Highly flexible, full-color, top-emitting quantum dot light-emitting diode tapes

Xuyong Yang,[1] Evren Mutlugun,[1,2] Yuan Gao,[1] Yongbiao Zhao,[1] Swee Tiam Tan,[1] Xiao Wei Sun (IEEE Senior Member)[1*] and Hilmi Volkan Demir (IEEE Senior Member)[1,2*]

[1] LUMINOUS! Center of Excellence for Semiconductor Lighting and Displays, School of Electrical and Electronic Engineering, School of Physical and Mathematical Sciences, Nanyang Technological University, Nanyang Avenue, 639798 (Singapore)
[2] Department of Electrical and Electronics Engineering, Department of Physics, UNAM – Institute of Materials Science and Nanotechnology, Bilkent University, Bilkent, Ankara, 06800 (Turkey)

E-mail: VOLKAN@stanfordalumni.org and EXWSun@ntu.edu.sg

Abstract: We report flexible tapes of high-performance, top-emitting, quantum dot based, light-emitting diodes (QLEDs) with multicolor emission, actively working even when flexed. The resulting QLED tapes reach a high peak luminance level of 19,265 cd/m^2.

Keywords: quantum dots; kapton tape; flexibility; electroluminescence; light-emitting diodes

Light-emitting diodes (LEDs) based on colloidal quantum dots (QDs), typically using a QD film thickness of only a couple of hundred nanometers, are very thin, making them virtually transparent and flexible, which renders them in principle suitable for integration onto flexible substrates. Despite some progress made in developing flexible QLEDs, the challenges remain. Currently, indium tin oxide (ITO) is still the main electrode material used for flexible QLEDs.[1] However, it has been demonstrated that ITO is not suitable for flexible optoelectronic devices because the material is quite brittle.[2] In addition, only limited flexible substrates such as poly(ethylene-terephthalate) (PET)[3] can be used in flexible QLEDs because QLEDs require solution-processed fabrication involving the use of various solvents such as toluene, which often damages organic substrates. Furthermore, annealing is also needed for removing solvents and functionalizing the solution-processed films. For example, the aqueous polyethylene dioxythiophene:polystyrene sulfonate (PEDOT:PSS), which is the most widely used buffer layer for the fabrication of QLEDs, is commonly annealed at ~150 °C.[4] Such high temperature annealing usually causes the destruction or distortion of flexible substrates, which thus requires the fabrication process to be completed at relatively low temperatures, and this then greatly limits the performance of the resulting flexible QLEDs.

Here, we show highly flexible tapes of efficient, top-emitting QLEDs in inverted thin film architecture, which actively works even when the tape is flexed (Figure 1a). The resulting QLED tapes (QLEDTs) exhibit excellent optical performance and mechanical properties. Using QLEDTs, full-color emission is also achieved, with the maximum luminance reaching 19,625 cd/m^2. In these QLEDTs, kapton tape is chosen as the substrate because it is extremely flexible, stable against many organic solvents, and can withstand a relatively high temperature. An additional advantage of the kapton tape is that it can be easily pasted on three-dimensional surfaces, which facilitates the use of flexible QLEDs. Additionally, Ag and Al were used as the anode and cathode, respectively, and a uniform ZnO nanoparticle film as the electron transport layer[5] was successfully deposited on Al electrode by spin-coating (although high-quality ZnO nanoparticle films on ITO have been achieved, this present case is quite different for the ZnO nanoparticle film on metals because of the big difference in their surface properties between ITO and metals).

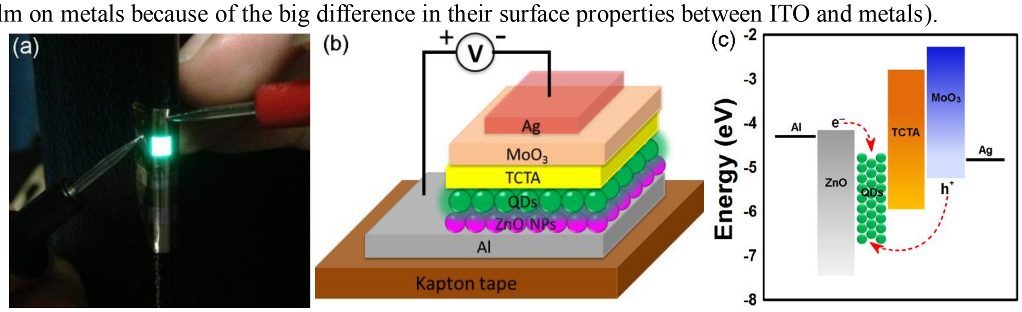

Figure 1. (a) Photograph of a QLEDT fabricated with a pixel size of 3 mm×3 mm pasted on a thin steel plate, (b) schematic of the device configuration and (c) energy level diagram of the QLEDTs.

A top-emitting device architecture is designed because kapton tape is not so transparent and the corresponding structure of QLEDTs comprises a multilayer thin film architecture of kapton tape/Al/ZnO

NPs/QDs/2,2',2"-tris-(N-carbazolyl)-triphenylamine (TCTA)/MoO_3/Ag, as shown in Figure 1b. CdSe/ZnS core-shell structured QDs, prepared according to a previous reported literature,[6] were used for the emissive layer. The uniform ZnO nanoparticles and QD films can be respectively obtained from ZnO nanoparticle butanol/isopropanol solution and QD toluene solution, and other layers were deposited by thermal evaporation. According to the schematic energy level diagram (Figure 1c), it can be observed that the electrons and holes can easily be injected from the charge transport layers into the QD layer. The output image of the QLEDT pasted and flexed around a thin steel plate was recorded at a luminance of 200 cd/m^2 (Figure 1a), which indicates the resulting QLEDT with bright and uniform green emission is highly flexible and easy to paste.

Figure 2a presents the output performance of an optimized flexible QLEDT. The electroluminescence (EL) spectrum of the QLEDT was recorded at a bias voltage of 6 V, showing a characteristic QD EL peak centered at ~508 nm with a full width at half maximum (FWHM) of ~34 nm. Figure 2b displays the current density-voltage (J-V) characteristics of the resulting QLEDT and here a relatively low turn-on voltage of 3.5 V is observed. The luminance-current density characteristics exhibit a peak luminance of 10,266 cd/m^2. Subsequently, using a 40 nm-thick tris-8-hydroxyquinoline aluminum (Alq_3) film as a top-capping layer, the performance of QLEDTs can be further improved and the peak luminance reaches 19,265 cd/m^2.

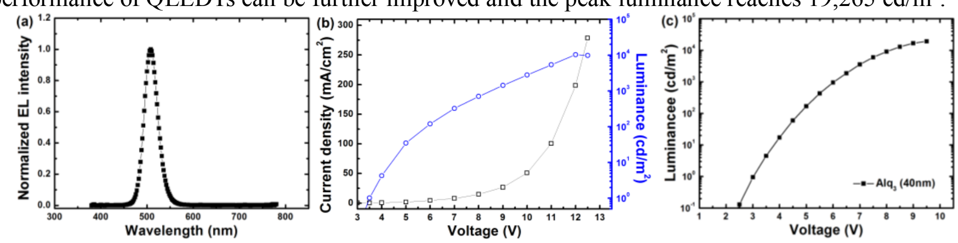

Figure 2. (a) EL spectrum and (b) current density-voltage characteristics of QLEDT, and (c) luminance of QLEDT as a function of current density.

The normalized electroluminescence spectra of the QLEDTs with multicolor emission at an applied voltage of 6 V are shown in Figure 3a (for which the red-emitting QDs used here with a structure of CdSe/CdS/ZnS, different than the blue and green CdSe/ZnS QDs, are prepared according to the same literature[6]). The inset shows photographs of the three operating devices, which display nearly saturated color emissions. The resulting QLEDTs exhibit maximum luminance values of 2,613 cd m^{-2} for the blue emission (peaking at 470 nm), 15,621 cd m^{-2} for the green-yellow emission (at 550 nm), and 8,215 cd m^{-2} for the red emission (at 630 nm).

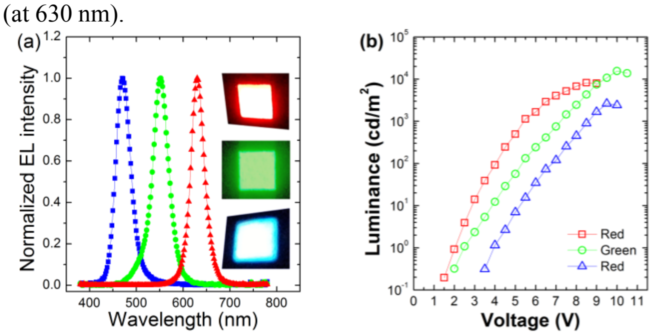

Figure 3. (a) Normalized electroluminescence spectra and images of QLEDTs with peak emission wavelengths of 470 nm (blue), 550 nm (green-yellow) and 630 nm (red). (b) Luminance of QLEDTs with multi-color emission as a function of current density.

In conclusion, these results indicate that QLED tapes are quite promising for flexible display applications and offer a practicable platform for the realization of high-performance flexible optoelectronic devices.

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References

[1] T. H. Kim, et al., Nature Photon. 2011, 5, 176.
[2] T.-H. Han, et al., Nature Photon. 2012, 6, 105.
[3] Z. Tan, et al., J. Appl. Phys. 2009, 105, 034312.
[4] X. Yang, et al., Adv. Mater. 2012, 24, 4180.
[5] L. Qian, et al., Nature Photon. 2011, 5, 543.
[6] W. K. Bae, et al., Nano Lett. 2010, 10, 2368.