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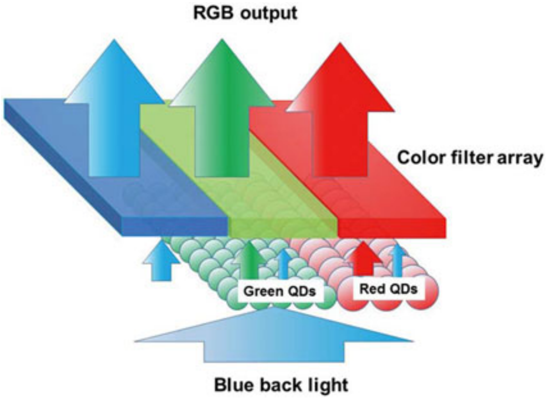

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A Quantum Dot Array for Enhanced Tricolor Liquid-Crystal Display

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Abstract: In the traditional liquid crystal display, at least two-thirds of the energy is wasted by tricolor separation color filter array due to its blocking working principle. In this paper, a well arrangement quantum dots (QD) array, which is excited by blue back light, was fabricated to spatially separate the red-green-blue (RGB) color. This QD array is further placed onto traditional color filter array, by matching the corresponding color filter pixel, in order to eliminate the blue light cross talk. In this case, the energy efficiency of this QD active color filter array no longer depends on its geometric arrangement and absorption properties, but depends on the quantum yield of QDs. Furthermore, 90% Adobe RGB color gamut can be achieved. One advantage of our fabrication method is synthesizing the QDs array onto the substrate directly, without the requirement of dissolving the QDs into other media. This technique may provide a new method to obtain higher color separation efficiency in liquid crystal display (LCD) than the traditional color filter matrix by enhancing the quantum yield of QDs.

Index Terms: Quantum dots (QD) array, tricolor.

1. Introduction

Liquid crystal display (LCD) has been serving as the most successful display technology in recent years, but the competition from the organic light emitting diode (OLED) and the quantum dots light emitting diode (QLED) have started to squeeze the application space for the traditional LCD. The drawbacks for a LCD over OLED and QLED mainly includes the usable power efficiency as well as the display quality measured with color gamut as. The former is indeed true as over two-thirds of the energy is wasted alone in tri-color separation color filter (CF) due to its color filtering, or blocking principle. However, for the latter, the display quality has been substantially improved to catch up the performance of OLED and QLED.

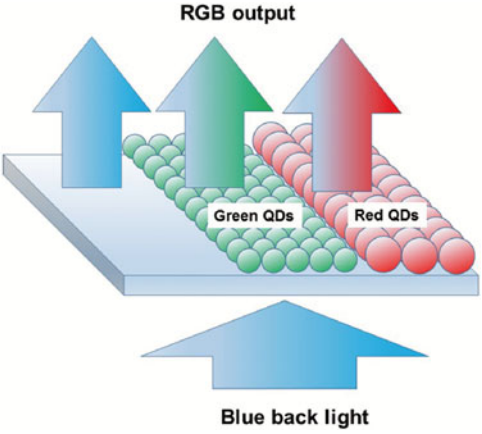


Fig. 1. Scheme of QD array.

In this work, well arranged quantum dots (QD) array is designed, fabricated and tested to show that it is a suitable candidate to substantially improving the performance of a LCD. For the QDs array excited by blue LED as the back light source, by designing the QDs array to avoid the color crosstalk, color gamut approaching 100% of adobe RGB is obtained. On the other hand, substantial improvement of the usable power efficiency is demonstrated and makes the color separation with the efficiency exceeding one-third, hence opening up the possibility to achieve significant improvement for the existing LCD.

One of the key components used in a LCD is a tri-color Red-Green-Blue (RGB) absorptive element in each pixel. Although this is one of the most ubiquitous filter technologies available on the LCD market today, it only has a maximum theoretical efficiency of one-third, because the geometric arrangement and intrinsically wastes at least two-third, of the incoming light signal [1], [2]. Various methods have been proposed to solve this problem. For example, field sequential color technique was used to output RGB color sequentially [3], [4]. Other efforts include color routing technique based on dispersive waveguide array to funnel RGB color into different channel [5]. Recently, QDs backlight by optical or electric field excitation are used to provide a wider color gamut for LCD. In the case of optical excitation, QDs with different sizes are excited by the blue LED and emit red or green light. Such combined combining with the blue LED provides three pure and highly saturate RGB color [6]–[11]. For example, commercial product with QDs backlight such as Kindle fire HDX 7 and Triluminos TV have been introduced by Amazon and Sony respectively, but due to the random distribution of QDs, this product still need tradition color filter with at least 2/3 light wastes [12]–[15].

In the case of electric filed excitation, QDs array for display was already fabricated by Samsung for the QLED display technique [16], However, this product would operate in high temperature (150) and high light intensity, which will reduce the quantum yield and life time of QDs [6]. underline QDs film can also fabricated by printing technique [17]. Furthermore, the QDs array is usually can also be fabricated by using direct laser writing technique [18], such technique is inefficient in manufacturing color filter array with large area up to several tens inches. Blue light excitation QDs array can also be achieved by desolving QDs into photoresist, but surface modification of QDs is required [19].

2. Quantum Dots Array

In this work, we fabricate QDs array on both ITO and traditional absorptive color filter array, based on photolithography technique. Compares to direct laser writing technique, such method is more suitable for fabricating large area devices. Under the illumination of the blue LED, color separation effect and the enhancement of color separation efficient can be observed.

The scheme of QDs array on ITO substrate is shown in Fig. 1. Here, red (625 nm) and green (550 nm) emission QDs and empty area are well arrangement. When these QDs array is excited by the blue light, the excitation light will be transfer to red or green light in the QDs area, while the

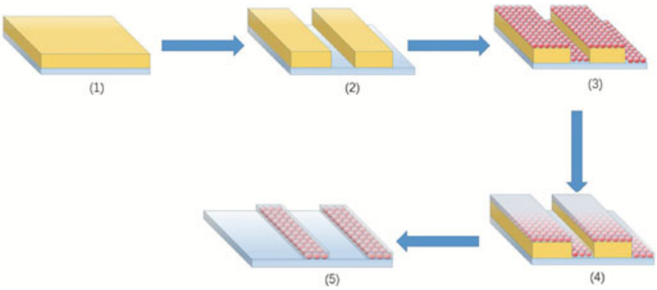
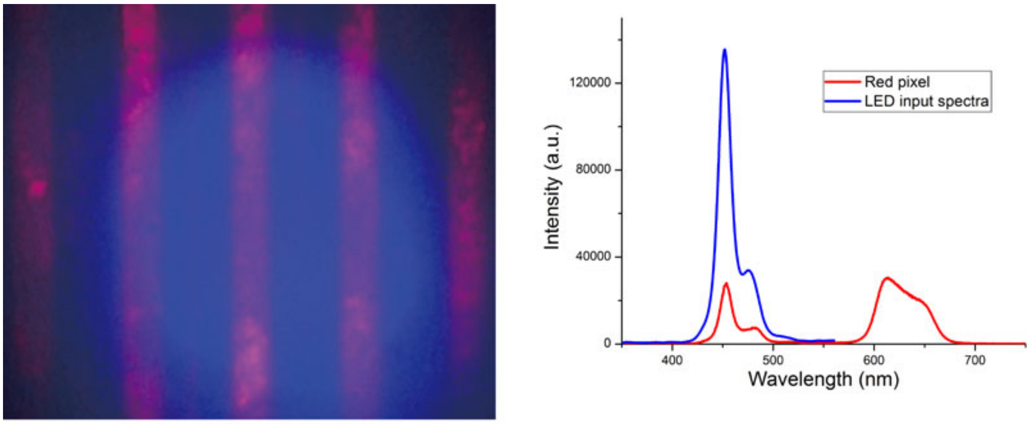


Fig. 2. The fabrication process of QDs array with red QDs.



(a) (b)

Fig. 3. (a) Microscope image of QDs array on ITO substrate. (b) Spectra of a single red QDs pixels. Due to the low transfer efficiency of blue light, the blue back light can be transferred into red light in the position with red QDs. Hence, a serious cross talk of blue light can be observed. The conversion efficiency can be obtained by calculating the area of blue input spectrum and red emission peak, which is about 45%.

empty area passes the blue light. In this case, RGB light are separated automatically through QD array and the energy efficiency of color filter array will be determined only by the quantum yield efficiency of the QDs. Based on the color conversion efficiency is up to 90% [12], the efficiency of tri-color separation can be enhanced.

2.1. Sample Fabrication

The QDs array was first fabricated on an ITO substrate with red emission CdSe/CdS QDs with diameter of 5.9 nm. They are pixelized base on UV photolithography technique, and the silica on the top of the QDs was used to protect the QDs during the fabrication process. The detail of fabrication process is listed below and shown in Fig. 2.

1) Photoresist AZNLOF2035 was spin coated onto the ITO substrate.

2) It was exposed by the UV photolithography machine uPG501 (from Heidelberg Instruments Mikrotechnik GmbH) and developed to fabricate the template. All the pixels are 1-D with 25 m width.

3) Deposit 100 s nm thickness QDs by spin coating the QDs solution with toluene (From Wuhan Jiayuan Quantum Dot Co. Ltd) onto the template. The concentration of QDs solution is 18 mg/ml. The thickness can be controlled by the spinning speed.

4) Deposit 70 nm thick silica on the QDs layer by using magnetron sputtering apparatus to protect the QDs during the fabrication process.

5) Remove the photoresist to get the QDs array by lift-off method.

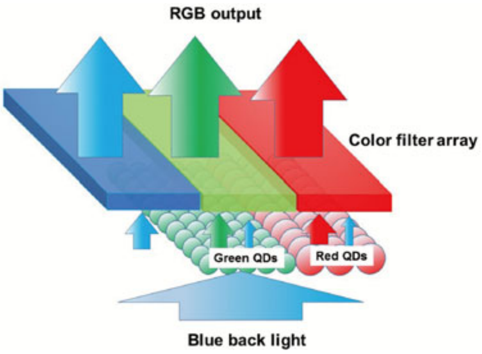


Fig. 4. Scheme of QD enhanced active color filter array.

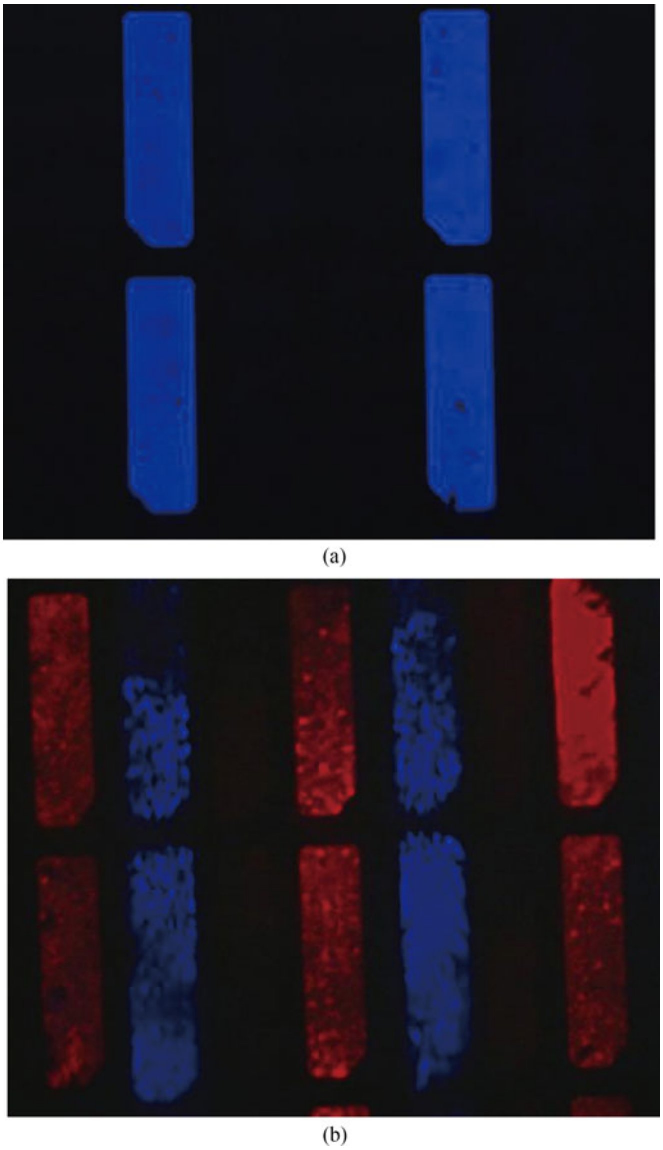


Fig. 5. (a) Microscope image of (a) traditional CF array, and (b) QDs enhanced active color filter array.

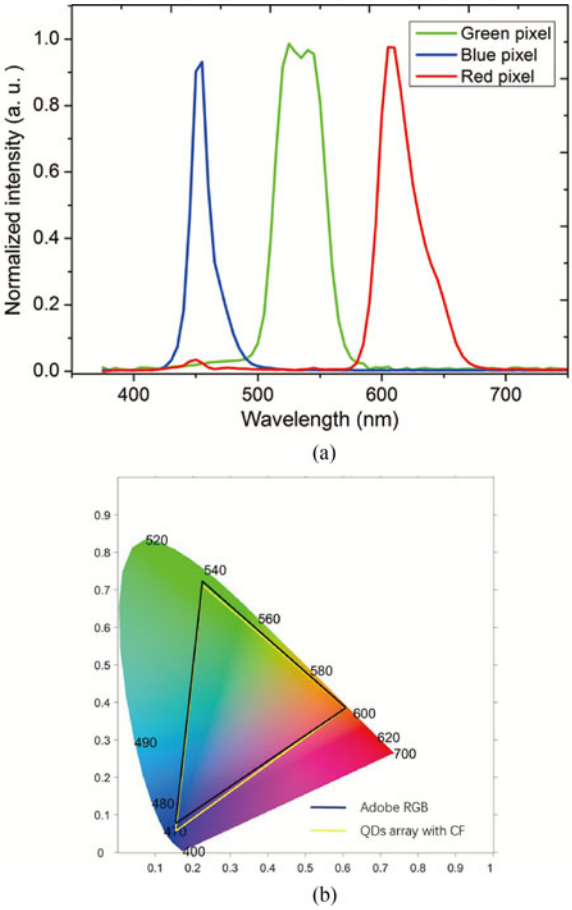


Fig. 6. (a) Emission spectrum observed in a single RGB pixel of QDs enhanced color filter array. Blue light cross talk is well eliminated. (b) Color gamut achieves by emission spectrum QDs enhanced color filter array in (a).

2.2. Measurement Result of QDs Array

The QDs array sample was first examined by a blue LED illuminating microscope (Fig. 3). As excited by the blue light, red and blue color was separated (see Fig. 3(a)). A confocal system is used to measure the spectra of a single red pixel of QDs array (see Fig. 3(b)). The conversion efficiency can be obtained by calculating the area of blue input spectrum and red emission peak, which is about 45%. The result shows the crosstalk of blue light is very serious for QDs array because of the low quantum yield of the red QDs.

3. QDs Array on Color Filter Substrate

To solve the blue light crosstalk problem, we further propose the QDs enhanced active color filter array by placing the QDs array onto the traditional color filter array. As shown in Fig. 4, the RGB light emitted from QDs array will be filtered. Only the required color can penetrate the color filter array, hence output the purified RGB colors in each pixel. Here, the color filter array is only used for purify the RGB color and no longer play the role of color spatial separation, thus the tri-color separation efficiency enhancement can be achieved if the quantum yield of the QDs is high enough. Furthermore, in the display application, QDs array will emit light not only by the illumination of blue black light, but also by the illumination of ambient light. In this QDs enhanced active color filter array, the blue ambient light can be blocked by the filter, and hence, the performance of QDs array under ambient excitation condition can be improved.

The microscope image of the QDs enhanced active color filter array under the blue light illumination is observed in Fig. 5. For traditional color filter array, the transmission of blue light in red area is zero, the transmission light can be only observed in blue pixels (see Fig. 5(a)). However, in the QDs enhanced active color filter array, the red transmission light can be observed in the red pixels due to the red light emission of QDs pumped by blue LED (see Fig. 5(b)).

Due to the poor quantum yield of the green QDs, thicker QDs are required for enhancing the emission. This makes more difficult in the lift-off process and further leads to serious inhomogeneous distribution of green QDs, which is not shown here. Even the poor fabrication, we can measure the spectra of a single RGB pixel (see Fig. 6(a)). The result shows that QDs color filter can provide well separation RGB spectra, and the blue crosstalk is well eliminated. Furthermore, based on the emission spectrum of Fig. 6(a), color gamut of adobe RGB can be calculated to be 99.4%, while this value is just 79% in the traditional color filter array [6].

4. Conclusion

In this work, QDs array was fabricated and excited by the blue LED backlight. Red emission can be achieved in specific pixels to obtain the spatial color separated output without using the blocking principle of traditional color filter array. For the purpose of eliminating color crosstalk and ambient excitation, QDs array was further fabricated onto traditional color filter to get 99.4% color gamut of adobe RGB. In this QDs enhanced active color filter array, the transmission efficiency of the color filter depends on the color conversion efficiency of QDs, but no longer depends on the geometry arrangement and absorption properties of color filter array. It means the most direct method of improving the color conversion efficiency is to improve quantum yield of QDs and makes the color separation with the efficiency far exceeding one-third possible. Besides of improving the quantum yield, increasing the thickness of QDs layer [19], [20] or using the brightness enhancement film to recycle the blue light [6] can improve the color conversion efficiency, as well as further increasing the tri-color separation efficiency. The polarization losing of QDs emission is indeed a serious problem that limits the application of QDs array in tri-color separation in LCD. However, by using Aggregation-Induced Emission (AIE) dye with circular polarized emission [21], such polarization loss can be eliminated. Using well aligned quantum rods is another solution for the polarization problem [22].In our fabrication method the QDs is directly deposited onto the substrate, without the requirement of changing the properties of the quantum dots or other emission dyes for the purpose of dissolving into other solvent such as photoresist, this gives a fixable way to achieve a light emission material array for tri-color separation.

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