200% Resolution Improvement by Pixelization using Multi-Color Device

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Abstract

We developed dual- and triple-color QLED devices with charge injection mechanisms and addressed alternative sub-pixel layouts, achieving 50 and 200% resolution improvement over conventional RGB sub-pixel layout. These devices enable precise color tuning and are ideal for high-resolution applications, including AR/VR systems.

Author Keywords

High resolution, Multi color device, Pixelization, PWM driving

1. Introduction

Immersive display technologies, such as augmented reality (AR) and virtual reality (VR), are becoming integral to modern life, necessitating displays with ultra-high pixel densities, often exceeding thousands of pixels per inch (PPI). Achieving such high PPI is crucial for delivering sharp, lifelike images and avoiding visual artifacts like the "screen-door effect," which can degrade the immersive experience. (1) Conventional displays typically operate at a few hundred PPI, but scaling this up to meet the demands of AR/VR devices presents significant technical challenges.

The traditional RGB pixel configuration, where red, green, and blue sub-pixels are arranged side-by-side to reproduce colors, is widely used in conventional displays. However, this layout becomes increasingly inefficient as pixel density rises. To achieve higher resolution using this configuration, two main strategies are typically employed: 1) increasing the overall panel size or 2) reducing the size and pitch of individual pixels. Both approaches face significant limitations—larger panels are impractical for near-eye applications like AR/VR headsets, while reducing pixel size leads to complex manufacturing processes and reduced aperture ratios, which in turn affect brightness and color accuracy.

Moreover, as pixel density increases, the geometric fill factor decreases, further complicating the challenge of maintaining brightness and efficiency. Emerging technologies such as electrohydrodynamic-jet printing, photolithography, transfer printing, and direct patterning have been explored to overcome these limitations. (2) However, these methods still struggle to meet the stringent requirements for AR/VR displays. New approaches involving alternative sub-pixel layouts—such as dual-color or multi-color emitting pixels—offer promising solutions by reducing the number of sub-pixels required for full-color reproduction. These innovations could significantly enhance display resolution without compromising on performance or manufacturability.

In this presentation, we introduce two dual-color quantum dot light emitting diode (QLED) devices and explore their application in achieving high-resolution displays. We propose a multi-color device capable of resolution improvement replacing conventional RGB configurations. For the dual-color devices, we developed two distinct structures: one utilizing electron-only injection and the other employing hole-only injection. Both structures demonstrated sufficient brightness and wide color gamut through pulse-width modulation (PWM) driving. To achieve pixelization, we employed lift-off processes and ink-jet printing to configure sub-pixel layouts. The proposed sub-pixel configurations—RG/B and RB/GB—successfully reproduced both primary and complementary colors using DC and AC driving. Importantly, our proposed approach can be applied to both QLED and OLEDs, offering a promising pathway for the high-resolution displays.

2. Experimental

Materials: PEDOT:PSS (Al40383) was purchased from Ossila. Poly(9-vinylcarbazole) (PVK), chlorobenzene, anisole, 1,4-dioxane, and aluminum doped zinc oxide nanoparticle (AZO NP) were purchased from Sigma-Aldrich. CdSe core red, green, and blue QD were purchased from Zeus (Korea) and dispersed 20mg/ml concentration in toluene. ZnO nanoparticles (NP) were synthesized and dissolved in 1-butanol as 160mg/ml concentration.

Synthesis of ZnO NPs: TMAH 0.3 M was dissolved in 10 ml ethanol. Zinc acetate dihydrate 0.5 M was dissolved in 20 ml DMSO. TMAH in ethanol solution was added to zinc acetate dihydrate in DMSO solution at 1ml/min speed. The mixture was stirred for 1h in ambient air and maintained 4℃. After stirring, acetone was added for rinsing to the mixture in 3:2 volume ratio, and the mixture was centrifuged at 8000 rpm for 5 min. Last, ZnO NPs were dispersed in anhydrous butanol at a concentration of 160 mg/ml.

Device Fabrication & Characterization: Patterned ITO glass is sonicated by acetone and IPA solution each 10min. Rinsed with DI water and annealed on 150°C hot plates. After cleaning, ozone treatment during 10 min. Spin-coating and annealing process were proceeded in dry-air flowing glovebox. PEDOT:PSS spin-coated as hole injection layer (HIL) 6000 rpm during 40 s and baked 120°C during 20 min. PVK spin-coated as hole transport layer (HTL) 6000 rpm during 40 s and baked 140°C during 20min. All QDs spin-coated as emission layer 6000 rpm during 40 s and baked 120°C during 20 min. (3) AZO NPs spin-coated as electron transport layer (ETL) 6000 rpm during 40 s and baked 140°C during 20 min. After spin-coating and baking process, metal deposited 100 nm by thermal evaporation under high vacuum. J-V-L measurements were conducted on source measurement unit and spectroradiometer (McScience M6100, Korea).

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3. Results & Discussion

Dual color device: To achieve dual-color emission under both DC and AC driving conditions, we developed QLED devices with charge injection and generation mechanism. These devices enable primary colors, such as red, green, and blue, to be achieved through DC driving, while complementary colors, including yellow, cyan, and magenta, are generated via AC pulse-width modulation (PWM) driving. This dual-driving capability allows precise control over color reproduction, making the devices highly suitable for high-resolution and high-color-performance displays.

To realize emission under both DC and AC driving modes, we designed QLED structures where one type of charge is injected from the electrodes while the other type is generated internally within the device. This design ensures that each emission layer can be selectively activated depending on the applied bias. Two distinct device structures were implemented: electron-only injection (EOI) and hole-only injection (HOI). In the EOI structure, electrons are injected from the electrodes under both forward and reverse biases, while holes are generated internally within the device and subsequently injected into the emission layers to facilitate recombination and light emission. Conversely, in the HOI structure, holes are injected from the electrodes into the emission layers under both forward and reverse biases, while electrons are generated internally within the device and injected into the emission layers.

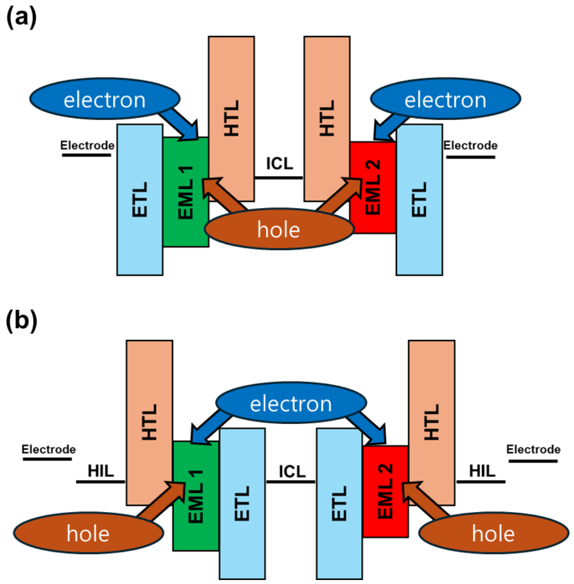

Figure 1. Schematic of dual color device (a) electron only injection structure (b) hole only injection structure.

We fabricated an electron-only injection QLED in 2020, utilizing green and red quantum dots (QDs) as the first and second emission layers (EMLs), respectively in Fig. 2a. (4) The driving mechanism of this device is illustrated in Fig. 2b. Under forward bias, electrons are injected from the aluminum (Al) cathode into the red QD EML, while holes are generated at the green QD/PVK junction within the device. These internally generated holes are subsequently injected into the red QD EML, where they recombine radiatively with the injected electrons to produce light emission. Conversely, under reverse bias, electrons are injected from the indium tin oxide (ITO) into the green QD EML, while holes are generated at the PVK/red QD junction. These holes are then injected into the green QD EML, leading to radiative recombination and light emission. This bidirectional charge injection and generation mechanism enables selective activation of each EML depending on the applied bias polarity, allowing precise control over which color is emitted.

To achieve mixed colors from both green and red EMLs, we adopted pulse-width modulation (PWM) driving. The concept of PWM driving is depicted in Fig. 2c. In this method, a duty cycle of 0% corresponds to exclusive reverse bias driving, resulting in pure green emission, while a duty cycle of 100% corresponds to forward bias driving, resulting in pure red emission. By modulating the duty cycle between these two extremes, we achieved a wide range of intermediate colors through controlled mixing of green and red emissions.

Figure 2d demonstrates this wide color-tuning range in the CIE color space, showcasing how PWM modulation allows for precise adjustment of color output. Detailed spectral data for mixed colors are presented in Fig. 2e. These spectra illustrate how varying the duty cycle enables smooth transitions between green and red emissions, confirming the effectiveness of PWM driving for achieving a broad color gamut. Additionally, Table 1 summarizes the optoelectronic characteristics of the electron-only injection QLED. A significant difference in external quantum efficiency (EQE) was observed between forward and reverse biases, primarily due to solvent damage to the green QD EML caused by PVK during fabrication. (5) Despite this challenge, these results highlight the potential of electron-only injection devices for achieving tunable dual-color emission with simple structural designs.

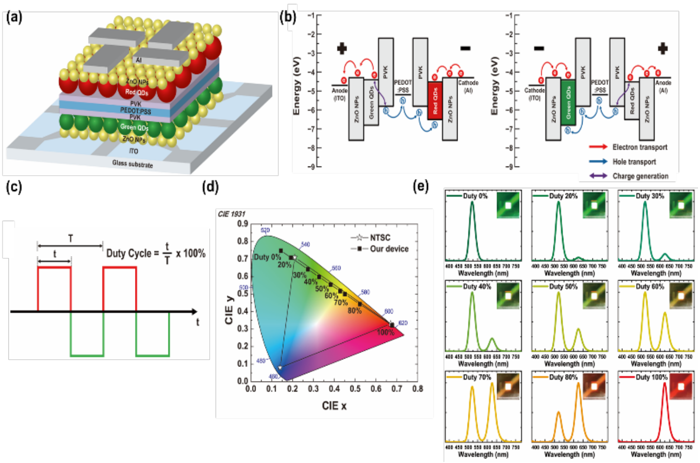

Figure 2. (a) Schematic of electron only injection QLED (b) Driving mechanism of device under both bias (c) Duty cycle of PWM driving (d) Color coordinate with PWM driving in CIE 1931 (e) Spectra of device with PWM driving.

Table 1. Opto-electric characteristics of EOI device.

Device	Bias	L_{max} [cd/m^2]	V_T [V]	V_{max} [V]
Green-Red	Forward (Red)	3389	6.8	40
	Reverse (Green)	2411	15.1	34

In Figure 3, we present the hole-only injection (HOI) QLED device and its performance under various driving conditions. (6) Fig. 3a and 3b illustrate the device structure and the driving mechanism under both forward and reverse biases. The HOI QLED was designed to enable selective emission from stacked emission layers (EMLs) by injecting holes directly from the electrodes while generating electrons internally within the device. This configuration ensures efficient charge recombination at the desired EML, enabling dual-color emission controlled by the applied bias polarity. (7) We fabricated three variations of the HOI QLED device, each utilizing different combinations of quantum dot (QD) EMLs: green-red, blue-green, and blue red.

Figure 3c shows luminous images of these devices under DC bias and PWM driving. Under DC bias, primary colors such as green, blue, or red were emitted depending on the activated EML. In contrast, complementary colors such as yellow, cyan, or magenta were achieved through PWM driving by modulating the duty cycle. This demonstrates the versatility of HOI QLEDs in reproducing a wide range of colors. The color modulation properties of the three devices are depicted in Figure 3d. By adjusting the duty cycle during PWM operation, we achieved smooth transitions between primary and complementary colors. The color gamut of the HOI QLED devices reached approximately 84% of the Rec. 2020 standard, highlighting their potential for high-performance display applications.

Detailed spectra of the devices under PWM driving are shown in Fig. 3e. These spectrums confirm that precise control over color mixing was achieved for all three device configurations, enabling a wide range of tunable colors. Table 2 summarizes the opto-electronic characteristics of the green-red, blue-green, and blue-red HOI QLED devices. The results show that each EML operates independently depending on the applied bias direction, ensuring efficient dual-color emission. Overall, these results demonstrate that HOI QLEDs provide a robust platform for achieving dual-color emission with high brightness and color tunability.

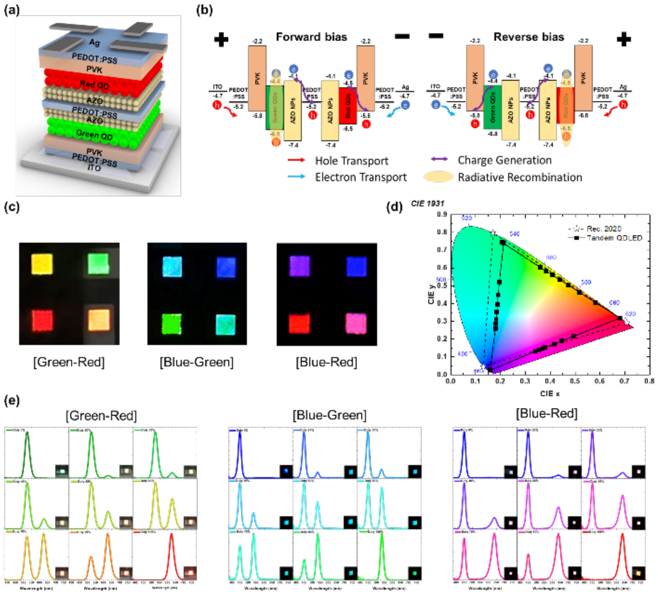

Figure 3. (a) Schematic of hole only injection QLED (b) Driving mechanism of device under both bias (c) Picture of green-red, blue-green, and blue-red device under DC & AC driving (d) Color coordinate of three device with PWM driving in CIE 1931 (e) Spectra of three device with PWM driving.

Table 2. Opto-electric characteristics of HOI devices.

Device	Bias (color)	L_{max} [cd/m^2]	V_T [V]	V_{max} [V]
Green-Red	Forward (Green)	8225.6	5	28.5
	Reverse (Red)	4096.9	12.5	23
Blue-Red	Forward (Blue)	307.29	10	28.5
	Reverse (Red)	4017.7	13	24
Blue-Green	Forward (Blue)	269.81	14.5	30.5
	Reverse (Green)	6172.2	7	26

Pixelization: To compose sub-pixel layouts using dual-color QLED devices, we employed two distinct fabrication techniques: the lift-off process and ink-jet printing. These methods allowed us to configure two types of sub-pixel layouts, RG/B and RB/GB, as illustrated in Figure 4. Each approach was carefully optimized to ensure precise patterning and reliable device performance.

In the lift-off process, we aimed to fabricate an RG/B sub-pixel layout as shown in Fig. 4a. (8) The process began by fabricating blue QLEDs on the substrate at the first. Afterward, a stripper solution was applied to selectively remove the blue QLED from specific positions on the substrate, leaving behind patterned blue sub-pixels. Subsequently, a red-green dual-color device was spin-coated onto the substrate to complete the configuration. In this layout, red and green emissions, as well as intermediate colors between red and green, were achieved through AC driving of the red-green sub-pixels. Meanwhile, blue sub-pixels were driven independently under DC bias. This configuration demonstrated efficient color separation and mixing while maintaining adequate performance.

For the RB/GB sub-pixel layout, ink-jet printing was utilized to pattern red and green quantum dots (QDs) directly onto the assistance layer. (9) This method followed the same dual-color device structure used in our previous designs. To achieve uniform deposition of QDs the coffee-ring effect on the red and green EML, we optimized the solvent ratio based on Hansen solubility parameters. This optimization ensured that the solvents used during ink-jet printing were compatible with both QD materials and adjacent layers, resulting in smooth and uniform EMLs. The RB/GB layout enabled emission of primary colors (red, green, and blue) as well as complementary colors through AC-driven color mixing in red-blue or green-blue sub-pixels. These results highlight the versatility of our fabrication processes in alternative sub-pixel layouts tailored for high-resolution displays.

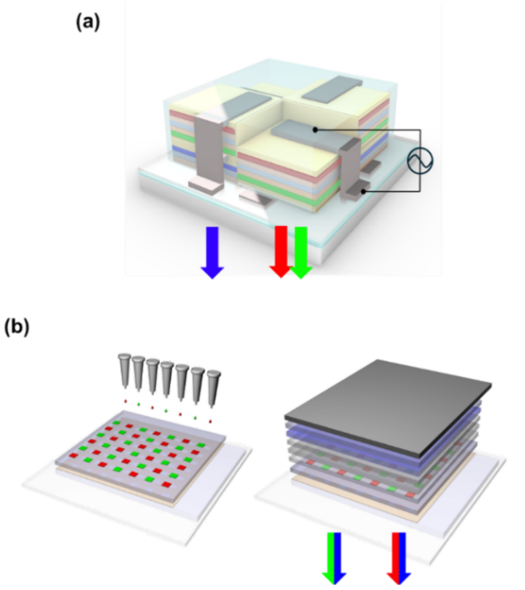

Figure 4. (a) Schematic of RG/B pixelization using lift-off process (b) Schematic of RB/GB pixelization using ink-jet printing.

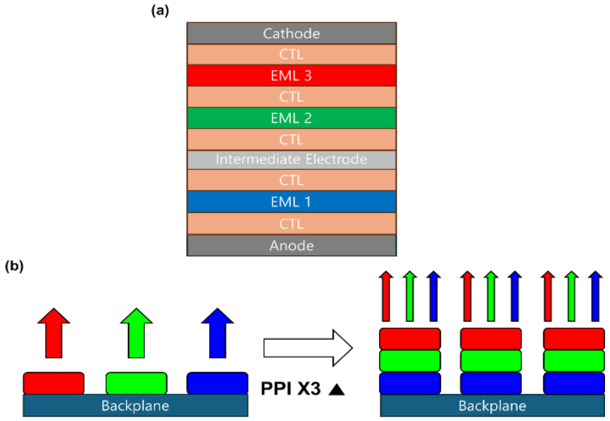

Figure 5. (a) Schematic of triple color device (b) Schematic of resolution improvement using triple color device.

Triple color device: We proposed an alternative approach to improving pixel resolution in conventional displays by utilizing dual-color devices and re-arranged sub-pixel layouts. Building upon this concept, we aim to develop a triple-color device capable of emitting both primary and complementary colors within a single device structure as shown in Fig. 5a. We expect this design to achieve a significant resolution enhancement of 200% compared to the traditional RGB pixel layout as shown in Fig. 5b. By adopting this approach in display applications, we envision applications not only in conventional displays but also in AR/VR systems.

4. Conclusion

In this work, we demonstrated innovative approaches to achieving ultra-high resolution and enhanced color performance in next-generation displays by leveraging dual-color and triple-color QLED devices. Through the development of electron-only and hole-only injection structures, we achieved precise control over emission layers under both DC and AC driving conditions, enabling the reproduction of primary and complementary colors.

By adopting advanced fabrication techniques such as lift-off processes and ink-jet printing, we successfully configured alternative sub-pixel layouts, including RG/B and RB/GB, which showcased efficient color mixing and reliable device performance. These results highlight the potential of dual-color QLEDs to overcome the limitations of conventional RGB layouts, offering a pathway to higher pixel densities.

Building on this foundation, we proposed a triple-color QLED device capable of emitting primary and complementary colors within a single pixel structure. This design offers a transformative solution for achieving a 200% resolution improvement compared to traditional RGB configurations, making it highly suitable for applications in AR/VR systems and other high-resolution display technologies. The ability to integrate these devices into existing manufacturing processes like OLED further underscores their practicality for commercial adoption. Our findings pave the way for future advancements in pixel design and display technology, addressing the growing demand for compact, high-performance displays in immersive applications.

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