Supporting Information

Flexible Quantum Dot Light Emitting Diode Based on ZnO Nanoparticles

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1. Optimized procedure of the QLED fabrication

In Figure S1 (a), as the QD layer fixed at 28 nm, the turn-on voltage (V_T) of the device increases from 1.5 V to 2.0 V when the ZnO layer thickness is increased from 22 nm to 55 nm. However, the maximum current efficiency of 5.2 cd/A is achieved with 30-nm-thick ZnO, with a thicker ZnO layer inducing a fast roll-off of the efficiency. For a 30 nm ZnO layer, increasing the QD layer thickness from 10 to 28 nm resulted in a steady increase of both V_T and current efficiency (Figure S1 (b)), but was much more dramatic for current efficiency. With the QDs being 7.5 nm in diameter, this suggests that multiple monolayers of QDs are needed for efficient recombination of electrons and holes to form excitons directly in the QD EML. Moreover, Figure S1 (b) suggests that an even higher efficiency could potentially be achieved with thicker QD layers. However, the thickness of the QD layer in our device is limited, because a rather slow spin speed of 800 r.p.m. has already been used to achieve the thickest uniform QD layer. Nevertheless, the gain in efficiency will eventually be offset by increased driving voltages for thicker QD layers, resulting in low efficiencies. It can be seen that the efficiency increases with increasing particle size of QD in Figure S1(c). Because the band gap of QD decreases with increasing size of QD due to quantum confinement effect, thus the energy barrier for injection of hole and electron into QD layer decreases, which leads to lower driving voltage and higher device efficiency.

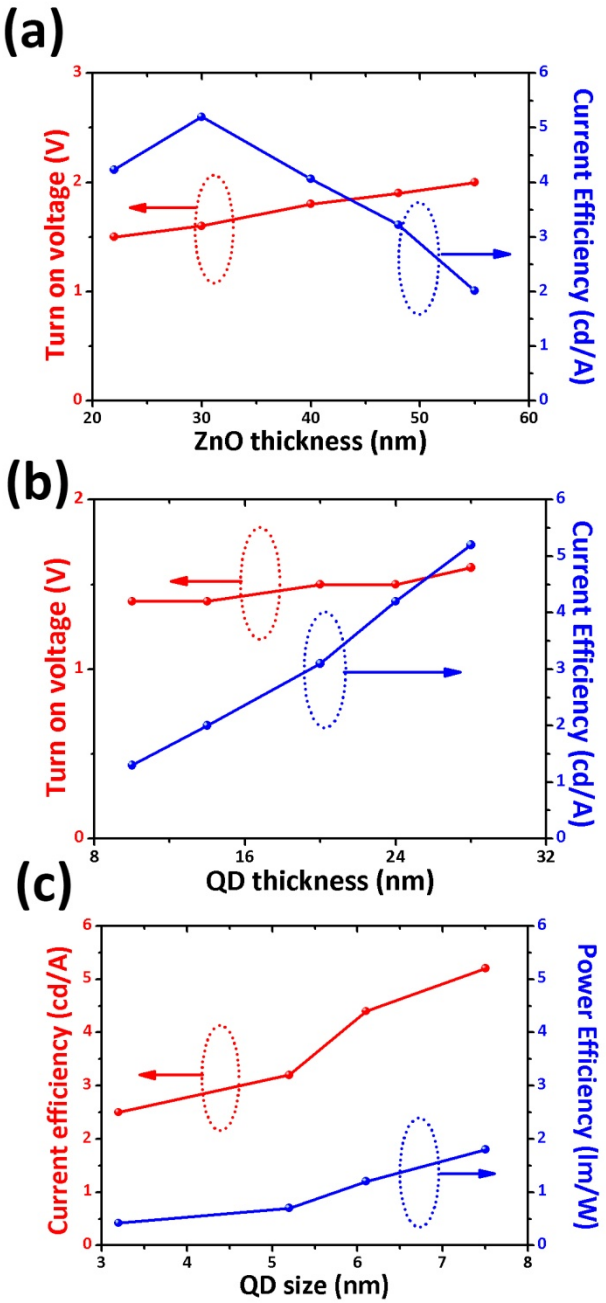

Figure S1 (a) Turn-on voltage (V_T) and maximum current efficiency versus ZnO NP layer thickness (QD layer thickness, 28 nm) (b) V_T and maximum current efficiency versus QD layer thickness (ZnO NP layer thickness, 30 nm) (c) Current efficiency and power efficiency versus QD size

2. Characteristic of the QD

Figure S2 (a) shows the TEM image of the ZnCdSes QDs. The average diameter of QD is around 7.5 nm, uniformly dispersed in toluene. The Room temperature UV-Vis absorption and photoluminescence (PL) spectra were measured as shown in Figure S2 (b). The absorption spectrum clearly displays the first excitonic transition peak at 610 nm. The PL spectrum shows a Gaussian-shaped peak located at 633 nm with a narrow FWHM of 35 nm, indicating red emission from the QD solution.

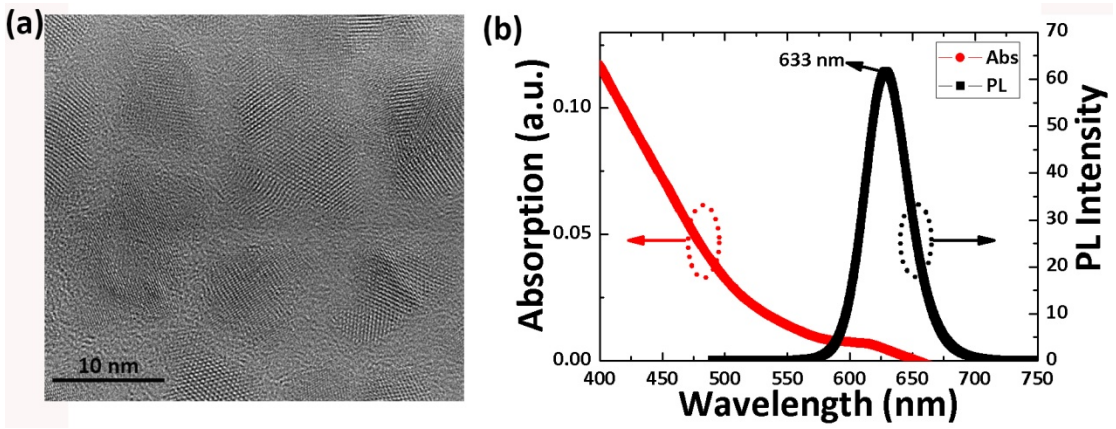

Figure S2.(a) TEM image of the red ZnCdSeS QDs (b) UV-Vis & PL spectra of ZnCdSeS red QDs

3. Characteristic of the ZnO NP film

Figure S3(a) displays the XPS pattern of ZnO NPs film deposited on ITO. It can be easily found the existence of Zn and O. In addition, the binding energy located at 1022.5 eV of the Zn 2p3 core level for the ZnO layer surface, as shown in Figure S3(b),was composed of two chemical bonds which were denoted as Zn–Zn and Zn–O.[1] It can be seen that the O1s core level of the ZnO surface in Figure S3(c) exhibited a dominated peak of approximately 531.2 eV with a tail extending to high binding energy. This curve was deconvoluted into two overlapping peaks, which were in turn associated with the O–Zn and O–H chemical bonds.[2]In Figure S3(d), relatively uniform surface morphologies of compactly packed ZnO NP layers by spin-coating process can be seen from SEM images. Figure S3(e) shows the Cyclic voltammogram (CV) characteristic of ZnO NPs film electrode in KCl (1 M, pH = 7) scanned at a rate of 10 mV/ s.

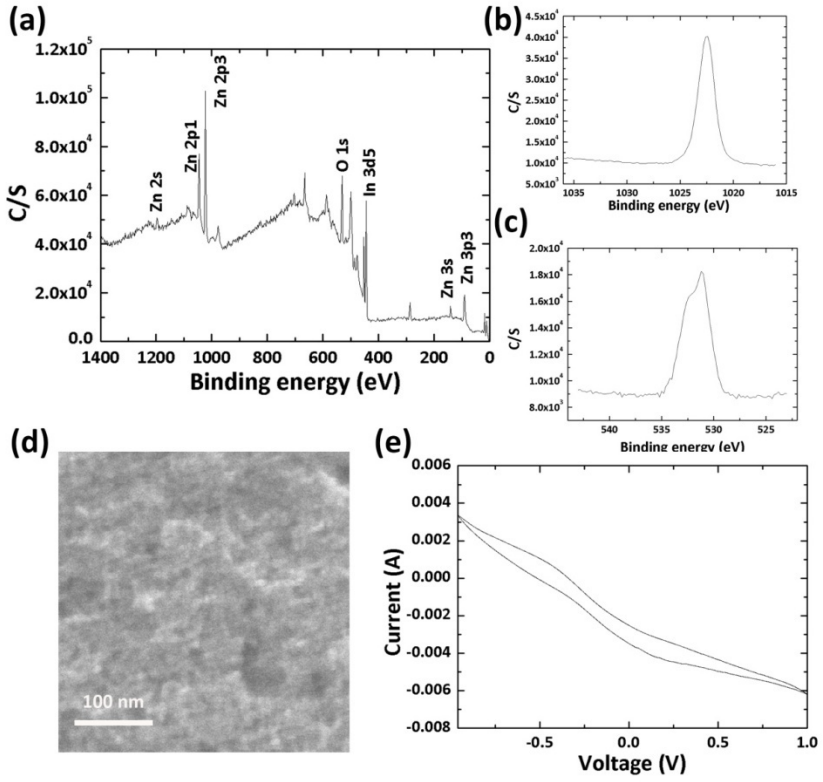

Figure S3.(a) XPS pattern for ZnO deposited on ITO. Binding energy of the (b) Zn 2p3 core level and (c) O1s core level for ZnO layer surface (d) SEM of ZnO film (e) CV of ZnO in 1 M KCl at a scan rate of 10 mV/s

4. Measurement of the energy band of ZnO film

From UPS spectrum of ZnO films, the valence band maximum can be calculated 7.32 eV for ZnO film according to the formula in the inset of Figure S4(a). The conduction band minimum of ZnO can be calculated as 3.67 eV for ZnO film utilizing the valence band maximum and the bandgap of the ZnO determined by UV-Vis absorption (3.65 eV).

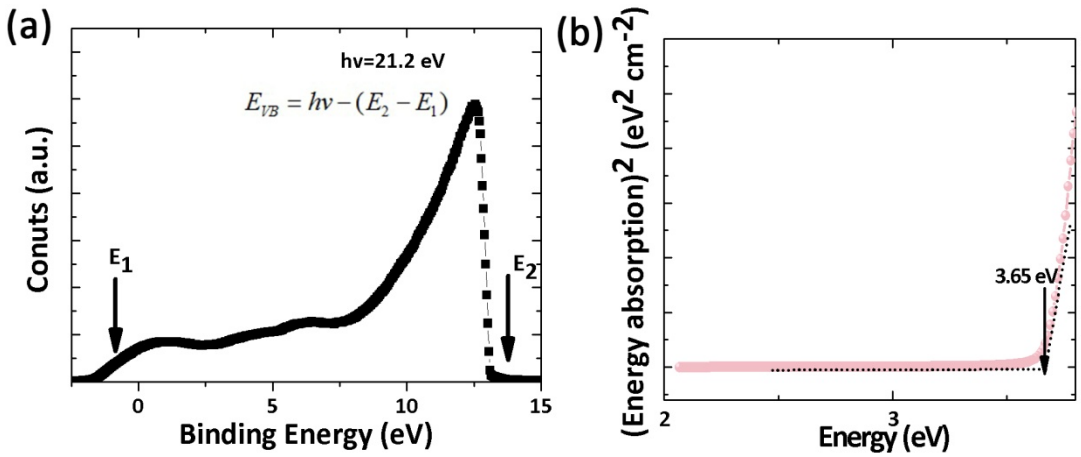

Figure S4. (a) UPS spectrum for the ZnO film (b) UV-Vis absorption spectrum for the ZnO film

5. Mobility Characterization of ZnO Nanoparticle Films

The structure of TFT based on ZnO film is shown in the inset of Figure S5. It consists of heavily doped Si substrates used as the common gate electrode and thermally grown 300 nm-thick SiO_2 gate dielectric layer (unit area capacitance: 11.5 nF cm^{-2}). Then ZnO nanoparticle films were spin coated on the SiO_2/Si substrates at 4000 rpm for 30s. Finally the patterned Al source and drain electrodes were thermally evaporated on top of the ZnO nanoparticle films through a shadow mask. The aspect ratio of channel width to length for the TFTs is 20**.** The mobility of ZnO nanoparticle is calculated as 4.8×10^{-3} $cm^2/V\cdot s$.

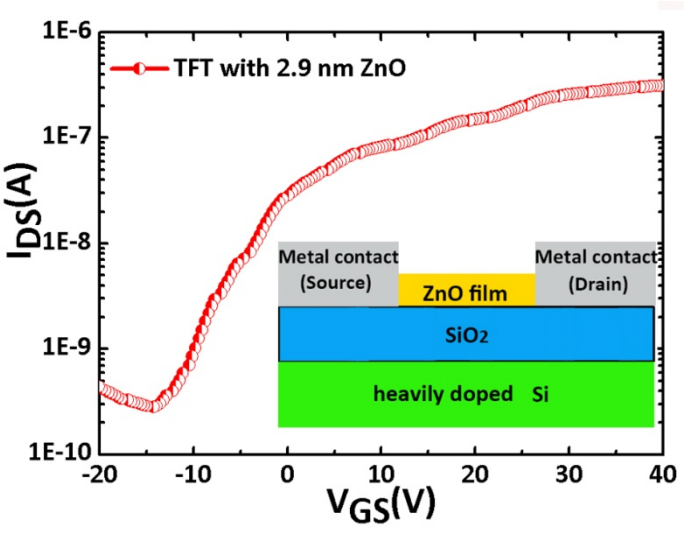

Figure S5. TFT characteristics of ZnO nanoparticle film. Inset shows the structure of TFTs

6 Detail description of the efficiency measurement

The process of efficiency measurement is summarized as follows. Firstly, the current-voltage (I-V) characteristics of QLED device were measured with a Keithley-2400 source-meter unit and the current density, which unit was mA/cm2 was got for different voltage. Secondly, the luminance of the devices, which unit was cd/m2 was calibrated using a Minolta luminance meter (LS-100) at different voltage. Thirdly, we divided the luminance by the current density at the same voltage and get the current efficiency, which unit is cd/A.

7. Illustration of the Auger-like energy up-conversion process

The process consisits of (1) recombination of interfacial charge transfer (CT) exciton, (2) resonant energy transfer between CT exciton and hole, (3) high energy Auger hole generation by energy transfer, (4) injection of the high energy hole across the PVK/QDs interface, and (5) radiative recombination in QDs.

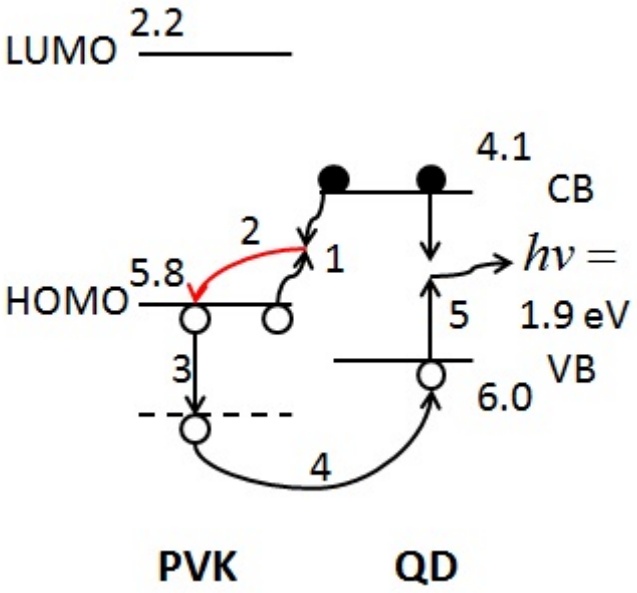

Figure S6. Illustration of the Auger-like energy up-conversion process at the PVK/QDs heterojunction

1. Chang, R.-H.; Yang, K.-C.; Chen, T.-H.; Lai, L.-W.; Lee, T.-H.; Yao, S.-L.; Liu, D.-S., Surface Modification on the Sputtering-deposited ZnO Layer for ZnO-based Schottky Diode. *J. Nanomater.* **2013,** *2013*, 15-15.

2. Li, C.; Liang, H.; Zhao, J.; Feng, Q.; Bian, J.; liu, Y.; Shen, R.; Li, W.; Wu, G.; Du, G. T., Influence of High-pressure Hydrogen Treatment on Structural and Electrical Properties of ZnO Thin Films. *Appl. Surf. Sci.* **2010,** *256*, 6770-6774.