Solution-Processed Inverted 3-Stack Tandem QD-LEDs with RGB Layer

Ha-Rim Jung*, Young-Jae Ko, Hyo-Bin Kim***, Jang-Kun Song*,**,*****
*Department of Display Engineering, Sungkyunkwan University, Suwon, Gyeonggi-do 16419, South Korea
**Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon, Gyeonggi-do 16419, South Korea
***Department of Display Convergence Engineering, Sungkyunkwan University, Suwon, Gyeonggi-do 16419, South Korea

Abstract

We fabricated a white 3-stack tandem QD-LED via solution processing and compared two devices with different EML sequences: BGR and RGB. We also analyzed the contribution of each emissive layer to the overall emission to understand performance differences between the configurations.

Author Keywords

QLED; Quantum dot; Tandem; White color; Inverted.

1. Introduction

Quantum-dot light-emitting diodes (QD-LEDs) are promising due to their high efficiency, color purity, tunable emission, and solution processability. Among these, solution processability is particularly advantageous for low-cost and scalable manufacturing, making QD-LEDs a promising candidate for next-generation display and lighting technologies. However, QD-LEDs face challenges, including lower efficiency and shorter lifetimes compared to organic light-emitting diodes (OLEDs). These limitations have hindered their widespread adoption in commercial applications. [1-5]

To address these issues, tandem device architectures have emerged as a promising solution. By stacking multiple emissive layers and charge-generation layers in a single device, tandem QD-LEDs can significantly improve luminance, operational stability, and overall device efficiency. This approach not only enhances performance but also aligns with the potential of solution processability for large-area applications. This study focuses on developing and optimizing tandem QD-LED structures to overcome the inherent limitations of single-layer QD-LEDs, paving the way for their use in advanced display and lighting technologies.[6]

Despite the advantages of tandem structures, the solution process in QD-LEDs faces significant challenges, particularly with multi-layer configurations. In these multi-layer structures, the use of solution processing can cause damage to the underlying layers or make it difficult to achieve a uniform coating. This necessitates careful selection of the solution materials to prevent any adverse effects on the layers below. In this study, PEDOT:PSS was mixed with ethanol in a 1:1 volume ratio to modify its wettability characteristics from hydrophilic to hydrophobic. This adjustment allowed the PEDOT:PSS to be uniformly coated onto the hydrophobic PVK layer, which inherently has low wettability, thereby addressing the issues related to coating consistency and layer compatibility.

The backplane for large displays commonly uses n-type oxide thin-film transistors (TFTs). However, the normal structure of QD-LEDs is not well compatible with n-type oxide TFTs due to unstable current flow. This lack of compatibility arises because the device must connect with the source electrode in a manner that leads to inconsistent current characteristics, which affects the stability of the device. In contrast, inverted structures are more suitable for integration with n-type oxide TFTs, as they can better accommodate the characteristics of n-type materials. Therefore, research on inverted QD-LED structures is necessary to ensure proper compatibility and improved stability for large display applications.[7-10]

In our study, we fabricated an inverted 3-stack white tandem QD-LED using a solution process. Two different devices were created by varying the sequence of the emissive layers (EMLs) from the bottom: Blue-Green-Red (BGR) and Red-Green-Blue (RGB). We compared the performance of these two configurations and analyzed how each EML contributed to the overall emission. Through this analysis, we observed that the bottom layers contributed first to the emission, and we further investigated the underlying mechanisms behind this phenomenon.

2. Experimental

Materials: All the materials were purchased. Zinc oxide nanoparticles (ZnO NPs) was purchased by Sigma-Aldrich, PEDOT: PSS (Al40383) was purchased by Clevios™ P AI 4083, Heraeus, Germany. PVK was purchased by Sigma-Aldrich, USA. Red QDs(CZO-620T), green QDs (CZO-530T), blue QDs(CZO-450T) were purchased by Zeus, Republic of Korea.

Device Fabrication: All layers except the electrode were fabricated by solution process with spin coating method in the glove box of ambient dry air condition. Patterned ITO glasses were washed with ethanol in an ultrasonic bath. The glasses were rinsed with deionized water and treated using oxygen plasma treatment at 50 W for 60 seconds. The ZnO NPs were spin-coated onto the ITO layer as the electron transport layer (ETL)/electron injection layer (EIL) at 4000 rpm for 30s, and baked 120 °C for 10 min. Next, the EML was formed by spin-coating a 20 mg mL−1 solution of CdSe/ZnS core–shell green QDs at 6000 rpm for 30 s, followed by baking at 120 °C for 15 min. The HTL layer was then formed by spin-coating PVK (Sigma Aldrich, USA) dissolving in 1,4 dioxane at a concentration of 6 mg/mL on top of the CdSe QDs layer at 6000 rpm for 30 s and baking at 120 °C for 15 min. The HIL layer was formed by mixing aqueous PEDOT: PSS (Clevios P AI 4083) with ethanol at a volume ratio of 1:1 to overcome the low wettability of the hydrophobic PVK layer. Finally, the Yb:Ag electrode was evaporated with a Yb rate of 0.16 and an Ag rate of 2, resulting in a total thickness of approximately 150 nm. Electrode was thermally evaporated with a shadow mask under high vacuum conditions (1.0×10-6 Torr).(4)

ISSN 0097-996X/25/5601-0236-$1.00 © 2025

3. Results & Discussion

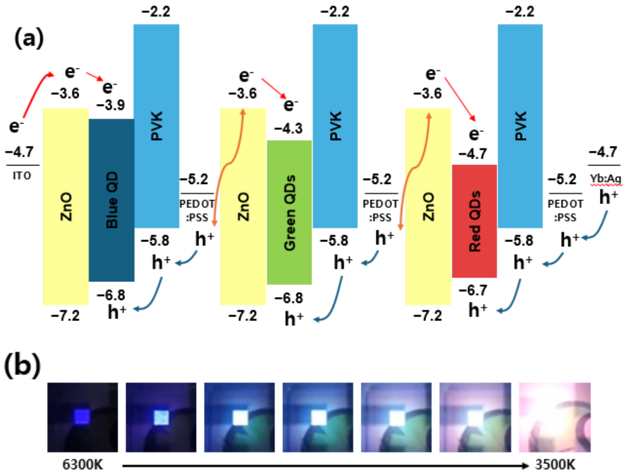

Figure 1. (a) Energy band diagram of inverted RGB 3stack structure QD-LED, (b) Photographs of the white QLEDs with the CCT from 6300 to 3500 K.

The structure of inverted 3-stack RGB tandem in Figure 1(a), reverse bias operation enables electron injection from the ITO cathode and hole injection from the Yb:Ag anode. Charge generation occurs at the PEDOT:PSS/ZnO interfaces, where electrons and holes are efficiently separated. This charge separation facilitates the transport of electrons and holes into the emissive layers (EMLs), where recombination occurs, resulting in light emission. The efficient charge generation and separation at the CGLs(charge generation layers) are crucial for balancing the charge transport and ensuring stable and uniform emission across all three EMLs.

At low voltages, strong emission was observed from the bottommost blue layer, which is closest to the ITO cathode. As the voltage increased, the emission gradually shifted to the green and red layers, resulting in a combined output that approached a white light emission. This progression shows voltage-dependent charge transport, with blue layer recombination dominating at low voltages. As the electric field strengthens with increasing voltage, charge carriers are efficiently transported to the green and red layers, enabling balanced recombination across all emissive layers for white light emission.

The sequential images in Figure 1(b) illustrate the shift in emission color temperature of the tandem device as the applied voltage is increased. At lower voltages, the emission exhibits a high color temperature of approximately 6300 K, indicating a strong contribution from the blue emissive layer. As the voltage increases, the color temperature gradually shifts towards lower values, reaching approximately 3500 K. This transition indicates that the emission becomes warmer, as contributions from the green and red emissive layers become more significant. The change from cool blue light (6300 K) to warm white light (3500 K) highlights the voltage-dependent balancing of charge recombination across the three emissive layers, resulting in a tunable white emission. This behavior demonstrates the device's potential for adjustable color temperature, which is desirable for applications in lighting and display technologies where customizable light quality is needed.

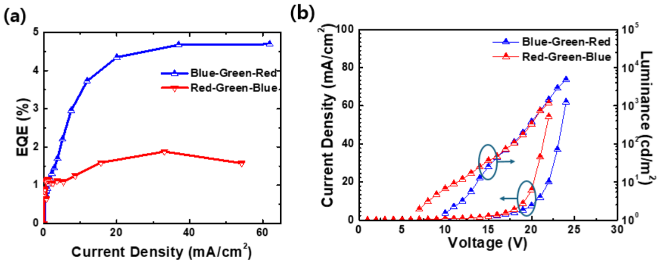

Figure 2. (a) EQE, (b) J-V-L characteristics of the inverted 3-stack tandem QD-LED device for two different layer sequences: Blue-Green-Red (BGR) and Red-Green-Blue (RGB)

Figure 2(a) shows that the Blue-Green-Red (BGR) structure achieves a significantly higher peak EQE of approximately 5%, compared to the Red-Green-Blue (RGB) structure, which peaks at around 1.5%. The higher EQE of the BGR sequence suggests more efficient charge injection, transport, and recombination due to favorable energy alignment. In contrast, the RGB sequence faces challenges in charge balance, resulting in lower efficiency.

Figure 2(b) illustrates the J-V-L characteristics of both configurations. The BGR structure exhibits a lower turn-on voltage and a steeper increase in luminance compared to the RGB structure, indicating superior charge transport dynamics. The favorable band alignment in the BGR structure facilitates easier charge injection and balanced recombination across all layers, resulting in better luminance and efficiency at lower voltages.

In comparing the BGR and RGB structures, it appears that the RGB structure suffers from reduced efficiency and brightness when measured from the bottom emission. This may be attributed to the fact that, in the RGB configuration, the red and green emissions generated in the bottom layers are reflected from the top interface, subsequently being absorbed by the blue emissive layer positioned above. This reabsorption process is likely to result in significant losses in emitted light, reducing the overall efficiency and luminance. In contrast, the BGR structure does not experience this same level of reabsorption because the blue emissive layer is positioned at the bottom, where it emits directly without significant interference or reflection from the layers above. As a result, the BGR configuration shows improved efficiency and higher luminance compared to the RGB configuration, highlighting the impact of layer order on device performance.

Overall, these results demonstrate that the order of the emissive layers critically affects device performance, with the BGR structure consistently showing better efficiency and luminance due to more efficient charge management and energy alignment.

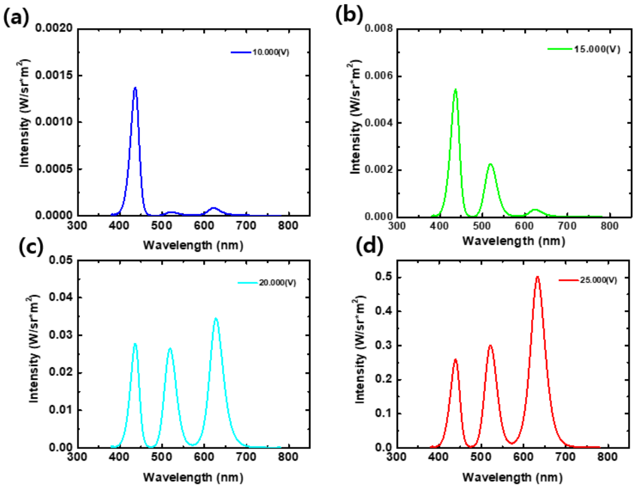

Figure 3. (a) to (d) presents the electroluminescence (EL) spectra of the inverted 3-stack RGB tandem QD-LED device at different applied voltages (10 V, 15 V, 20 V, and 25 V, respectively).

The electroluminescence spectra in Figure 3 show the voltage-dependent activation of different emissive layers in the inverted 3-stack RGB tandem QD-LED. At 10 V, blue dominates, while increasing the voltage activates green and red sequentially, leading to white emission.

The phenomenon is closely related to how the electric field distributes across the device at different voltages. At low voltages, the electric field is primarily concentrated at the bottommost layer, resulting in blue emission. As the applied voltage increases, the electric field becomes stronger and extends across the entire device, enabling charge carriers to reach the higher energy barriers of the green and red layers, leading to full RGB emission. This demonstrates that the electric field plays a crucial role in determining which layers are activated and when, ultimately influencing the color output of the device.

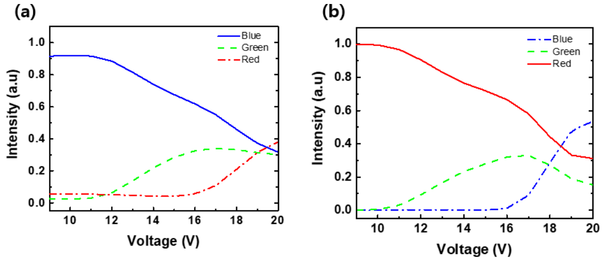

Figure 4. (a) Blue-Green-Red(BGR) structure, (b) Red-Green-Blue(RGB) structure each of the Blue, Green, and Red layers how contributes to the emission as the voltage increases.

The graphs in Figures 4(a) and 4(b) illustrate the voltage-dependent contribution of the blue, green, and red layers in an inverted 3-stack tandem QD-LED device. In Figure 4(a), the Blue-Green-Red (BGR) sequence shows that at low voltages (10–12 V), the blue layer primarily dominates the emission due to its favorable positioning for initial electron injection. As the voltage increases (12–16 V), the green layer becomes active, contributing to the overall emission, and at higher voltages (>16 V), the red layer also starts to contribute, leading to a balanced RGB emission.

In Figure 4(b), which shows the Red-Green-Blue (RGB) sequence, the emission is dominated by the red layer at lower voltages, as it is positioned at the bottom, allowing for easy charge injection. As the voltage increases, the green layer becomes active, followed by the blue layer at even higher voltages. The eventual balanced contribution from all three layers demonstrates how voltage influences the activation of each emissive layer, resulting in full RGB emission at higher voltages.

The results show that electric field distribution is key in determining which emissive layer dominates at different voltages. At low voltages, the field is concentrated in the bottom layer, enhancing emission near the cathode. As voltage increases, the field extends upward, balancing recombination and emission across all layers, highlighting the need for voltage and layer sequence optimization for efficient RGB emission.

4. Conclusion

In this study, we successfully developed an inverted 3-stack white tandem QD-LED using a solution process, comparing two configurations with different emissive layer orders: Blue-Green-Red (BGR) and Red-Green-Blue (RGB). Our analysis revealed that the BGR structure showed higher efficiency and luminance compared to the RGB structure, largely due to more efficient charge management and reduced light reabsorption. The sequential activation of the bottom layers contributed significantly to the initial emission, highlighting the impact of electric field distribution and layer sequence on device performance. Our findings highlight the need for careful material selection, device design, and process optimization to advance QD-LED technology for high-efficiency displays.

5. Acknowledgment

This work was supported by korea institute for Advancement of Technology(KIAT) grant funded by the Korea Government (MOTIE) (RS-2024-00418086, The Competency Development Program for Industry Specialist)

6. Reference

1.Sun Y, Han C, Li R, Xiang C, Zhang T, Qian L. Fully solution-processed red tandem quantum dot light-emitting diodes with an EQE exceeding 35%. Journal of Materials Chemistry C. 2024;12(27):10053-60.

2. Kim, H. B., Yoo, J. I., Kang, S. C., & Song, J. K. (2023). 69-3: Late-News Paper: Enhanced Performance of Quantum Dot Light Emitting Diode via Optimizing PVK and Poly-TPD Mixture Ratio for Hole Transport Layer. In *SID Symposium Digest of Technical Papers* (Vol. 54, No. 1, pp. 978-981).

3. Lee, S. H., Yoo, J. I., Kim, H. B., Jang, J., & Song, J. K. (2024). 44-5: Late-News Paper: Investigating Thymine, a DNA Base, as the Hole Transport Layer for Enhanced Performance in Quantum Dot Light Emitting Diodes. In *SID Symposium Digest of Technical Papers* (Vol. 55, No. 1, pp. 592-594).

4. Jang, J., Yoo, J. I., Panov, V. P., Kim, H. B., Kang, S. C., Choi, E. Y., & Song, J. K. (2024). P-223: Late-News Poster: Alleviating Gamma Curve OLED Device with Inductor by AC Driving. In *SID Symposium Digest of Technical Papers* (Vol. 55, No. 1, pp. 1483-1485).

5. Yoo, J. I., Kim, H., Kang, S. C., Kim, K. H., Jang, J., Kim, G., & Song, J. K. (2023). Analysis of Various solvents for Hole Transport Layer in Tandem Structure Quantum Dot Light Emitting Diode. In *Digest of Technical Papers-SID International Symposium* (Vol. 54, No. 1, pp. 1766-1769).

6.Zhang H, Sun X, Chen S. Over 100 cd A−1 Efficient Quantum Dot Light-Emitting Diodes with Inverted Tandem Structure. Advanced Functional Materials. 2017;27(21).

7.Kim MG, Kanatzidis MG, Facchetti A, Marks TJ. Low-temperature fabrication of high-performance metal oxide thin-film electronics via combustion processing. Nat Mater. 2011;10(5):382-8.

8. Kim, H. B., Choi, E. Y., Yoo, J. I., Kang, S. C., & Song, J. K. (2024). P-162: Green solvent for fabricating inverted QD-LED. In *SID Symposium Digest of Technical Papers* (Vol. 55, No. 1, pp. 1997-1999).

9. Kim, J. B., Yoo, J. I., Kim, H. B., Jang, J., & Song, J. K. (2024). Investigation on Enhanced Performance of All-solution Inverted Quantum Dot Light Emitting Diode via Changing a Solvent

10. Kim HB, Yoo JI, Kang SC, Song JK. Green Solvent Selection for All Solution-Processed Inverted Quantum Dot Light Emitting Diode. Small. 2024;20(4):e2304051.