Light Recycling in Quantum-Dot Organic Light-Emitting Diode Using Side-Wall Reflector Formed by a Secondary Sputtering Lithographic Technique

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Abstract

In quantum dot-organic light-emitting diode (QD-OLED), the emission from the blue OLED is absorbed by QDs and re-emitted to implement green and red subpixels. To prevent optical crosstalk between pixels, black matrices (BMs) are utilized. During the color conversion process, re-emitted light is released in random directions. If a reflective layer is formed on the BMs, the light can either be reabsorbed by the QD layer for reuse or emitted externally without being lost in the BM layer. In this study, a BM structure was directly formed on the blue OLED and a secondary sputtering lithographic technique was used to fabricate reflective side-walls. The process was conducted without damaging the OLED device. By forming the QD layer between the reflective walls, a 20% improvement in color conversion efficiency was observed compared to when reflective walls were not used.

Author Keywords

Quantum Dot; Organic light-emitting diode; Secondary Sputtering; Color Conversion

1. Introduction

Quantum dot-organic light-emitting diode (QD-OLED) displays have garnered significant attention by combining the self-emissive and fast response time characteristics of OLED displays with the superior narrow emission spectrum of QDs [1]. However, challenges remain in improving absorption of blue emission from OLEDs by QDs, even when the thickness of the color conversion layer (CCL) is increased to several micrometers and scattering particles are included to extend the light path within the CCL. As a result, light within the CCL disperses randomly, necessitating the use of a black matrix (BM) to prevent optical crosstalk between pixels [2]. However, this leads to another issue: light absorbed by the BM reduces the color conversion efficiency (CCE), which is defined as the ratio of emitted red or green light to the absorbed blue light.

In addition to material-based approaches, such as enhancing the intrinsic photophysical properties of QDs or applying highly absorptive materials like perovskites, there are structural approaches to reduce light loss, such as forming reflective layers on the side surface of the BMs. However, the conventional method of forming reflective layers—depositing a metal thin film, photoresist (PR) patterning, metal etching, and then PR removing—has the disadvantage of being complicated multiple processes. In this study, we fabricated a silver (Ag) reflector on the side surface of the BM through secondary sputtering lithographic (SSL) techniques using argon ion bombardment [3, 4]. By directly forming a BM on top of the blue OLED protected by thin-film encapsulation (TFE) through photolithography and applying Ag reflectors using SSL techniques, it was demonstrated that the color conversion efficiency (CCE) of the red QD CCL improved by 20% without causing any damage to the OLED device.

2. Experiment

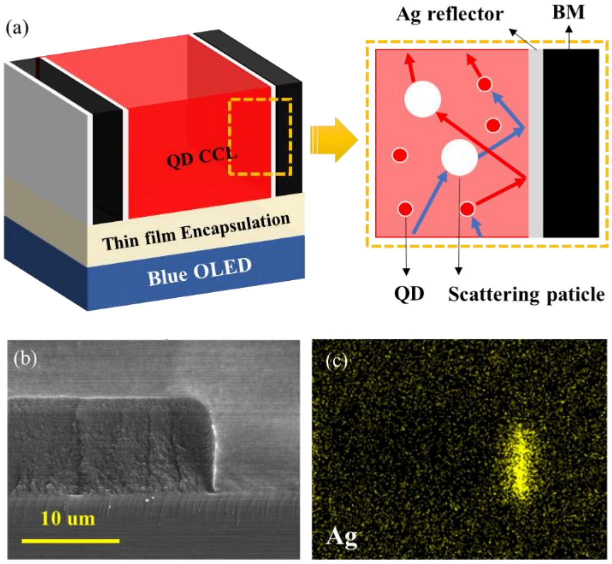

Figure 1. (a) Schematic diagram of the QD-OLED with an Ag-reflector and ray paths utilized in light-recycling. (b) SEM images and (c) SEM-EDS elemental analysis mapping images of a BM with an Ag-reflector

Figure 1(a) shows the structure of a QD-OLED with an Ag reflector on the side surface of the BMs. The blue OLED consists of a bottom electrode made of ITO/Ag/ITO and organic layers, including the blue-emitting layer. [5] A 15 nm-thick Mg:Ag top electrode was deposited onto the structure. Following the fabrication of the OLED device, TFE layers were sequentially deposited using atomic layer deposition for Al_2O_3 (60 nm) and plasma enhanced chemical vapor deposition (PECVD) for SiNx (1 μm). On top of the encapsulation layer, the BMs were patterned via photolithography with varying hole sizes and spacings. To form the Ag reflector, an Ag thin film was first deposited, followed by the application of argon ion bombardment to the thin

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film. By adjusting the ion bombardment time, the metal thin film on the planar surface was completely removed, leaving only a thin layer of several nanometers on the side surfaces of the BM. The QD CCL, which consists of InP/ZnSe/ZnS core-shell red QDs and titanium dioxide (TiO_2) scattering particles, was formed by a spin coating.

3. Results and discussion

Figure 1(b) and 1(c) show a scanning electron microscope (SEM) image and a SEM-energy dispersive X-ray spectroscopy (SEM-EDS) image of the structure with the Ag reflector formed on the side walls of the BM, respectively. As shown in the EDS mapping data, the Ag that was initially deposited on the planar surface is detected exclusively on the BM side walls after the SSL process.

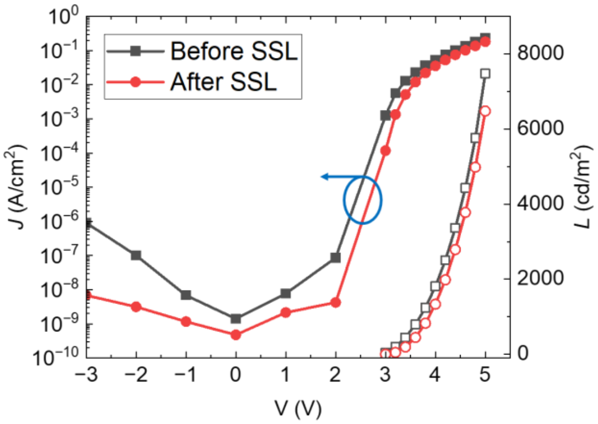

Figure 2. the current density-voltage-luminance (*J-V-L*) characteristics of the blue OLED before and after secondary sputtering lithographic (SSL) techniques.

Figure 2 presents the current density-voltage-luminance (*J-V-L*) characteristics of the blue OLED before and after ion bombardment. The results indicate that the OLED device exhibits no significant degradation in electrical and optical performance even after ion bombardment. This stability can be attributed to the PECVD SiNx layer, which serves as a 1 µm-thick TFE barrier, effectively protecting the underlying OLED layers from physical damage caused by ion bombardment. These findings suggest that the encapsulation structure plays a crucial role in maintaining OLED performance under processing conditions involving ion bombardment.

Figure 3 show emission spectra of the QD-OLED. The color conversion characteristics were evaluated by adjusting the hole size and spacing within the same unit area. Complete color conversion is not achieved, resulting in simultaneous emission of blue light from the OLED and red light from the QD CCL. Since the same current density was applied to the blue OLED, the intensity of the blue emission remains constant. However, as the BM hole size increases and the spacing decreases, the intensity of the blue light also increases. Similarly, since the QD CCL is formed within the BM holes, the red intensity also increases with larger hole sizes and smaller spacing.

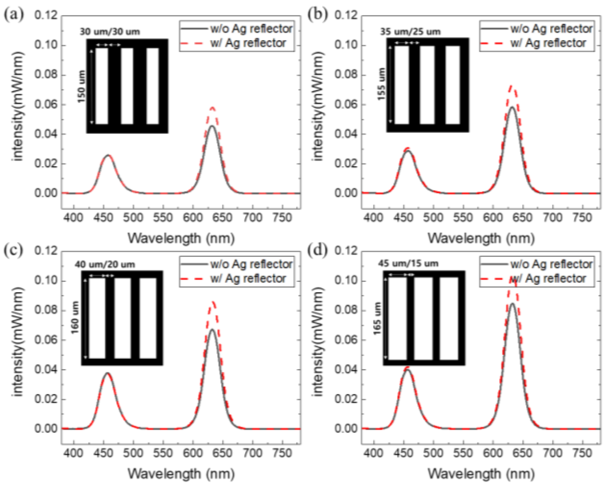

Figure 3. Emission spectra of QD-OLED without and with Ag reflectors for various BM resolutions. Inset: BM hole size and spacing design. (a) 150 um X 30 um hole with 30 um spacing, (b) 155 um X 35 um hole with 25 um spacing, (b) 160 um X 40 um hole with 20 um spacing, and (d) 165 um X 45 um hole with 15 um spacing.

When comparing the characteristics with and without the Ag reflector, only the red intensity increased across all tested BM resolutions, while the blue intensity showed a much smaller change compared to the change in red intensity. Referring to the ray paths utilized in light-recycling depicted in Figure 1(a), the blue light from the OLED, scattered by the scattering particles, is reflected by the Ag reflector instead of being absorbed and lost in the BM. This reflection allows the blue light to be reabsorbed by the red-emitting QDs, increasing red emission. Alternatively, the light reflected from the Ag reflector may escape directly without being absorbed by the QD CCL. As a result, for blue light, the advantages and disadvantages coexist, leading to a change in intensity that is very small relative to the change in red intensity.

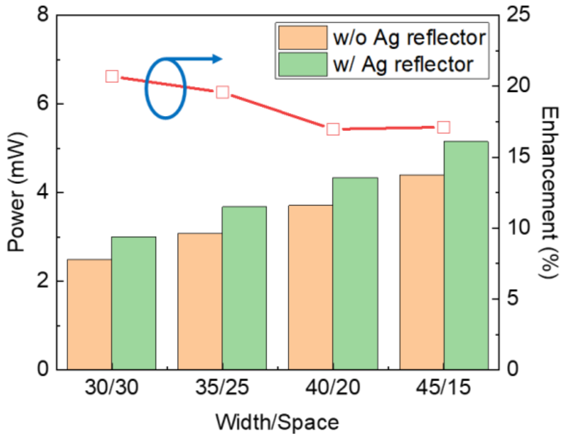

Figure 4. Power and its enhancement of QD-OLED without and with Ag reflectors for various BM resolutions.

For red light, the Ag reflector offers only advantages. As previously mentioned, the reflected blue light from the Ag reflector can be reabsorbed by the QDs, contributing to the red emission. Additionally, the down-converted red light, which could be scattered by the scattering particles in the CCL and absorbed by the BM, is effectively prevented from being lost due to the presence of the Ag reflector. As a result, a significant improvement in red intensity can be observed.

The power of QD-OLEDs with various BM resolutions was measured, and the power enhancement due to the presence of the Ag reflector was calculated (Figure 4). As previously mentioned, power increases as the BM hole size grows and the spacing decreases. For the same BM resolution, the power enhancement ratio due to the Ag reflector ranges from 17% to 20%. As shown in the spectra in Figure 3, the blue intensity remains largely unchanged, while the red intensity improves significantly. Therefore, this power enhancement ratio indicates how much additional light was converted to red. The enhancement ratio tends to be higher when the hole size is smaller and the spacing is wider. This trend can be attributed to the surface area of the Ag reflector relative to the volume of the QD CCL; smaller holes result in a greater influence of the Ag reflector.

4. Conclusion

The Ag reflector was successfully formed using SSL technology without causing damage to the OLED device. SSL is a photomask-free process, reducing process steps compared to conventional photolithography while enabling the formation of the Ag reflector. The Ag reflector can be applied to BM side-walls with varying resolutions. The Ag reflector formed using SSL effectively recycled light within the QD CCL, resulting in a 20% improvement in the CCE of the QD-OLED.

5. Acknowledgements

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6. References

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