Transparent Flexible Dual-Color AC Tandem

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Abstract

QD-LED displays offer a wide range of colors, high purity, brightness, and ultra-thinness. Our research combines QD-LED with technologies of transparent electrodes, flexible and dual-color AC trends to create a high-resolution, flexible and transparent display device that can be used in various ways.

Author Keywords

QLED; Quantum dot; AC tandem; Dual color; Flexible

1. Introduction

The main purpose of the display device is to reproduce the natural visual experience by imitating the color and brightness of the actual scene on a flat surface. Most flat panel displays produce a variety of colors by arranging three subpixels (red (R), green (G), and blue (B) side by side.[1-3] However, this configuration is less resolved and less efficient due to its low geometric fill factor, and requires a complex and expensive manufacturing process, especially for organic light emitting diode (OLED) and quantum dot light emitting diode (QD-LED) applications. Among them, QD has various advantages such as wide color gamut, high security, brightness, and ultra-thin form, but to address the side-by-side structure problem, our research group developed a tandem structure that vertically stacks QDs of two different colors (R-G), allowing the device to switch colors according to the polarity of the applied voltage. The brightness can also be controlled by adjusting the voltage intensity. Applying a square wave AC voltage of 60 Hz or higher, the device can mix colors to display shades between R and G.[4-6] This dual-color device reduces the number of subpixels from three to two. Here, We increased the color combination of the AC tandem to R-G, G-B, and B-R to apply this utilization to a better place, and I made a flexible play element using a transparent polyethylene terephthalate (PET) substrate using Yb:Ag, a transparent electrode.[7-12] A transparent display has advantages in terms of space utilization, aesthetics, information provision and interaction, and energy efficiency. In addition, in terms of flexibility, durability, high portability, new forms of innovative design are possible using the PET flexible substrate, which is lightweight and energy-saving. I wanted to suggest the possibility of a highly utilized display by combining the advantages of AC tandem, transparent electrode, and flexible display.

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, green, blue QDs were purchased by Uniam, Republic of Korea.

Device Fabrication: All layers except the electrodes were fabricated by solution treatment using the spin coating method in a glove box under ambient dry air conditions. The patterned ITO PET substrate was successively washed with ethanol and 2-propanol in an ultrasonic bath. The PET substrate was rinsed with deionized water and then treated with oxygen plasma at 50W for 60 s. ZnO NPs were spin-coated and baked in the ITO layer with an electron transport layer (ETL)/electron injection layer (EIL) at 4000 rpm. Next, 20 mgmL-1 solution of CdS/ZnS core shell green, red, and blue QD was spin-coated at 6000 rpm for 30 s and then baked at 120°C for 20 min to form EML. The HTL layer was formed by spin coating (PVK) dissolved in 1,4-dioxane (Sigma Aldrich, USA) on the Cds/ZnS QD layer at 8000 rpm for 30 s and baking for 20 min. The HIL layer was formed by mixing water-soluble PEDOT: PSS (Clevios PAI 4083) with ethanol at a volume ratio of 1:1 to overcome the low wettability of the hydrophobic PVK layer. The second HTL layer was then spin-coated on the PEDOT layer with PVK (Sigma Aldrich, USA) dissolved in 1,4-dioxane at 8000 rpm for 30 seconds and baked for 20 minutes, and on that layer, a solution of CdS/ZnS core shell blue, green, and red QD 20 mgmL-1 was spin-coated at 6000 rpm for 30 seconds and then baked at 120°C for 20 minutes to form a second EML. The ZnO NPs were then formed at 4000 rpm to form a second residue transport layer (ETL)/electron injection layer (EIL). Finally, the Yb:Ag electrodes were thermally evaporated with a shadow mask under high vacuum conditions (1×10-6 Torr).

3. Results & Discussion

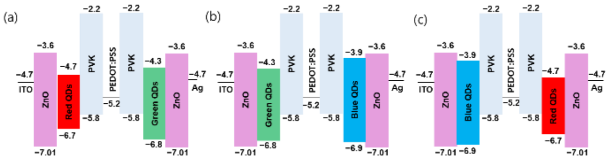

Figure 1. Schematic of AC tandem structure QD-LED, (a) R-G dual color AC tandem, (b) G-B dual color AC tandem, (c) B-R dual color AC tandem

The AC tandem structure has HOD and EOD structures, and also has various uses.[4,13-15] It was manufactured with EOD as shown in Figures 1a, 1b, and 1c. The first and second EML layers were manufactured using R-G, G-B, and B-R in that order.

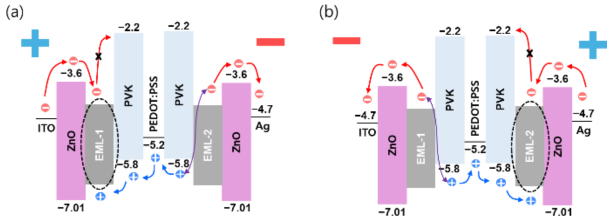

Figure 2. Flow of holes and electrons (a) when a constant voltage is applied, (b) when a reverse voltage is applied

In Figure 2, an exciton, a quasi-particle formed by an electron and a hole, emits light upon recombination. While electron-only devices (EODs) typically cannot exhibit electroluminescence (EL) due to their exclusive injection of electrons, EL becomes possible if charge generation within the EOD structure produces holes. [5,6] As shown in Figure 2a, applying a positive voltage injects electrons from the silver electrode, while holes are blocked by the high highest occupied molecular orbitals (HOMO) of ZnO nanoparticles. These electrons are confined in EML2 due to PVK's low lowest unoccupied molecular orbitals (LUMO). Simultaneously, holes are generated at the PVK and EML1 interface through Zener breakdown and move to EML2, where excitons form and induce light emission from EML2. Conversely, in Figure 2b, under a reverse voltage, electrons inject from the ITO electrode, and holes are generated at the EML2/PVK interface, leading to exciton formation in EML1 and resulting in light emission. The emitting layer (EML) can be selected based on the electric field direction, while luminance is adjustable through voltage magnitude. Since the human eye perceives light flickering above 60 Hz as a blended color, applying a square AC voltage enables color mixing.[4]

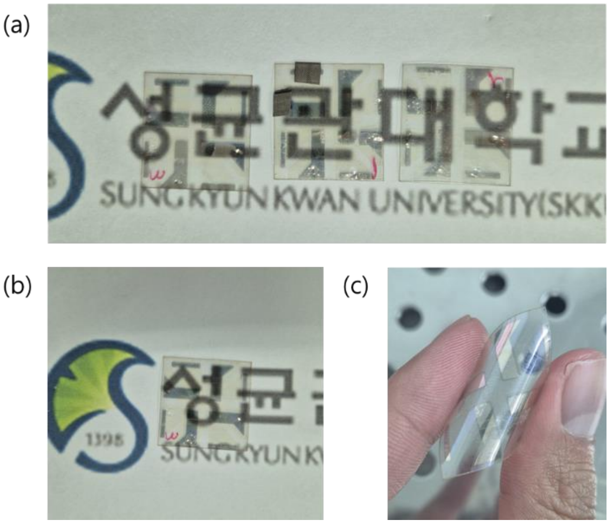

Figure 3. (a) a picture of the finished element, (b) Transparent properties of substrates, (c) Flexible properties of substrates

The transparent and flexible AC tandem made the device. The colors are made of R-G, G-B, and B-R in the light emitting layer, as mentioned earlier. Figure 3a shows the actual appearance of the device. Figure 3b confirmed the transparent properties by placing the transparent electrode Yb:Ag on the letters because the cathode was used.[7] Figure 3c shows the flexibility of the completed device by bending the substrate to show its properties.[8]

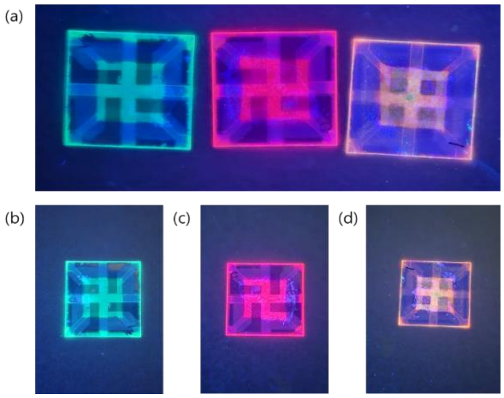

Figure 4. (a) Full appearance when UV light is applied to the device, (b) G-B cyan, (c) B-R purple, (d) R-G yellow

To see if the appropriate light emitting layer was installed with this finished device, we first checked what color was emitted by shining UV light. If you look at Figure 4a, you can see that the light emitting layer is well laid overall. If you look more closely, you can see that in Figure 4b, the green and blue light emitting layers are mixed with G-B to emit cyan light. You can see that 4c is B-R, which is purple, and 4d is R-G, which is yellow.

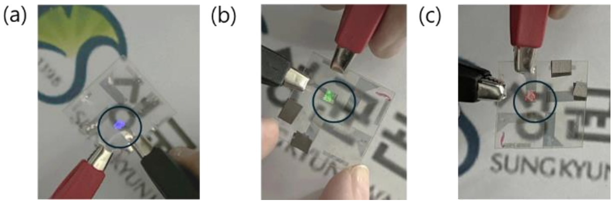

Figure 5. Photographs that emit light in the device (a) blue light (b) green light (c) red light

We tried electroluminescence on this device. If you look at Figure 5a, 5b, and 5c, you can see that these transparent flexible devices emit light, blue, green, and red, respectively, which are the colors of the first emission layer. And when you give a reverse voltage, they emit light from the second EML layer.

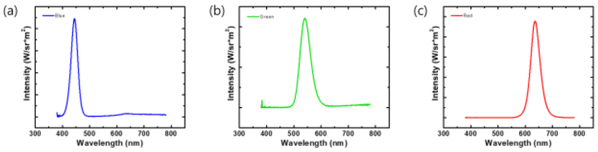

Figure 6. Electrical Spectrum (a) blue peak, (b) green peak, (c) red peak

We checked that the EL spectrum emits the right light that matches the color we saw. If you look at Figure 6a, 6b, and 6c, you can see that they emit light in the blue, green, and red wavelength bands. However, I think optimization problems are still necessary due to problems such as low efficiency and short lifetime. However, if we solve these problems, we think we can show various applications, so we are going to study it further while developing it in future studies.

4. Conclusion

In this study, we successfully developed a transparent and flexible dual-color AC tandem QD-LED device with a vertically stacked structure. By combining transparent electrodes, flexible substrates, and AC voltage operation, we demonstrated a high-resolution display capable of emitting a variety of colors through effective color mixing. The use of a PET substrate further enhanced the device's flexibility and portability, paving the way for innovative design possibilities. Despite challenges such as low efficiency and limited lifetime, our findings highlight the potential of this technology for diverse applications, including advanced displays and interactive devices. Future research will focus on optimizing performance and expanding its practical applications.

5. Acknowledgment

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