Optical cross-talk reduction in a quantum-dot-based full-color micro-light-emitting-diode display by a lithographic-fabricated photoresist mold

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Received 29 March 2017; revised 12 June 2017; accepted 23 June 2017; posted 26 June 2017 (Doc. ID 291611); published 17 August 2017

In this study, a full-color emission red–green–blue (RGB) quantum-dot (QD)-based micro-light-emitting-diode (micro-LED) array with the reduced optical cross-talk effect by a photoresist mold has been demonstrated. The UV micro-LED array is used as an efficient excitation source for the QDs. The aerosol jet technique provides a narrow linewidth on the micrometer scale for a precise jet of QDs on the micro-LEDs. To reduce the optical cross-talk effect, a simple lithography method and photoresist are used to fabricate the mold, which consists of a window for QD jetting and a blocking wall for cross-talk reduction. The cross-talk effect of the well-confined QDs in the window is confirmed by a fluorescence microscope, which shows clear separation between QD pixels. A distributed Bragg reflector is covered on the micro-LED array and the QDs’ jetted mold to further increase the reuse of UV light. The enhanced light emission of the QDs is 5%, 32%, and 23% for blue, green, and red QDs, respectively.

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OCIS codes: (120.2040) Displays; (160.4236) Nanomaterials; (230.2090) Electro-optical devices; (230.3670) Light-emitting diodes.

https://doi.org/10.1364/PRJ.5.000411

1. INTRODUCTION

As a low-power-consumption, low-cost, and highly luminous light source, gallium-nitride-based light-emitting diodes (LEDs) have attracted much attention, where applications include visible light communications [1–11], vehicle headlights [12,13], and backlight units (BLU) in liquid crystal displays (LCDs) [14–19]. Furthermore, micro-LEDs with micrometer-scale (<100 μm) sizes have different properties from the large-scale (scale of a few hundred micrometers) LEDs, such as high current density operation and thus high optical power density [20]. By fabricating the micro-LEDs into an array, they can function as a high-brightness, high-quality BLU in an LCD display. However, in order to achieve the full-color display, red–green–blue (RGB) light-emitting units should be distributed on the same panel, which is difficult to realize by epitaxial or fabrication effort. Such an issue can be overcome by using an alternative emitting source of colloidal quantum dots (QDs) and exciting the QDs optically by the LEDs [21]. QDs have attracted much attention, particularly because of the large-area color gamut than can be achieved with their narrow linewidths. In our previous research [22], a full-color emitting panel is achieved by combining RGB QDs with micro-UV micro-LEDs of 35 μm × 35 μm pixel size and in 128 × 128 arrays. In common, the light utilization efficiency of the LCD display system is caused mostly by the loss by the LCD backlight system. Use of a photoluminescence (PL) QDs display can replace the color filters and with a very large color gamut (1.52 times that of NTSC 1976). Color gamut was an evaluation metric, which was determined by the maximum colors in the display. A new color triangle was devised to strictly define the color gamut standard, which is called Rec. 2020. Our previous research demonstrated a QD microdisplay with over 80% of the color gamut of Rec. 2020 [23]. To accurately locate QDs on the micro-LED array, the aerosol jet (AJ) technique was used as the key technology to realize such a QD-LED display. However, our previous results also showed that, even with the optimized AJ parameters, the cross-talk effect still occurred during the QD deposition due to the overflow of QDs during the solvent evaporation.
In this work, we demonstrate a significant reduction in the cross-talk effect during the AJ printing process by using a photoresist (PR)-defined mold with a blocking wall to confine QDs. Furthermore, by adding a distributed Bragg reflector (DBR), the utilization of UV light can be more effective due to the fact that the reflected UV light can be reabsorbed by QDs, and the issue of human body safety can also be explored.

2. RESULTS AND DISCUSSION

Figure 1(a) shows the schematic illustration of an AJ system, which is developed by the Optomec Corporation. As described in Section 3, the QDs in the solvent are atomized in an ultrasonic atomizer and then transferred to the nozzle to jet the QDs. Regarding the QDs used in this study and similar to our previous research, CdSe QDs were purchased from the UT Dots Corporation, and the average sizes of the QDs were confirmed that it can be well controlled at about 14 and 35 μm. However, the heights of the QDs have a corresponding change with linewidth. As shown in Fig. 2(c), for linewidths of 14.3 and 33.2 μm, the heights of the jetted QDs are 0.44 and 3.75 μm, respectively. For the small linewidth, the emission intensity would be too weak. As a consequence, the linewidth is limited to 30–40 μm.

The micro-LED array used in this study is similar to the one in our previous work [22], with an emission wavelength of 395 nm, a single pixel size of 35 μm × 35 μm, and a pitch of 40 μm. The total array number is 128 × 128 in a chip area of 5 mm × 5 mm. The UV micro-LED is chosen instead of the blue micro-LED because the RGB QDs have higher quantum yields in the UV region than in blue region. In order to reduce the optical cross-talk effect in the previous work, a mold with open windows and blocking walls was fabricated by a PR and using the simple lithography technique. The window size here is the same as the micro-LEDs, and the unopened region forms the blocking wall that is just the shape of the trench between micro-LEDs, as shown in Fig. 3(a). The window size is about 35 μm × 35 μm with a pitch of 40 μm, which is the same as the micro-LED array. Figure 3(b) shows the laser scanner microscope image of the PR mold, and the height of the PR wall is 11.46 μm. The PR mold was fabricated by the photolithography process by the AZ 5214-E (from MicroChem). The definition of the mask for the PR mold fabrication was modulated with a similar pitch size as for the micro-LED array—this was convenient to align in the followup. The PR mold covering may reduce the cross talk of QDs, and the sidewall was silver coated to reflect the leakage of light from the sidewall and prevent new cross talk from occurring.

Figure 4(a) shows that the UV passive-matrix micro-LED arrays were fabricated on UV epiwafers with a peak wavelength of 395 nm and a pitch size of 40 μm. The 128 × 128 micro-LED pixels fabricated in the same column share a common electrode of the n-type GaN. All of the stripes of the micro-LED array have been created as isolation trenches via dry etching of GaN down to the sapphire substrate. By the dry etching process, SiO2 was used as the hard mask. Finally, the p-electrode stripes were defined on top of the chips, the n-electrode stripes were defined on the n-GaN layer, and then a connection was made to all of the pixels in the same row. By aligning the windows of the mold to the micro-LED mesa, as shown in Figs. 4(b)–4(e), the AJ RGB QDs can be effectively deposited on the micro-LED mesa region but prevent overlap with the trench region. In order to fit the window size, the printing parameters are optimized. The adjustable parameters include the working distance between the nozzle and the substrate,

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Fig. 1. (a) Schematic illustration of the AJ system. (b) The PL emission spectra of QDs with emission wavelengths of 450, 535, and 630 nm.

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Fig. 2. AJ red QD NCTU pattern observed by (a) optical microscopy, (b) fluorescence microscopy, and (c) the measured height of the deposited red QD by laser microscopy.

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Fig. 3. (a) Optical microscopy image of PR square windows with the pixel size of 35 μm × 35 μm, where the pitch is about 40 μm. (b) The laser scanner microscope image of the PR square wall, where the height of the wall is 11.46 μm.
the carrier gas flow rate, the sheath gas flow rate, and the stage speed. Table 1 summarizes the optimized parameters. The working distance and stage speed are fixed due to the fact that it might cause too wide of a range of change. Hence, in our case, only the carrier gas flow rate and the sheath gas flow rate are changeable. The concentrations of the RGB QDs in this study are controlled in the same condition. However, the RGB QDs were with different particle sizes because the wavelengths of the QDs were modulated by the particle sizes. The size-dependent properties of the QDs will alter the deposition condition of the AJ system. As a result, different flow rates are needed to control of the AJ system. Usually, we need to increase the carrier gas flow rate as the particle size grows. At the same time, when the carrier gas increases, the flow rate of sheath gas needs to increase as well to hold the linewidth of the deposited QDs, which is about 35 μm in this study.

Before the RGB QDs are jetted, alignment between the PR mold and the micro-LED array was necessary. Alignment between the PR mold and the micro-LED array was performed by an X–Y stage system and an optical microscope (OM). The PR mold was fabricated by the photolithography process, and the definition of the mask was modulated to be suitable for the micro-LED array. The X–Y stage system used in this study was with 1 μm resolution, and then we placed the micro-LED array in a sticking position and observed the alignment process in the OM image. We defined an alignment cross in a sticking position of the micro-LED array, as shown in Fig. 5(a). Next, we focused on the PR mold in the OM image and moved the PR mold to align the alignment cross, as shown in Figs. 5(b)–5(c). Finally, the PR mold was pasted on top of the micro-LED array, thereby completing the alignment process.

After the deposition of QDs on the UV micro-LEDs via AJ and window-confined PR mold, the RGB pixel of the micro display has been demonstrated. Figure 6(a) shows the OM image of the well-deposited QDs on the micro-LEDs, which are isolated from the adjacent region. To further investigate the QD distribution characteristics, fluorescence microscopy was conducted. The result shown in Fig. 6(b) reveals that the light-emitting region from the QDs has a clear boundary. Compared to the AJ printing result without a PR mold, as shown in Fig. 6(c), the fluorescence image shows that no clear separation between printed QDs can be seen. It is obvious that the cross-talk phenomenon has been observed in the blue QD line while the green and red QD lines have been aggressed by blue QD line. The top-view image of the microdisplay in our previous research is shown in Fig. 7(b) [22]. The red line depicts the overlap of the blue and green lines, which caused the cross-talk effect to induce the pixels with a color shift. Cross talk has been defined as a metric to express how much of

Table 1. Parameters of the AJ Printing Technique for Different QDs

<table>
<thead>
<tr>
<th>QD Wavelength (nm)</th>
<th>Working Distance (mm)</th>
<th>Carrier Gas Flow Rate (sccm)</th>
<th>Sheath Gas Flow Rate (sccm)</th>
<th>Stage Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>630</td>
<td>1</td>
<td>83</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>535</td>
<td>1</td>
<td>72</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>450</td>
<td>1</td>
<td>66</td>
<td>11</td>
<td>10</td>
</tr>
</tbody>
</table>

Fig. 5. Alignment approach. (a) The OM image focused on the micro-LED array and the defined alignment cross in a sticking position. Parts (b) and (c) show the OM image focused on the PR mold and the location moved to align the alignment cross, respectively.

Fig. 6. (a) Microscope image of the full-color micro-LED after jetted QDs in the PR mold. (b) The RGB pixel array observed by fluorescence microscopy. (c) The fluorescence microscopy image of the jetted QD pixels without the PR mold.

Fig. 7. (a) Top-view image of the micro-LED layout with the pitch of 40.2 μm defined as the intended channel. (b) Our previous work by the QD lines without the PR mold for the microdisplay, which caused cross talk. (c) The QD droplets jetted in the PR mold to confine the size and resolve the cross-talk effect.
the value is obtained for a particular display system, which is referred to as Wood’s research [24]. The cross-talk value is defined by

$$\text{Crosstalk(\%)} = \frac{\text{Leakage}}{\text{Intended channel}} \times 100\%,$$  \hspace{1cm}(1)

where “Leakage” is the luminance of light that leaks from the unintended channel to the intended channel, which is defined as the overlap area. We find that the intended channel is about 40.2 μm, as shown in Fig. 7(a). The overlap area of the red line for the previous design in Fig. 6(b) is about 13.4 μm (the deviation between 53.4 and 40.2 μm). The cross-talk value of the previous design is about 32.8%. The PR mold can limit the QD area in the intended channel, and with the silver coating to reflect the leakage of light from the sidewall, as shown in Fig. 7(c), it means that a lower cross-talk value (near zero) has been demonstrated in this study.

On the other hand, a spot pattern could waste QDs. Based on calculations, the material costs of 128 × 128 pixels (area of 5 mm × 5 mm) is about 9.7 nL of red QDs, 18.8 nL of green QDs, and 21.8 nL of blue QDs. We believe that the design of a PR layer can reduce material costs for a large-area microdisplay for the mass production process in the future.

This study resolves the coffee ring effect by the PR layer for our micro-LED. The significant coffee ring effect means that the ring-like QD particles deposit along the perimeter and with a pinhole when the QD droplets dry on a solid surface. At the perimeter, evaporation of the liquid is swifter than at the middle because the perimeter has a thinner thickness than the middle. However, the height profile must maintain the spherical cap shape dictated by surface tension and needs to prevent shrinkage [25–27]. The QD solution must flow outward, and then the QD particles were brought to the perimeter by the solution during evaporation. The QD particles were deposited along the perimeter to produce a coffee ring, where the mechanism is as shown in Fig. 8(a). Figure 8(c) shows that the OM image of the GaN substrate with QD drops, which was observed to produce the coffee ring effect. The mechanism of the PR mold to resolve the coffee ring effect is as shown in Fig. 8(b). The mold has been designed to control similar liquid thickness in the perimeter site and the middle site by confining the solution. A similar liquid thickness would cause similar rapid evaporation, which could prevent the QD particles from being brought to the perimeter or middle site by the solution. Figure 8(d) illustrates that QD drops could be confined in the hole, thereby resolving the coffee ring effect.

In order to increase the UV light utilization, and avoid biological damage, a DBR structure has been designed for the microdisplay. The DBR structure is prepared via alternative deposition of 17.5 pairs of HfO2/SiO2 multilayers on a quartz glass. The measured reflectance of the DBR is shown in Fig. 9(a). The stop-band width and stop center of HfO2/SiO2 of the DBR is 80 and 395 nm, respectively. The maximum reflectance of the DBR is 92.5% at 395 nm. The DBR structure was composed of multiple pairs of different refractive index dielectric layers to achieve higher reflectivity in the selected wavelength. The basic equation to design the DBR structure is

$$d = \frac{\lambda}{4n \cos \theta},$$  \hspace{1cm}(2)

where \(\lambda\) is the selected wavelength, the thickness \(d\) of the stacking dielectric materials depends on the refraction index and incidence angle \(\theta\), \(m\) is the number of stacked layers, and \(n_{sub}\), \(n_1\), and \(n_2\) represent the refractive indices of the substrate and the stacking dielectric layers, respectively [28,29]. After covering the prepared DBR on the QDs-deposited LED array, the measured electroluminescence (EL) spectrum shown in Fig. 9(b) reveals that the light output from the QDs is enhanced by 23%, 32%, and 5% for red, green, and blue, respectively. The relative small enhancement in blue QDs is due to the unoptimized DBR reflectance at 450 nm, which is comparatively higher than the DBR reflectance for green and red QDs, as shown in Fig. 9(a). This can be further improved by designing the DBR layer stack with a layer thickness of \(\lambda/(4n)\). Two rows of the RGB pixels have been driven, and this enables individual addressable excitation of each pixel, as shown in Fig. 10(a). The difference brightness of each
By calculation, the OCE of the blue, green, and red emission that was driven individually by the RGB micro-display is about 228.5 cd/m² for blue light, and 283.1 cd/m² for a single green pixel, and 228.5 cd/m² for a single blue pixel, respectively. Most indoor LCD displays have brightness values in the range of 300–350 cd/m², and our microdisplay had a luminance of 358.5 cd/m² in full color, which is enough for display applications.

3. MATERIALS AND METHODS

A. Fabrication of the UV Micro-LED Array

The epitaxial structure of the UV micro-LED was grown by metal organic chemical-vapor deposition, which consists of an undoped GaN buffer layer on a sapphire substrate, followed by n-GaN, a multiple quantum well with a peak emission wavelength of 395 nm, p-GaN, and a current-spreading layer (CSL) for metal contact. The UV micro-LED array was fabricated as follow: mesa dry etching down to n-GaN via inductively coupled plasma (ICP), p-metal deposition on the CSL, n-metal deposition on the n-GaN layer, and then the trench opened by ICP etching down to the sapphire substrate in order to isolate each micro-LED from each other, and sidewall passivation by plasma-enhanced chemical vapor deposition-deposited SiO₂.

B. AJ System

The aerosol system consisted of two major parts: an ultrasonic atomizer and a spraying chamber. First, the RGB QDs with concentrations of 5 mg/mL in solvent were prepared in a tube that is inside the ultrasonic atomizer, and then the suspension was atomized by the ultrasonic vibration. The resulting AJ was consequently transferred to the nozzle by nitrogen gas flow. After the nitrogen gas input, the AJ was tightly focused at the end of nozzle to produce small drops, enabling narrow linewidth and high resolution.

4. CONCLUSION

In conclusion, we demonstrated a full-color microdisplay with a composite of a UV micro-LED array and RGB QDs by using the AJ technique, whereby the linewidths of the QDs could be well controlled to fit the sizes of micro-LEDs. Furthermore, a mold was made by simple lithography to reduce the optical cross-talk effect, the QDs were jetted into the window of the mold with clear separation between each pixel. A HfO₂/SiO₂ DBR provided a more efficient utilization of UV light and enhanced the QD emission intensity by 23%, 32%, and 5% for red, green, and blue, respectively. With these techniques, high-quality microdisplays can be achieved.

Funding. Ministry of Science and Technology, Taiwan (MOST) (MOST104-3113-E-009-002-CC2, MOST105-2622-E-009-023-CC2).

Acknowledgment. The authors would like to thank the Electronic and Optoelectronic System Research Laboratories of the Industrial Technology Research Institute and the Ministry of Science and Technology of Taiwan for their financial support.

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