Color Temperature Control of AC Tandem QD-LEDs Using AC Driving Scheme

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Abstract

In this study, we developed a AC-driven tandem QD-LED that allows wide tunable color temperature for white light. This device enables the creation of a lighting environment where the color temperature can be easily adjusted based on the user's preferences, environment and physical response for enhanced comfort.

Author Keywords

QD-LED; Color temperature control; lighting; PWM driving

1. Introduction

In the past, humans relied on natural light, but now we are utilizing artificial lighting to make better use of "light". With the advent of artificial lighting, we have become subject to its influence both day and night, and it has a significant impact on our psychological, emotional and physical well-being. In particular, users are greatly affected by the color temperature of the lighting. A color temperature below 3300K emits a warm yellow light, while a color temperature above 5000K creates a cool blue light. Generally, cool blue lighting helps clear the mind and improve concentration, so higher color temperature lighting is used in spaces such as offices and schools during daytime activities to boost focus and energy. Conversely, warm orange lighting is used in spaces like restaurants and homes where relaxation is needed, helping to relax both the body and mind. In Figure 1, it shows the appropriate color temperature of lighting according to the user's work environment. Since lighting has various effects on our physical and emotional states, it is important to adjust the color temperature based on the function of the space and the user's mood. (1)

Since lighting environments affect users' psychological changes, lighting systems with adjustable color temperature are highly versatile. Typically, lighting devices have a fixed color temperature, which limits the atmosphere that can be created with a single device. However, there are many instances where a single space must serve multiple purposes. For example, in an office, cool lighting is used for most of the day for work, but warm lighting during break times, such as lunch, can help improve work efficiency by allowing for sufficient relaxation. In home spaces, a bedroom is both a space for rest and, at times, a space for work or study. Thus, lighting that can freely adjust the color temperature is an efficient tool for using a single space for various purposes. Additionally, since each user may have different preferences for color temperature, lighting that covers a wide range of color temperatures is more practically usable.

This study introduces a QD-LED device with adjustable color temperature using AC driving and explores how it can be applied to lighting systems. The QD-LED structure used is a tandem structure that supports both DC and AC driving. This structure utilizes hole-only injection and an n-p-n interconnecting layer, where the bottom EML emits light under forward bias and the top EML emits light under reverse bias. (2) AC PWM driving controls the emission times of bottom EML and top, allowing for color temperature adjustment. The bottom EML contains a mixture of blue, cyan and green QDs in appropriate ratios, while the top EML contains a mixture of yellow and red QDs in suitable ratio. In this study, the ratios of QDs in the bottom and top EMLs were adjusted to move along the Planckian locus in the CIE 1931 color space, providing a wide range of color temperature modulation and high CRI. This approach is expected to enable the creation of a user-customized lighting environment.

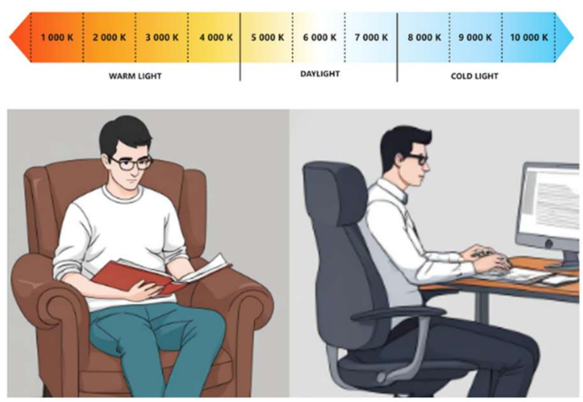

Figure 1. Approprate color temperature of lighting according to user's work environment.

2. Experimental

Materials: PEDOT:PSS (Al40383) was purchased by Ossila. Poly(9-vinylcarbazole) (PVK), chlorobenzene, 1,4-dioxane, and aluminum doped zinc oxide nanoparticle (AZO NP) were purchased by Sigma-Aldrich. CdSe core red, green, blue, yellow and cyan QDs were purchased by Zeus (Korea) and dispersed 5mg/ml concentration in toluene.

Ratios of QD EML: In bottom EML, The ratio of blue, cyan and green QDs was combined in a B:C:G=5:4:0.5 ratio. In top EML, The ratio of yellow, red QDs was combined in a Y:R=7:3 ratio.

Device Fabrication & Characterization: Patterned ITO glass is sonicated by acetone and IPA solution each 10min. Rinsed with DI water and annealed on 150℃ hot plates. After cleaning, UV-ozone treatment during 10min. Spin-coating and annealing process were proceeded in dry-air flowing glovebox. PEDOT:PSS spin-coated as hole injection layer (HIL). In the first step, coated 3000rpm during 30s and baked 120℃ during 15min and the remaining steps are coated 6000rpm during 60s and baked

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100℃ during 15min. PVK spin-coated as hole transport layer (HTL) 6000rpm during 30s. PVK with chlorobenzene is baked 120℃ and PVK with 1,4-dioxane is baked 100℃ during 15min. All QDs spin-coated as emission layer 6000rpm during 30s and baked 100℃ during 15min. AZO NPs spin-coated as electron transport layer (ETL) 6000rpm during 30s and baked 100℃ during 15min. After spin-coating and baking process, metal deposited 100nm by thermal evaporation under high vacuum. J-V-L measurements were conducted on source measurement unit and spectroradiometer (McScience M6100, Korea).

3. Results & Discussion

As shown in Figure 2, we implemented a white QD-LED using a tandem structure. The bottom EML was designed with cold-tone white, including blue, cyan, and green QD. While the top layer was designed with warm-tone white, including yellow and red QD. By utilizing AC PWM driving, the color temperature could be adjusted according to the operation time of the bottom and top EMLs. This device can be applied as a QD-LED lighting solution that is capable of achieving a wide range of color temperatures, from low to high, within a single pixel, depending on the duty cycle.

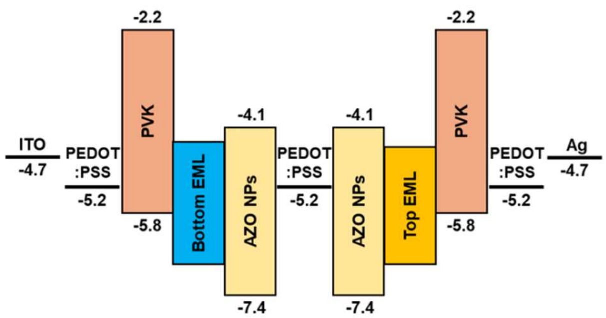

Figure 2. Schematic of AC driven tandem QD-LED

To create lighting close to white light, we repeatedly conducted experiments while adjusting the QD ratio to implement a QD-LED that closely follows the Planckian locus in the CIE 1931 color space. Through AC PWM driving, we found the QD ratio of the bottom and top EMLs that moved along the Planckian locus. For the bottom EML, a ratio of blue 5, cyan 4, and green 0.5 was found, while for the top EML, a ratio of yellow 7 and red 3 yielded results closest to the Planckian locus. In Figure 3a shows the color coordinates in CIE 1931 when the device we created was driven with DC/AC. Figure 3b shows the normalized intensity of the device under AC PWM driving. When driven by AC, we observed that the color coordinates of the QD-LED white light closely followed the Planckian locus, depending on the emission ratio of forward and reverse biases. When the forward bias emission ratio was set to 20% (with reverse bias ratio at 80%), the intensity of yellow and red in the top EML was higher, and the color temperature was measured lower. Conversely, when the forward bias emission ratio was set to 80% (with reverse bias ratio at 20%), the intensity of blue, cyan, and green in the bottom EML was higher, and the color temperature was measured higher. In this case, the highest CRI was 92, and the color temperature ranged from 2000 to 8000K. This device has a high CRI, which enables accurate color reproduction of objects, making it highly useful from a commercialization perspective. Additionally, due to the wide range of color temperatures that can be expressed, its practicality is also expected to be high.

Figure 4 shows the emission characteristics of the upper and lower EMLs of the device we created under DC driving. Figure 4a shows the EQE of each EML layer. The top EML exhibits a maximum emission efficiency of over 0.6%, while the bottom EML, though less efficient than the top EML, shows an emission efficiency close to 0.2%. Additionally, referring to previous studies that improved QD-LED emission efficiency by adjusting the type and thickness of the auxiliary layers, it is worth conducting further experiments to enhance the efficiency of the Bottom EML. (3)-(7) Figure 4b shows the luminance of each EML layer based on the applied voltage. Emission from both the bottom and top EMLs is possible within the voltage range of approximately 9 to 17V, and it can be observed that the luminance of the top layer is higher when the same voltage is applied. From the results of Fig. 4a and b, it can be confirmed that, with appropriate applied voltage and color temperature settings, QD-LED lighting has the potential to be used efficiently in daily life.

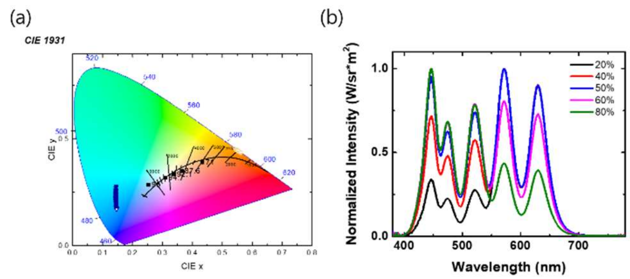

Figure 3. (a) CIE 1931 coordinates by DC, AC driving. (b) Normalized intensity of AC PWM driving

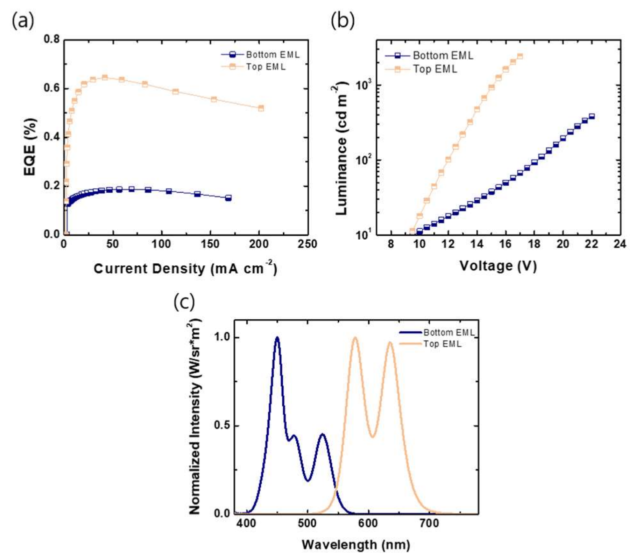

Figure 4. (a) EQE characteristics of each EML under DC bias. (b) Luminance of each EML under DC bias. (c) EL spectra of each EML under DC bias.

4. Conclusion

In this study, we proposed a QD-LED device that utilizes quantum dots and AC driving to achieve a lighting system with adjustable color temperature according to user requirements. By using an appropriate ratio of quantum dots in the bottom and top EML layers of a tandem structure device, we were able to reproduce white light with adjustable color temperature through duty cycle control via AC PWM driving. The color temperature range of the device spans from 2000 to 8000K, which, compared to the previous study by Hong et al. that varied color temperature between 5000 and 7500K, (8) demonstrates the potential for a broader color temperature modulation range in QD-LED devices. Moreover, the wide color temperature modulation range and high CRI further emphasize the commercialization potential of QD-LED lighting compared to conventional LED lighting. Through research on QD-LED Tandem technology using Ink-Jet Printing (9), improving the productivity and popularity of QD-LED devices will make the technology more accessible and familiar to consumers in their daily lives. Our findings present an alternative pathway for the advancement of QD-LED display technology and provide the ability to create lighting devices tailored to user preferences, responding to the growing demand for QD-LED displays.

5. Acknowledgements

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