MEET4-2
Invited

Optimization of Quantum Dot Mixed Layer for White Light-Emitting Diodes with Wide Color Correlated Temperatures

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Keywords: Quantum dots, White, Color correlated temperature, Color rendering index

ABSTRACT

White quantum dot (QD) light-emitting diodes (QLEDs) is advantageous for implementing white devices using mixed QDs in the emitting layer. Here we fabricated white QLEDs based on mixed QD layers, which exhibit a high color rendering index and a wide range of color correlated temperature by changing the QD-mixing ratios.

1 INTRODUCTION

Colloidal nanocrystal quantum dots (QDs) have attracted attention especially for QD based light-emitting diodes (QLEDs), owing to the easy color tunability by controlling the size of the QD core, simple solution processibility, and great colloidal stability.[1, 2] QLEDs emitting red, green, and blue colors have thus been widely investigated for the next-generation display technologies based on QLEDs. However, white QLEDs have not been studied that much compared to those monochromatic QLEDs. Development of white-emitting devices is highly required for their possible application in solid-state lighting and future display devices with color filters. White QLEDs have several merits by comparing with commercialized white organic light-emitting diodes (OLEDs); first, OLEDs require highly complicated deposition processes to form stacked blue/yellow or blue/green/red emitting layers (EMLs).[3] On the contrary, white QLEDs have a simple fabrication process by mixing several colors of QDs in solution and used it as a single EML.[4] Second, in white OLEDs, to change or tune the white emission spectrum, it is necessary to design and synthesize new light-emitting materials. In case of QDs, by precisely controlling the size of QDs and adjust blending the ratio, a desired emission spectrum can be obtained.

For the white light sources, a color rendering index (CRI) and a color correlated temperature (CCT) are the important factors to present the quality of white light. The CRI is an index that estimates the ability of reproducing the colors of objects in comparison with the natural light. Also, the CCT should be controlled based on the purpose of the lighting device because it significantly affects the our lives, for instance, the growth of plants and human metabolism.[5, 6] However, there are few researches on the CRI and CCT in QLEDs.

Here we demonstrated white QLEDs composed of six primary colors, covering a wide range of CCTs by simply change the blending ratio of the QDs. The CCT was controlled from 4000 K to 7600 K which corresponding to evening sunlight to overcast sky, maintaining a high CRI of >90. The white quality was intensively investigated and we anticipate that white QLEDs can be a promising device for solid-state lighting.

2 RESULTS AND DISCUSSION

To get wide range of spectrum, we used six QDs of red (InZnP/ZnSe/ZnS QDs), yellow (InZnP/ZnSeS QDs), green (InZnP/ZnSeS QDs), cyan (CdZnS/ZnS QDs), blue (CdZnS/ZnS QDs), and violet (CdZnS/ZnS QDs). The device was fabricated in an inverted bottom emission structure of indium-tin-oxide (ITO)/ZnO/ZnMgO (ZMO)/mixed QDs/4,4'-bis(N-carbazolyl)-1,1'-biphenyl (CBP)/MoO_3/Al (**Figure 1a**). Generally, the energy

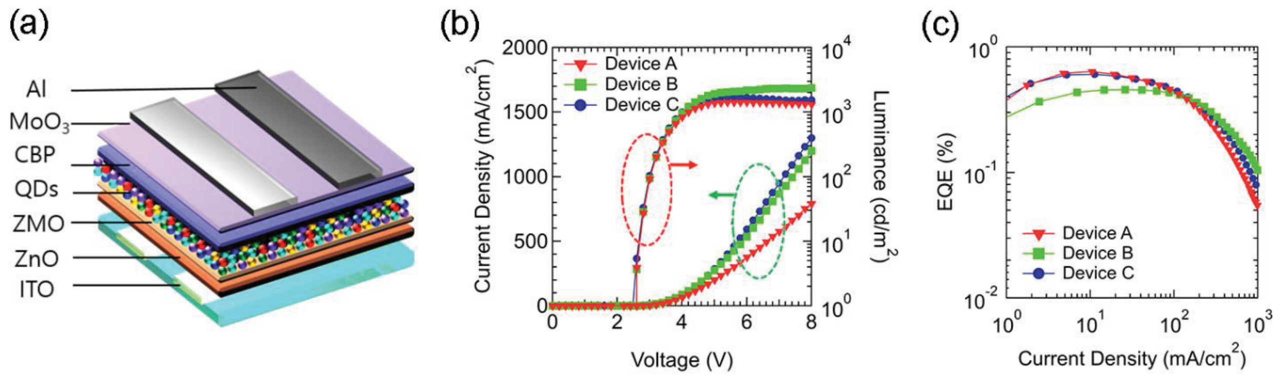

Figure 1. Performance of device A, device B, and device C: a) The device structure, b) current density–voltage–luminance plot, and c) EQE–current density plot.

barrier for hole carriers is much higher than that of electron carriers in a QLED structure, because of the deeper valence energy states of QDs than highest occupied molecule orbital (HOMO) level of typical organic hole transporting materials. It results in a difference in light-emitting characteristics among various colored QDs and a huge color coordinate shift. Therefore, it is important to enhance hole injection to the mixed EML. We used CBP as the hole transporting layer due to its deep HOMO level (5.9 eV) that can reduce the energy barrier for hole injection into QDs. To achieve a wide range of CCT from 3500 K to 7500 K, the QD-mixing ratio has been slightly adjusted based on a simple spectral simulation. The optimized mixing ratios of the QDs for the device A, device B, and device C were red:yellow:green:cyan:blue:violet = 17:24:55:2:12:62, 12:17:58:3:7:67, and 12:17:45:2:5:58, respectively. Figure 1b and 1c shows the characteristics of device A, device B, and device C. Due to the higher content of QDs in device A, it shows slightly decreased current density than device B and C. Except for current density, all performance of white QLEDs were almost similar due to slightly adjusted the ratio of QDs.

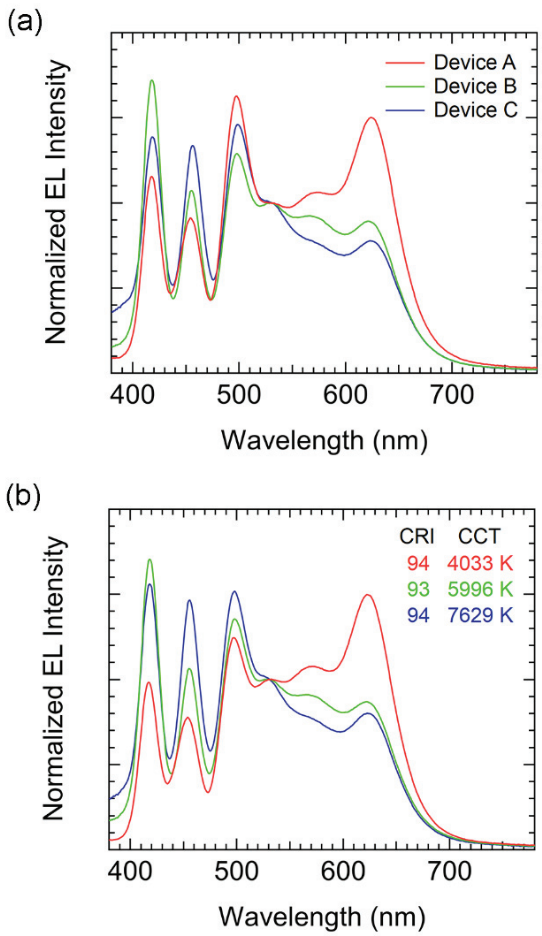

Figure 2. (a) Normalized emission spectra of the devices with different ratios of QDs at 6 V. (b) The spectra for the highest CRI.

Figure 2a shows the normalized emission spectra of the devices at an applied voltage of 6 V. To compare the spectrum of each device with different mixing ratios, the spectra were normalized at the peak of green. Although there is some difference due to the spectrum change during the driving voltages, overall distribution of the spectrum was similar to the mixing ratios. The spectra for the highest CRI in each device was shown in Figure 2b. Considering that the CRI of the standard GaN-based white LED is 83, this is considered high values among the solid-state light-emitting devices. The CCTs were 4033 K, 5996 K, and 7629 K with a high CRI of >90. By slightly changing the ratios of QDs, we could easily tailor the spectrum from warm white to cold white.

Furthermore, each white QLED exhibits a wide range of CCTs in a single device. Figure 3a shows the CCT of the white QLEDs as a function of the current density. At the range from 100 mA/cm^2 to 1000 mA/cm^2, device A, device B, and device C exhibit the CCT range of 3645–4033 K, 4110–5996 K, and 4708–7629 K, respectively. Due to the lack of deep red and abundant deep blue spectrum, the high CCT of the cool white area was implemented. Figure 3b shows the CRI of each device depending on current density, showing that all the devices possess high CRIs.

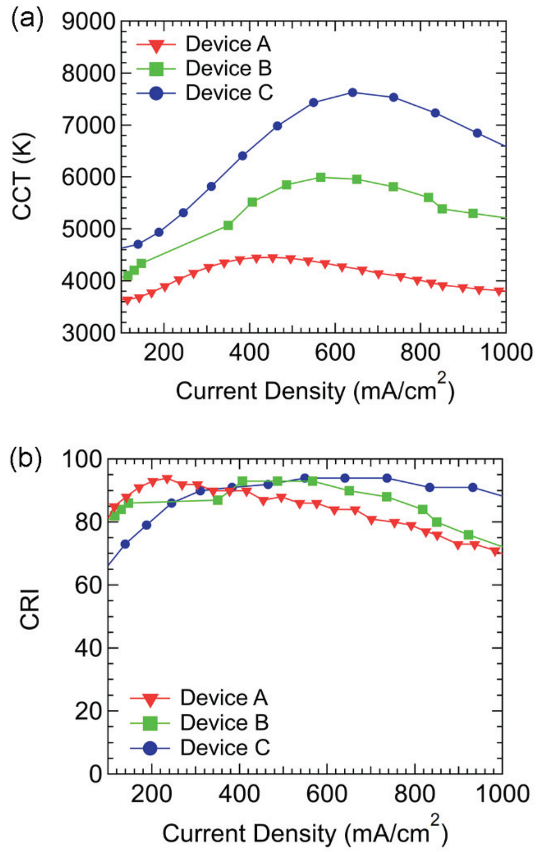

Figure 3. (a) CCT and (b) CRI of the white QLEDs with different mixing ratio depending on current density.

3 CONCLUSIONS

In summary, we fabricate white QLEDs with a diverse range of the CCT by slightly adjust the mixing ration of the QDs. With maintaining the high CRI of >90, warm white to cool white was achieved in the devices. Furthermore, each device could render a wide range of CCT in a single device which corresponds to evening sunlight to overcast sky. We believed this study can be a guidance for further research on a next-generation solid-state lighting sources.

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