The Effect of Particle Size on the Optical and Electrical Characteristics of Quantum Dot Light-Emitting Diode using Zinc Oxide Nanoparticles

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ABSTRACT

The electrical and optical characteristics of QLEDs with 3 and 8 nm ZnO nanoparticles (NPs) were investigated. The QLED with 8 nm ZnO NPs exhibited maximum luminance of 64,360 cd/m^2 and 4.5 times higher current efficiency compared to the 3 nm ZnO device.

1 INTRODUCTION

Quantum dots (QDs) based light-emitting diodes(QLEDs) have attracted significant attention due to the size tunable emission wavelength, the outstanding color purity, high quantum efficiency and solution processability.[1-2] In 1994, QLEDs were firstly reported and then they have been considered one of the promising applications.[3] Many efforts have attempted to improve the performances of the QLEDs. Device structures were adjusted to enhance charge balance.[4-6]

The metal-oxide materials were used as electron transport layers to overcome drawbacks such as low efficiencies, thermal instability and oxygen/moisture induced degradation.[7-8] In this works, zinc oxide nanoparticles (ZnO NPs) are applied in the QLEDs to enhance the device performances. ZnO NPs are suitable to electron transport layer (ETL) owing to their higher thermal stability, insensitivity of oxygen and considerable electron mobility (2 x 10^{-3} cm^2/V·s).[9-11] Thus, ZnO NPs have been considered as a strong candidate for the ETL in QLEDs.

Nevertheless, QLEDs still face some issues, low stability, efficiency roll-off and inadequate lifetime, all of which are associated with charge transport materials and structure. In this work, we synthesize the ZnO NPs which have different sizes, and then designed and fabricated QLEDs to investigate the size dependency of the ZnO NPs on the QLEDs performance.

2 EXPERIMENT

The sol-gel method was used for synthesis of ZnO NPs. For the ZnO NPs, zinc acetate dihydrate, dimethyl sulfoxide (DMSO), tetramethyl-ammonium hydroxide (TMAH) and ethyl alcohol (ethanol) were prepared. Zinc acetate dihydrate was dissolved in 15 ml of DMSO at room temperature. Thereafter, TMAH in 5 ml ethanol was added dropwise into the zinc acetate dihydrate solution with continuous stirring. The mixture was stirred for 0 ~ 24 hrs under ambient conditions. Then sol was precipitated by adding ethyl acetate and collected from the solution by centrifugation. The ZnO NPs were washed and dispersed in ethanol to form a ZnO NPs solution.

The glass substrates with patterned Indium Tin Oxide (ITO) were rinsed with acetone, iso-propanol and de-ionized water. Then the glass was treated with O_2 plasma to increase the work function and to modify surface characteristics. The poly[N,N'-bis(4-butylphenyl)-N,N'-bisphenylbenzidine] (poly-TPD) solutions, which was used as a hole transport layer, were layered onto ITO/glass at 500 rpm for 5 sec, 3,500 rpm for 20 sec. Then CdSe/ZnS core-shell structured QDs (5 mg/ml in heptane) were spin-coated at 2000 rpm for 5 sec. To compare 3 nm and 8 nm ZnO NPs ETL, the ZnO NPs were deposited by spin coating. The thicknesses of the poly-TPD, QD, ZnO NPs were 40 nm, 10 nm and 40 nm, respectively. The Al cathode (100 nm) was deposited using a thermal evaporation under a high vacuum of about 10^{-7} torr.

We used a Keithely-2400 source-measure unit for current density-voltage (J-V) characteristics and the luminance of the devices was measured using a calibrated Si photodiode. The electroluminescence (EL) intensity was measured with Minolta CS-1000 spectrophotometer.

3 RESULTS

Fig.1 shows the transmission electron microscope (TEM) images of ZnO NPs. ZnO NPs have average particle sizes of 3 nm (Fig. 1(a)) and 8 nm (Fig. 1(b)). The figure shows a clear image involving the lattices inside the NPs, indicating the high quality of ZnO NPs.

The device structures of QLEDs are ITO/poly-TPD/QDs/ZnO NPs/Al, in which poly-TPD, CdSe/ZnS QDs, ZnO NPs are hole transport layer (HTL), emission layer (EML), electron transport layer (ETL), respectively. The corresponding energy diagram and the device are shown in Fig. 2. According to fig. 2(b), the electron can be easily injected to QD layer from Al cathode and holes are blocked by the ZnO NPs of the electron affinity of 4.0 eV and ionization potential of 7.4 eV. In addition, the large energy offset between poly-TPD and QD stems the injection of electrons into poly-TPD layer. On the other hand, the injected holes from the anode can be accumulated at the poly-TPD adjacent to the poly-TPD/QD interface owing to large energy barrier of about 0.8 eV at the poly-TPD/QD interface. Nevertheless, the ZnO NPs facilitate the injection of holes by the auger-assisted energy up-conversion process.[12-13] The injected electrons and holes tend to be accumulated at poly-TPD/QD layer. Then, when the hole obtained the high energy from recombination of electron-hole pair, holes gained high-energy can inject to the QD layer and recombine with the electrons inside the QD layer.[14-15]

Fig. 3 shows the EL spectrum of the QLEDs. The peak wavelength of the QLEDs with ZnO NPs is about 541 nm. However, the figure shows additional tails around 600 nm and second peak in 430 nm, it means that charge carriers recombine in poly-TPD and ZnO NPs layer.

To investigate the effect of ZnO NPs size on the performance of the QLEDs, devices with ETL used ZnO NPs were fabricated. The fig. 4 shows a comparison of the device performance and optical properties of QLEDs based on ZnO NPs of 3 nm and 8 nm. The current density and luminance curves as a function of voltage are shown in fig. 4(a) and (b). As shown in fig. 3(a), the 3 nm ZnO NPs based QLEDs exhibit slightly higher current density at high driving voltage region, it seems to be that 3 nm ZnO NPs have the higher electron mobility compared to the 8 nm ZnO NPs. The turn-on voltage of the QLEDs with 3 nm ZnO NPs (~ 2.29 V) is also lower than 8 nm ZnO NPs (~ 2.37 V). It regards that 3 nm ZnO NPs have the higher quantum confinement compared to 8 nm ZnO NPs, and it enhances electron transport.[16] Whereas, the maximum luminance of the QLED with 8 nm ZnO NPs reaches to 17,490 cd/m^2, which is about 3.5 times higher than that (64,360 cd/m^2) of the 3 nm ZnO NPs based device. Also, according to fig. 4(c), the current efficiency of 3 nm ZnO NPs device is 5.43 cd/A, while the efficiency of 8 nm ZnO NPs device is remarkably improved to 22.87 cd/A. This result indicates that the much better charge balance in the 8 nm ZnO NPs devices results in considerable high current efficiency.

4 CONCLUSIONS

The QLEDs with 8 nm ZnO nanoparticles exhibited much higher maximum luminance and current efficiency compared to the 3 nm ZnO device. On the other hand, the driving voltage of 8 nm ZnO device was slightly higher than that of the 3 nm ZnO device. The higher efficiency in the 8 nm ZnO devices was attributed to the better charge balance.

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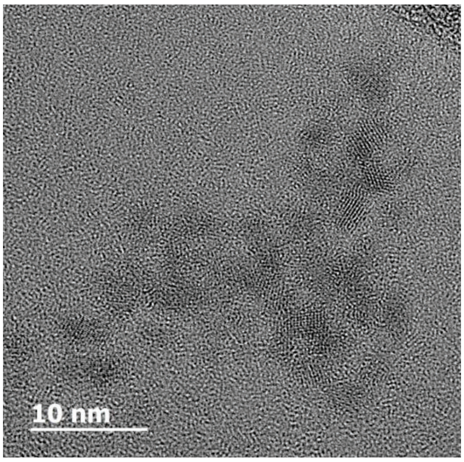
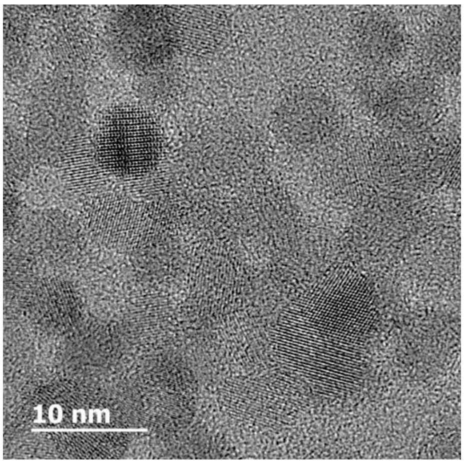
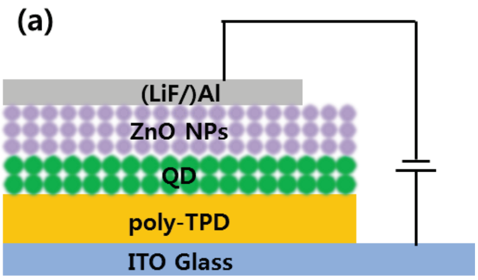


(a)



(b)

Fig. 1 Tem image of (a) 3 nm ZnO NPs (b) 8 nm ZnO NPs



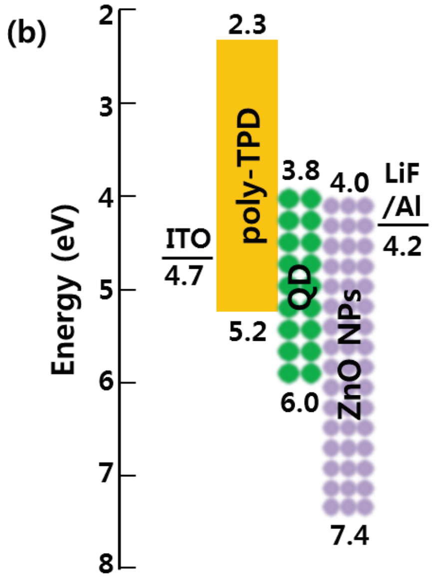


Fig. 2 (a) energy level and (b) device structure of the QLED

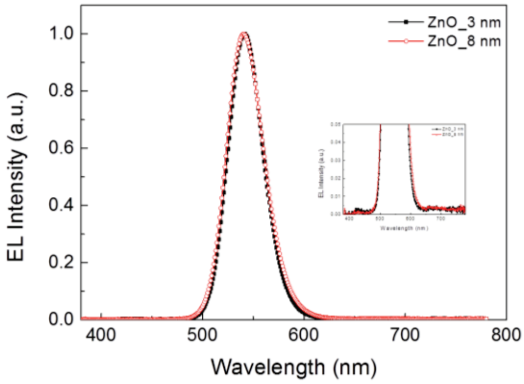
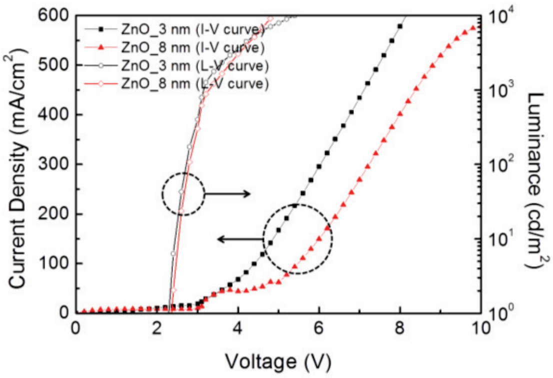
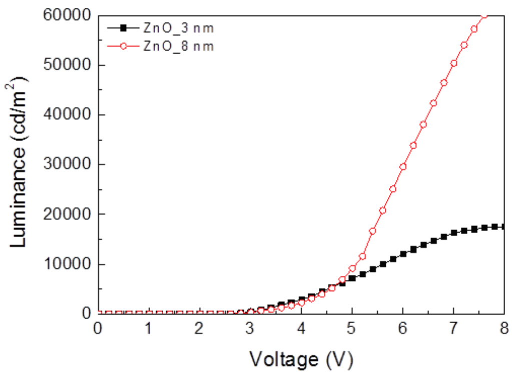


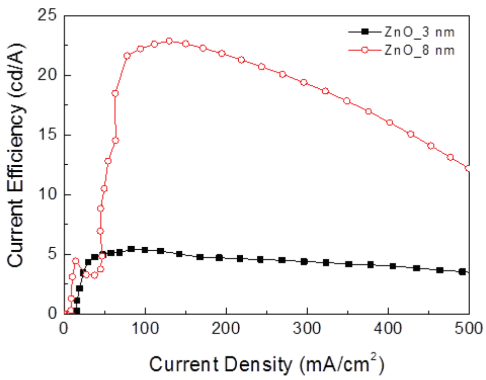
Fig. 2 EL Spectrum for the 3 nm and 8 nm ZnO NPs based QLEDs



(a)



(b)



(c)

Fig. 3 (a) Current density, luminance versus voltage (b) luminance versus voltage, and (c) current efficiency versus current density characteristics for the QLEDs