fabricated BRGR sub-pixel structure have a perfect square shape and uniform brightness, confirming that the openings in the PDL template are fully filled and the thickness of the layers is uniform. The blue subpixel areas appear black because the TiO2-filled ink does not emit blue light.

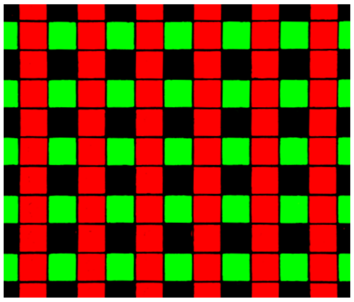

Figure 5. The fluorescence image of the QD pixel array measured by a confocal laser scanning microscope.

3. Test results

To test the performance of the fabricated color filter arrays, we first measure the total integrated reflection. The sample is placed behind an integrating sphere, and a collimated white LED (6500K) is used to illuminate the sample through the sphere.

Figure 6. Total reflection spectra for the conventional CF array and the sample with QD layers.

The light collected by the sphere is passed by a multimode fiber to an Ocean Optics QE 65 Pro spectrometer, recording the reflection spectra. The measurement results are presented in Figure 6. As can be seen from Figure 6, the total reflection is significantly enhanced in the QD sample, by about 1.35x in the green (550nm) and as much as 2.5x in the red (650 nm). The value of the effective reflectivity in red reaches as high as 0.9, which would be typical for a polished aluminum mirror. We note that this difference between green and red is not only because red QD ink is excited by both blue and green spectral components of the white LED output but also because each of the pixels of the array has two red and only one green sub-pixel. For a better color balance, it would be a better choice to have two green and only one red sub-pixel in every pixel or to change the relative sub-pixel size, but this has only become obvious after the fabrication and testing were completed. It is interesting that the reflectivity in blue (450nm) is also increased by about 1.15x, while no blue QD are used. This is due to the TiO_2 particle-filled ink applied to the blue sub-pixels of the QD samples having a slightly higher reflectivity than the blue CF surface in the reference sample.

While the total reflectivity of the reflective display panel is an important parameter, it does not fully determine the user experience. To emulate the real-life use case, in the second experiment, we use a microscope illuminator (with white 6500K LED sources, like in typical office lighting fixtures) to flood light the samples and a Photo Research PR670 spectroradiometer to record the normal direction luminance spectra. The second experiment results are presented in Figure 7.

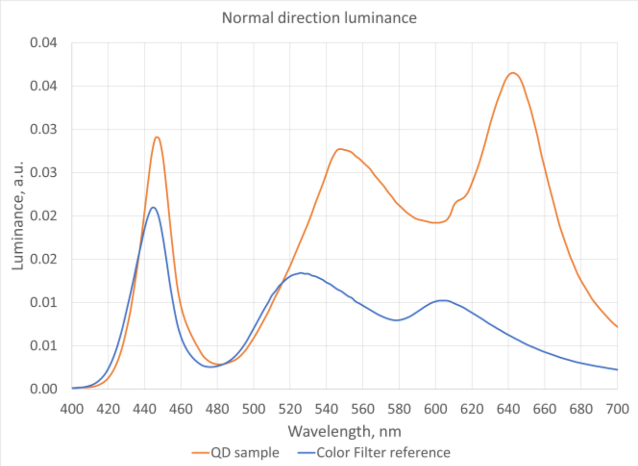

Figure 7. Normal direction luminance spectra with flood white (6500K) light illumination for the conventional CF array and the sample with QD layers

As is evident from Figure 7, the luminance is significantly increased for all three primary colors, with the largest increase still in red. Averaged over the entire spectrum, the QD sample luminance is 2.5x higher than that of the reference conventional CF sample. A larger benefit of QD layers for the normal direction luminance than for the total reflection is explained by the presence of scattering particles in QD inks, which are commonly added to increase the blue light absorption, and, in this case, help redirect oblique light rays perpendicular to the component surface. Also, the emission from QD is isotropic, so there is a probability for an oblique ray to be absorbed and re-emitted in the normal direction. It can be noted from Figure 7 that the peaks of the QD emission are mismatched from the transmission of the CF, indicating that the benefit could be even higher if the CF pigments and QD inks were co-designed.

4. Discussion and Conclusions

In conclusion, we reported on the color filter component using additional red and green QD ink layers to increase the effective reflectivity. The test results confirm a 1.35x increase in the total reflectivity and a 2.5x increase in the on-axis luminance for white light illumination. The component can be used to significantly improve the performance of reflective LCD or electrowetting displays using the so-called upside-down or bottom emitting configuration, where the TFT array is on the top and the color filter is on the bottom glass panel. Since only the color filter component is modified, the design is perfectly compatible with additional performance improvement measures, such as light-shaping diffusers [6] or micro-structured bottom reflectors.

An even more intriguing possibility could be to employ the same concept for a transflective display design. Using QD layers in a transflective LCD was previously described in [7]. To enhance the performance both in reflective and transmissive modes, the bottom reflector can be replaced by a dichroic mirror, such that the blue light from the backlight could reach the red and green QD cells, but the red and green emission from the QD was reflected towards the user [8].

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