Ultra-Bright Quantum-Dot Light-Emitting Diodes

Shuming Chen , Yizhe Sun, Heng Zhang, Qiang Su

Department of Electrical and Electronic Engineering, Southern University of Science and Technology, Shenzhen, 518055, P. R. China

Keywords: quantum dot, light-emitting diodes, device structures, ultra-bright, thermal management

ABSTRACT

Thermal stability of quantum dots (QDs) and thermal management of QD light-emitting diodes (QLEDs) could significantly affect the performance, especially the efficiency roll-off behaviors of QLEDs. With effective thermal management, the efficiency roll-off is significantly suppressed and consequently our developed green QLEDs exhibit an unprecedented high brightness of over 10^6 cd/m^2 at a current density of J=3500 mA/cm^2 and a external quantum efficiency of ~10%, which is an order of magnitude higher than that of all reported QLEDs.

1. INTRODUCTION

Colloidal quantum dot light-emitting diodes (QLEDs) are recognized as promising candidates for next generation displays. In this talk, we will review our recent progress on QLEDs, particularly emphasizing the influence of device structures on the performance of QLEDs.

We first engineer the light-emitting layer by using the binary QD structure. Recently, advances in chemical synthesis have enabled QDs to show near-unity peak quantum yield (QY). For example, the QDs dispersed in solvents with the peak photoluminescence (PL) QY over 90% have been routinely obtained. However, when individual QDs are close-packed as a film, the QY is often significantly reduced due to the Förster resonance energy transfer (FRET) among QDs. The limited QY of QDs film may limit the further improvement of device efficiency, thus affecting the practical application of the devices. The FRET rate is very sensitive to the distance between the donor and the acceptor. Therefore, by separating the QDs, the FRET could be prevented. This could be realized by overlaying a thick shell or doping the QDs with polymer. The shell or polymer could function as spacer to separate the QDs and therefore prevent the FRET among QDs. However, the thick shell or polymer could block the injection of charge carriers, thus decreasing the device efficiency. In this work, we tend to suppress the FRET by developing a binary QD structure. In the proposed red: blue binary QDs structure, the red QDs are doped with the blue QDs, where the blue QDs function as spacers to prevent the FRET among red QDs. Due to the suppressed FRET, the QY of red QDs and the external quantum efficiency (EQE) of the resultant QLEDs are greatly improved.

We then modified the ligand of QD so as to improve the thermal stability of QD and realize QLED with ultra-high brightness. We found that thermal stability of quantum dots (QDs) and thermal management of QD light-emitting diodes (QLEDs) could significantly affect the performance, especially the efficiency roll-off behaviors of QLEDs. With effective thermal management, the efficiency roll-off is significantly suppressed and consequently our developed green QLEDs exhibit an unprecedented high brightness of over 10^6 cd/m^2 at a current density of J=3500 mA/cm^2 and a external quantum efficiency of ~10%, which is an order of magnitude higher than that of all reported QLEDs.

2. RESULTS AND DISCUSSION

There exist FRET among QDs. We the QDs are in solution state, the QY is quite high, but when the QDs are assembled into solid films, the QY is recued significantly. Also, the PL spectrum is red shifted and the exciton lifetime is decreased. This is because when the QDs are assembled into solid films, the exciton generated in one QD can transfer its energy to surrounding QDs via multiple FRET. As shown in Figure 1, if there are exist a quenching site, then after FRET, the surrounding excitons could be quenched, leading to a reduced QY. Because FRET is sensitive to the distance, therefore we can suppress the FRET by increasing the shell thickness. But when the shell thickness is increased, the charge injection could be degraded. We can also dope the QD into polymer film. But due to phase separation, the polymer tends to aggregate and hence the QD can not be perfectly isolated by the polymer.

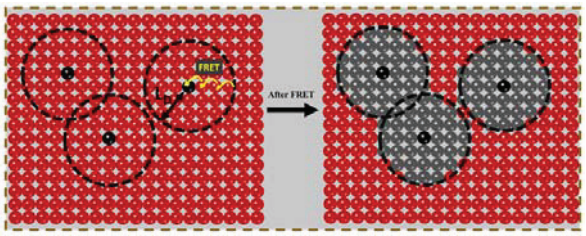

Fig. 1. FRET process in red QD solid film.

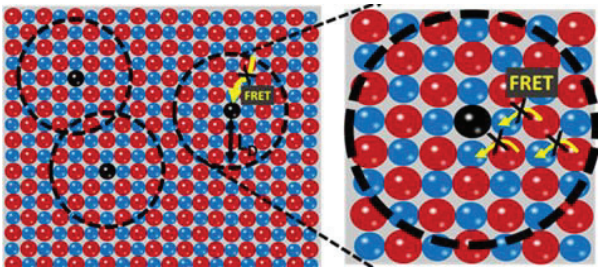

Fig.2. FRET process in the binary QD film. The blue QDs function as spacers to separate the red QDs and thus preventing the FRET among red QDs.

To address this problem, we use the binary QDs as the emitting layer (EML). That is, we doped the red QDs with blue QDs. As shown in Figure 2, after mixing, the red QDs can be separated by the blue QDs. That means, the blue QDs function as spacers or solid solvent to isolate the red QDs, so as to suppress the FRET among the red QDs. As a result, the exciton lifetime of the red QDs is increased. Also, the QY is enhanced from 50% to 75% after mixing the red QDs with the blue QDs, as shown in Figure 3. The improved QY could further contributes to a enhanced device performance. Indeed, device with binary QDs EML exhibit a high EQE of 21.64%, which is ~1.36-fold higher than that of device with neat QDs.

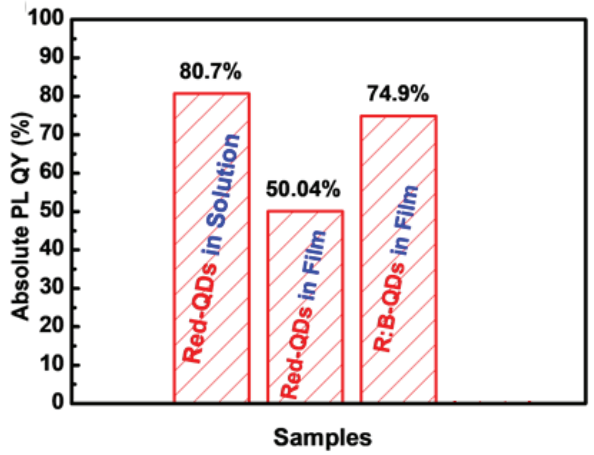

Fig.3. When the QDs are assembled into solid film, the QY is decreased greatly due to the FRET among QDs. By using the binary R:B QDs, the FRET among red QDs is suppressed, leading to a improved QY.

We then modified the ligand of QD so as to improve the thermal stability of QD and realize QLED with ultra-high brightness. QLED with different brightness can find a wide variety applications including cell phone, pad/laptop, TV, lighting, projector and vehicle head lamp. However, typical QLED usually is operated at a brightness from 100 to 10000 cd/m^2. It is difficult to realize a brightness higher than 10^5 cd/m^2 due to the efficiency droop or efficiency roll-off at high current density. The brightness is proportional to the current density and current efficiency. The decrease of efficiency at high current density therefore limits the achievable brightness and this could further limit QLED's application in high brightness field. The efficiency droop is due to the Auger recombination, and this is can be suppressed by using QD with gradient alloyed structure and improving the charge balance of the device. Besides Auger recombination, another key factor is the Joule heat. The generation of Joule heat could increase the device temperature and leads to the debonding of ligands, thus introducing new traps and consequently decreasing the QY of QDs. Therefore, to suppress the efficiency roll-off, the thermal stability of QD has to be improved.

By replacing the conventional oleic acid (OA) ligands with 1-dodecanethiol (DDT), the thermal stability is greatly improved, as shown in Figure 4. We have investigated the thermal stability of QD with conventional OA ligands and with DDT ligands. We found that the QY is decreased with increasing temperature. This is because at high temperature, the ligands could detach from the surface of QDs due to the poor binding between OA and QD. Due to the debonding of ligands, new surface defects could be generated, which could quench the emission of QD. With DDT ligands, the decrease of PL intensity is not so significant due to the strong binding between DDT and QDs. The improved thermal stability of QD could contribute to a suppression of efficiency roll-off at high current density.

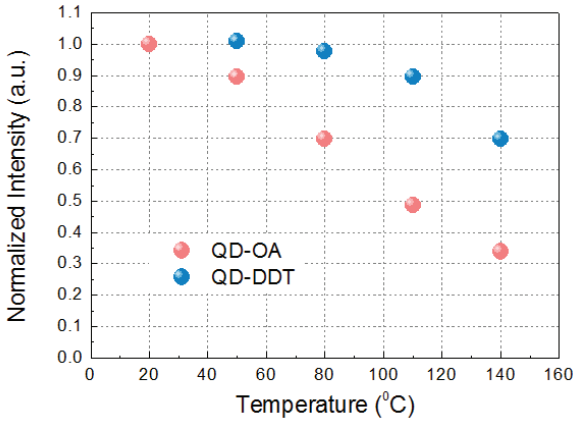

Fig.4. By replacing the conventional oleic acid (OA) ligands with 1-dodecanethiol (DDT), the thermal stability is greatly improved which could contribute to a suppression of efficiency roll-off at high current density.

As shown in Figure 5, due to the improved thermal stability, QLED with DDT ligands exhibit higher performance. We can see that the J-V characteristics is very similar, but with DDT, the efficiency is improved by 1.6-times. Also, with DDT, the devices can be operated at a higher current density without catastrophic failure and they exhibit a reduced efficiency roll-off especially at

high current density. We can see that the current can be up to 3.5 A/cm^2, however, for conventional QD with OA ligands, at high current, the EQE is decreased dramatically. Due to the improved thermal stability and suppressed efficiency roll-off, the QLED the QLEDs can be operated at a very high J up to 3550 mA/cm^2, thus enabling the devices to exhibit a very high brightness of over 10^6 cd/m^2, which is an order of magnitude higher than that of all reported QLEDs. The superior PL and EL performance of QD-DDT indicates that it could be the ideal candidate for efficient and ultra-bright QLEDs.

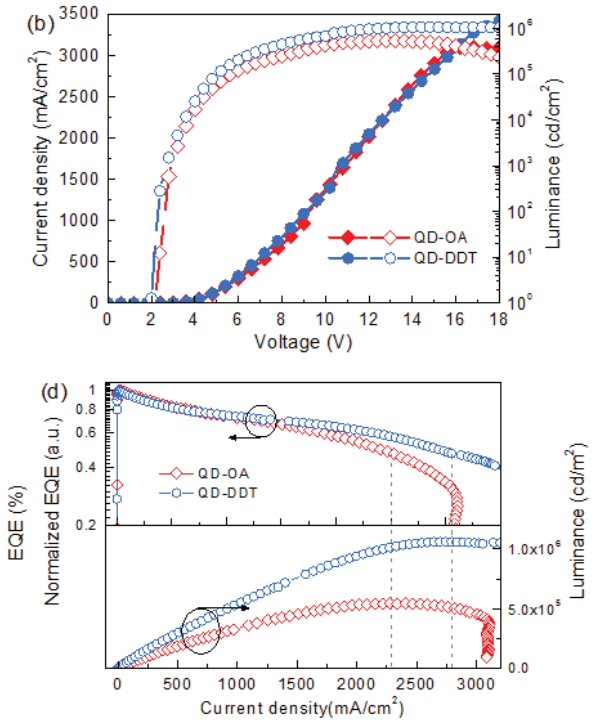

Fig.5. Device performance of the green QLEDs based on QD-OA and QD-DDT. (a) J-V-L and (b) Normalized EQE and luminance as a function of current density..

3. CONCLUSIONS

In summary, we have engineered the EML of QLED. By using the wide bandgap QDs as spacers, FRET among smaller bandgap QDs can be effectively suppressed, leading to a improved QY. As a result, QLED with binary QD EML exhibited a EQE of over 22%. We then engineered the ligand. By replacing the conventional OA ligand with DDT, the thermal stability of QDs is improved. Because of the improved thermal stability and effective heat dissipation, our green QLEDs exhibited a peak EQE of ~16% and a record-high brightness of over 10^6 cd/m^2. Our results show that thermal stability of QDs and thermal management in QLEDs could significantly affect the performance, especially the efficiency roll-off behaviors of QLEDs.

REFERENCES

[1]. Heng Zhang, Qiang Su, Shuming Chen, “High-Efficiency Quantum-Dot Light-Emitting Diodes Enabled by Reducing Förster Resonance Energy Transfer in Close-Packed Quantum-Dot Thin-Film”, to appear.

[2]. Yizhe Sun, Qiang Su, Heng Zhang, Fei Wang, Shengdong Zhang, Shuming Chen, “Investigation on Thermally Induced Efficiency Roll-Off: Towards Efficient and Ultra-Bright Quantum-Dot Light-Emitting Diodes”, to appear.