Colloidal Quantum Dot Enhanced Micro LEDs

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ABSTRACT

To meet the requirement of full-color and fine-pitched micro-displays, efforts have been put in the research of micro-LED arrays. To use a color conversion layer can alleviate the complexity of mass-transfer in small devices, but the efficiency of the color conversion layer and the micro-assembly methods need to be addressed. We focused on our efforts in colloidal quantum dots and highly efficient micro-LED arrays which shall play important roles for full-color micro-displays.

1 INTRODUCTION

The demand for highly efficient and highly reliable micro display has driven recent increase in the corresponding research and business activities. Many devices have been investigated for potential implementation on micro-display and one of them is micro-/mini- light emitting diodes (LEDs). For the general purpose, there are two separate categories for micro- and mini- LED displays: monochromatic and full-color arrays. If only the required information is needed or the text-content is sufficient, monochromatic display is good enough, and this is already happening in our daily life such as electronic billboards. However, if more complex information is involved or animation is preferred, a full-color content is a must. To illustrate this need, full-color information display has been a highly sought-after item. Three different methods can be implemented for full color scheme: pure color filter method, RGB chips method, and color conversion method. In the traditional design, such as our current TV or computer monitor, a background white light is generated and guided throughout the display panel. The individual pixel can install color-filter element which is basically a band-pass filter for red, green and blue color. While this method is mature and prevailing, the photonic energy lost in the structure is high and shall be improved. Another method is to use self-emissive elements of pure red, green and blue color to form matrices of pixels. Without color filters in the structure, this method could be the most energy-saving design because of the direct photon acquisition without loss. The major issue associated with this scheme is that the wavelength separation among these three colors is large enough to essentially prohibit any monolithic epitaxy on the same substrate. Without direct epitaxy growth of different colors of active materials, one can use either organic light emitting materials or using mass-transfer to assemble RGB together [1, 2]. While the OLEDs have been widely accepted in the current mobile phone and TV products, the concerns on their reliability are still looming. The mass-transfer method, on the other hand, becomes more dominant for mini-LEDs and micro-LEDs with larger sizes due to the limitation of current transfer technologies. For a high-resolution display, for example higher than 1000 pixels per inch (PPI), the sub-pixel size approaches 8 to 9 micron in average, and to move such a small size chip becomes really critical for the manufacture engineering. So for the high PPI display or panel, the third method of color conversion layer becomes quite attractive. In this method, there is another layer of color conversion material which can transform high energy photons into red and green ones. With this capability, one can focus on a monolithic and monochromatic micro LED array using advanced semiconductor fabrication technologies. Usually ultra-violet (UV) or blue color is preferred for the emission wavelength of this micro LED array.

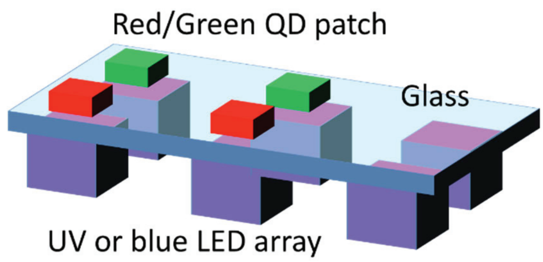

Fig. 1 A conceptual diagram for integrated color conversion layer with micro-LED array.

2 General Design Rule

In this section, we will discuss several different methods to be applied in the color conversion technique. In Fig. 1, the generic diagram of the hybrid assembled full-color LEDs are shown. The basic idea is to have a color-conversion layer with monochromatic LED arrays combined together. With different materials applied in this design, different assembly techniques should be considered. In Fig. 2, three different methods are illustrated, and they are: quantum-dot-photoresist (QDPR), inkjet spray, and nano-scale imprint template.

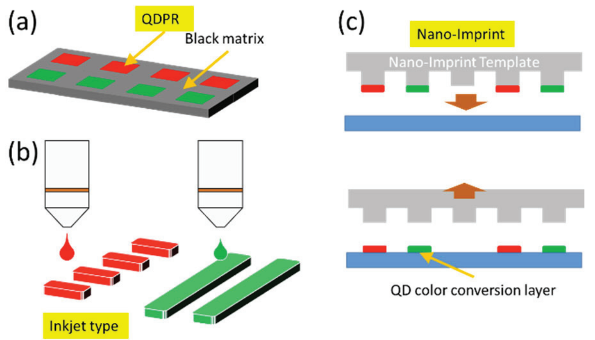

Fig. 2 Three different methods to implement a fine-pitched color conversion layer: (a)QDPR, (b) Inkjet spray (c) Nano-Imprint.

2.1 QDPR

One of the potential solutions to patterned QD is to use photosensitive material mixed with QD to form a quantum dot photoresist (QDPR). The combination of viscous photoresists and QD provide us a good way to increase the total thickness and the patterning capability at the same time. The absorption of blue photons can be described as the following:

$$\mathrm{I} = I_0 e^{-\alpha z} \quad (1)$$

The parameters of α (the absorption coefficient) and z (the thickness of the layer) can be optimized to enhance the QD utilization. Usually the thicker the layer , the more conversion will be. However, there is a compromise between them, which is the resolution of the pattern. Photolithography capability can be determined on how the photo-sensitive resin reacts with exposing UV light and this can be greatly reduced once the nano particles are spread inside the layer. The QD can take out lots of UV photons and interfere the uniformity of the exposure inside. These conditions raise the uncertainty on the finest pattern that a certain thickness of QDPR can achieve.

2.2 Inkjet-type QD spray

Another quite popular method these days is to use the direct deposit of CQD solution on top of the host structure. The host structure could be a piece of glass or the surface of LED device. This method eliminate the necessity of QD patterning because all the pattern was designed by the depositing system. Thus it is the machine accuracy that will determine the final resolution of the display panel in this method. .

2.3 Nano-scale imprint stamps

The progress of current nano-fabrication technology also bring us some advantages on this front. The nano-imprint lithography (NIL) is very simple to be applied in the fine pattern with proper chemicals and imprint stamp template. As small as an array of 6-μm patterns was shown for large area or flexible substrates [3]. The nano-scale fabrication technology of Si wafers has made this method very attractive although the current price for such template is still high and special treatment on the quantum dot mixture is still necessary.

2.4 Monochromatic LED arrays

The LED array underneath the color conversion layer holds the key to the success of this design. It acts like a power engine for the whole machine, and the emitted photons from the LED chip can excite the illuminative quantum dots to provide us red and green colors. The quantum efficiency of the individual device is very important for the overall efficiency, because it can be described as :

$$\text{Total efficiency} = \eta_d \times \eta_{QD} \times \eta_{optics} \quad (2)$$

, where η_d is the original device efficiency, η_{QD} is the photoluminescence quantum yield (PLQY) of the quantum dots, and η_{optics} is the yield of the overall optical effect (diffraction, absorption, scattering from the package structure). As we can see here, even if we have a 100% quantum yield in QD, there is still strong influence from the LED device. In the past, researchers have demonstrated very good results for GaN based micro LEDs with small sizes [4, 5]. But the limiting factor of surface recombination is still an important barrier to be overcome. Currently less than 10% of input power can be converted to photonic power in general [4]. With advances of wafer processing, we are able to have a uniform result across full wafer with efficiency close to this level. .

3 RESULTS AND DISCUSSION

3.1 Microchip Performances

The team from ITRI has been working on this topic since 2009. We demonstrated a monochromatic micro-display of 0.55 inch (blue and green) with a very high resolution of 1984 ppi [2]. The mass-transfer technology is also implemented in the lab and a full-color screen of 30 cm by 30 cm based on printed circuit board (PCB) was demonstrated in the CES 2020 (the related technology was first revealed in SID Display Week 2018 [2].)

3.2 QD patterning

Both methods of QDPR and inkjet type were tried in the lab. The QDPR resolution can reach less than 30 μm with good recurrence. As shown in Fig. 3(a), the pattern is clear under excitation by high-energy photons. Using multiple exposure steps, a full-color array can be achieved.

For the inkjet type method, the viscosity of the QD solution and the controlled spray are crucial for successful deposition of the QD patch onto the right place. The precision of the machine is very important. The throughput of this process is not particularly high. In Fig. 3(b), we can demonstrate a good 6 μm spot on the GaN micro LED chip [6]. With a proper protective layer, the deposited quantum dot layer can sustain continuous excitation from the LED chip underneath for more 100 hours without significant degradation [6].

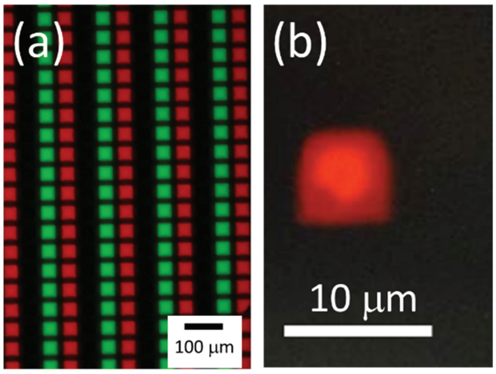

Fig. 3 (a) The finished QDPR array under UV light; (b) The small quantum-dot spot, whose size is close to 6 μm, produced by inkjet type technology.

3.3 Color Quality

One of the characteristics of the quantum dots is the wide range of emission colors. With careful control in the synthesis process, the emission spectral linewidth can also be very narrow. The resultant color gamut for these QD-type conversion layer can be very good: the combination of blue micro LED and red and green QD can achieve 87% of the rec. 2020 space and 117% of NTSC 1953 space equivalently. It is needless to say that the highly saturated colors provided by quantum dots can be one of the key advantages of this type of materials. The color gamut can be further extended if we can adjust the red and green colors more.

4 CONCLUSION

In conclusion, in the past few years, the development of micro-/ mini- LEDs and their related applications in displays has brought up a new wave of innovation. The color conversion layer can supplement the required high resolution needs and relieve some of the difficulties in full-color fine-pitched LED arrays. We investigate in different methods for fabricating these color conversion layers and also improve the efficiencies of micro LEDs. These efforts will pave the way for the next generation of full-color micro-displays.

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