Recent progress in the device architecture of white quantum-dot light-emitting diodes

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ABSTRACT
White-light-emission quantum dot light-emitting diodes (WQLEDs) have attracted great attention of late because they could have potential applications in both flat-panel displays and solid-state lighting due to their advantages of tunable emission spectra, low driving voltage, high luminous efficiency, and high brightness. Over the past decades, with the rapid development of both quantum dot (QD) materials and device structures, WQLEDs have achieved tremendous progress. This review investigates the influence of device architectures on the performance of WQLEDs. The importance and status of the WQLEDs based on CdSe-QDs are first discussed. Then WQLEDs with a mixed-QD single light emission layer (EML), a multilayered QD EML, and tandem structures are reviewed. WQLEDs based on cadmium-free QDs are also briefly introduced. Finally, the key challenges that WQLEDs are currently facing are identified, and some possible solutions are proposed for further developing stable and efficient WQLEDs.

1. Introduction
Colloidal quantum dots (QDs) are fascinating semiconductor nanocrystals with unique properties, such as excellent color tunability, high photoluminescence quantum yield (PLQY), narrow emission linewidth, and simple solution processibility [1–13]. These features make QDs very attractive for light-emitting diode (LED) applications. With the great efforts being devoted to this field, QD-based light-emitting diodes (QLEDs) have attained much progress of late, and the performance of CdSe-based QLEDs is approaching that of the state-of-the-art organic light-emitting diodes (OLEDs) [1,4,7,14–18]. In particular, QLEDs can offer much higher color purity than OLEDs. Therefore, QLEDs are regarded as a very promising candidate for the next-generation large-area, wide-color-gamut, ultra-thin, and flexible display applications.

There are mainly two technological ways of realizing the full-color QLED display. In the first scheme, as shown in Figure 1(a), the red, green, and blue (R/G/B) pixels are arranged side by side, which means that the QD light emission layer (EML) should be finely patterned. As the QDs cannot be evaporated like the organic small molecules used in OLEDs, solution-processed methods like inkjet printing have to be used for QD patterning. The uniformity and surface morphology of the printed films are quite low, however, which will deteriorate the device performance [19–21]. In addition, the solution-printing methods are far from mature, and their performances have not been successfully verified in industrial applications. Instead of patterning the EML, another way of realizing the full-color display is using the white + color filters (CFs) scheme (Figure 1(b)). In this scheme, the CFs can be patterned using the mature photolithography technology, which has a relatively high resolution. By combining patterned CFs with white QLEDs (WQLEDs), the high-resolution full-color QLED display can be realized. In particular, this method has been proven to be an effective strategy for the realization of large-area and high-resolution full-color displays, and has been adopted by panel makers like LG and eMagin to mass-produce the large-area OLED TV and high-resolution OLED microdisplay [22,23]. To meet the industrial requirements, stable, efficient, and bright-white devices have to be developed.

Besides display application, WQLEDs can also have great potential application in solid-state lighting. Compared with OLEDs, QLEDs can achieve brighter emissions...
due to the adoption of ZnO nanoparticles as an electron transport layer (ETL), and the inorganic QDs as emitters, which have higher electron mobility and better thermal stability than their organic counterparts [4,24]. This enables the QLEDs to be operated at a higher current density and higher luminance, which is vital for lighting application.

Due to the important application of WQLEDs in both display and lighting, they have attracted much attention of late. This review aims to provide a comprehensive overview of the progress attained in the development of WQLEDs. To date, nanocrystalline QDs based on CdSe, InP, ZnCuIn(Ga)S, carbon, and perovskite nanocrystal CsPbBr$_x$Cl$_{3-x}$ have been actively investigated as emitters for LEDs. Among these materials, colloidal CdSe QDs are the most promising emitters due to their excellent optoelectronic properties. Therefore, this review mainly focuses on the CdSe-based WQLEDs. The device structures have played an important role in the performance of WQLEDs. Therefore, this paper is organized mainly based on the progress of the device structures. The WQLEDs with a mixed-QD single EML, which have been rather active of late, will first be discussed in section 2. Then the more advanced structure, the multilayered WQLEDs, and the tandem WQLEDs, will be reviewed in sections 3 and 4, respectively. Section 5 will present the cadmium-free WQLEDs. Finally, the challenges first and the perspective of WQLEDs will be summarized in section 6.

2. WQLEDs with a mixed-QD single EML

In the early stage of the QLED development, charge injection into QDs is relatively inefficient due to the use of organic charge transport layers (CTLs), which are usually designed for OLED application. Due to the inefficient charge injection, the exciton recombination zone is located at the CTLs that are adjacent to the QD layer [25,26]. The observed QD emission resulted from the Förster resonant energy transfer (FRET) from the CTLs to the QDs [27–29]. Due to the incomplete FRET process, however, emission from the CTLs is also observed. As a result, the combination of emission from the CTLs and QDs could lead to the generation of white-light emission [26–31]. Moreover, in the early development stage, the performance of the blue QDs is quite poor. To obtain efficient white-light emission, blue organic luminescent materials are often used to replace the blue QDs. For example, the red and green QDs are usually blended with the blue organic emitters. The resultant white-light emission is the combination of the complementary emissions from organic materials and QDs. Using this method, Park et al. demonstrated the white hybrid LED with the emitting layer composed of a blue-emitting polymer and two different CdSe QDs. The resultant hybrid WLED exhibited a white light near the CIE 1931 coordinates (0.33, 0.33) [30]. In 2006, Gigli et al. successfully realized the WQLEDs with the emission solely originating from the QDs. As shown in Figure 2(a), by mixing the R-, G-, and B-QDs with the CBP (4,4′,N,N′-diphenylcarbazole) host, balanced white-light emission was obtained [32]. In this device, the excitons are generated on QDs via two mechanisms: (1) direct charge injection and recombination on QDs and (2) FRET from the adjacent CTLs (CBP and Alq$_3$) to the QDs (Figure 2(b)). Due to the low QY of the QDs and the inefficient charge injection, the demonstrated WQLEDs exhibited low current efficiency (CE) (∼ 1.8 cd/A) that is far from the requirement of industrial application.

In 2007, WQLEDs with a mixed-QD single EML were investigated by Bulović et al. [33]. As shown in Figure 2(c and d), the EML consists only of R:G:B mixed QDs, which can dramatically simplify the device structure. In this device, much of the emission is mainly originated from the R-, G-, and B-QDs, although a weak parasitic emission from Alq$_3$ can still be observed due to the inefficient charge injection and poor exciton confinement. As the emission linewidth of QDs is relatively narrow, the resultant WQLEDs exhibited a low color rendering index (CRI), which is unfavorable for lighting application. To
improve the CRI, Lee et al. developed inverted WQLEDs with the EML consisting of trichromatic (R, G, B) and tetrachromatic (B, cyan, yellow, R) QDs, as shown in Figure 2(e and f) [34]. Due to the use of one more QD, the spectrum can fully cover the visible spectral region, and as such, the resultant tetrachromatic WQLEDs exhibited a CRI of 92, which is significantly higher than the CRI of the trichromatic WQLEDs (69). In this device, the inorganic ZnO nanoparticles were employed as the ETL, which greatly enhances the electron injection due to the high mobility of ZnO and the matched energy levels between ZnO and QDs. As a result, the WQLEDs demonstrated high brightness over 5000 cd/m², thus enabling the WQLEDs to be applied as a display backlight and a lighting source, respectively (Figure 2(g and h)).

After 2014, due to the development of material synthesis, device structures, and fabrication processes, the performance of the monochromatic QLEDs and WQLEDs rapidly improved. For example, in 2015, an all-solution-processed WQLED with a record-high external quantum efficiency (EQE) of 10.9% was realized by Yang et al. (Figure 2(i and j)) [35]. In this device, due to the close contact of different colored QDs, the excitonic energy could transfer from the wide-bandgap QDs to the small-bandgap QDs via the FRET process (Figure 2(k)). It is well known that the FRET between QDs can lead to
energy loss. Consequently, the EQE of the demonstrated WQLEDs is limited to 10.9%, which is significantly lower than that of the state-of-the-art monochromatic QLEDs. In addition, the WQLEDs with a mixed-QD single EML exhibit low color stability, which is unfavorable for practical application. As shown in Figure 2(l), the red-light emission is gradually reduced as the driving voltage increases. This is because the exciton recombination zone is migrated from the small-bandgap QDs to the wide-bandgap QDs when the driving voltage increases. To further improve the efficiency and color stability, the FRET between QDs should be suppressed, and the exciton recombination zone should be well confined in each colored QD. This could be achieved by separating the QDs spatially using the multilayered EML or the tandem structure, as will be discussed in the next sections.

3. WQLEDs with a multilayered EML

Instead of mixing all QDs in a single EML, through the layer-by-layer deposition of the QDs, the multilayered WQLEDs can dramatically reduce the direct contact of the different colored QDs, thus leading to the suppression of FRET between the R/G/B QDs. As the solvents of the R/G/B QDs are not orthogonal, however, the underlying QD layer will be severely damaged by the solvent of the following QDs when the traditional spin-coating methods are used. In this regard, the fabrication of a uniform and high-quality layered R/G/B QD film is a big concern for the realization of high-efficiency WQLEDs.

In 2015, Yang et al. successfully realized an all-solution-processed multilayered WQLED with the EML consisting of layered yellow (Y) and B QDs (Figure 3(a and b)) [36]. To protect the bottom QD film from being dissolved by the solvent of the upper QDs, the surface of the bottom Y QD film was modified with a hydrophilic ligand of 3-mercaptopropionic acid (MPA) prior to the deposition of the upper layer. Even though a rather balanced white-light emission spectrum was achieved, the efficiency of this device was still very low (EQE, 0.6%). This fabrication method can be used to fabricate the R/G/B-QD-layered WQLEDs, but the surface
modification process may deteriorate the surface of the QD film, leading to the degradation of the device performance.

Recently, the same group presented R/G/B-QD-layered WQLEDs with 15.9 cd/A current efficiency (CE) using an all-solution-processed conventional structure (Figure 3(c)) [37]. In the demonstrated device, an ultra-thin ZnO nanoparticle buffer layer was inserted between the different-colored QD layers, which prevented the underlying QD layer from being damaged by the following process, leading to the successful fabrication of the layered WQLEDs (Figure 3(d)). The emission color of the presented WQLEDs was still unstable as the driving voltage was changed (Figure 3(e)), which was mainly caused by the migration of the exciton recombination zone. Recently, Chen et al. reported conventional WQLEDs with a Y/B QD bilayered EML and with a higher CE of 24.6 cd/A (Figure 3(f)) [38]. In this device, the same ZnO nanoparticles were employed as a buffer layer to prevent the under-QD layer from being damaged by the solvent of the upper QDs. Moreover, magnesium-doped zinc oxide was employed to promote the charge balance of the device, resulting in the improved efficiency of the device.

With the adoption of the multilayered EML structure, although the FRET between the colored QDs can be suppressed at a certain degree, there are still some shortcomings in the structure. In a conventional QLED device, electron injection is more efficient than hole injection, and thus, to balance the charge injection, the hole injection should be enhanced whereas electron injection should be blocked. In the multilayered WQLEDs, however, the ZnO interlayer, which is inserted between the QD layers, can block the hole injection and thus further deteriorate the unbalanced charge injection. In addition, the thickness of the ZnO interlayer is only ∼3 nm, which is too thin to completely suppress the FRET between the adjacent QD layers. Also, the defects of ZnO can quench the excitons. Finally, the exciton recombination zone can still migrate from the small-bandgap QDs to the wide-bandgap QDs as the driving voltage increases, leading to low color stability. To realize higher efficiency and a more stable emission color, other interlayers should be developed.

4. **Tandem WQLEDs**

In the past decades, the performance of WQLEDs with a single or multilayered EML was gradually improved, but at present, it still cannot meet the requirements for a display or lighting application, for the following reasons. First, the reported highest EQE of the WQLEDs with single or multilayered EMLs is only ∼10%, which is still much lower than the 20% of the state-of-the-art monochromatic devices; thus, further device engineering or fabrication process optimization is needed. On the other hand, the emission color is not stable because it changes as the driving voltage is varied, which is unfavorable for practical application. Furthermore, for lighting or display application, the WQLEDs should be operated at a brightness of 1000 ~ 10000 cd/m², but at such a high brightness, the lifetime of WQLEDs is quite short due to the poor stability of the blue QDs.

Tandem structures have been widely used to make WOLEDs with simultaneous high brightness and a long lifetime. For lighting and display applications, tandem WOLEDs have been proven to be among the best device structures, and have been used to mass-produce OLED TV and OLED lighting panels. The tandem architecture has begun to be used of late for fabricating WQLEDs. The tandem QLED was first reported by Jang et al. in 2016 and was recently further developed by these authors [39–41]. The proposed schematic diagram and relative charge motion trajectory of the tandem device structure are shown in Figure 4(a). As depicted in the said figure, the tandem structure, which consists of two or more QD light-emitting units (LEUs), are connected in series by an inter-connecting layer (ICL), and when bias is applied, the ICL and electrodes can inject multiple electron–hole pairs into different LEUs, resulting in emitting multiple photons simultaneously. Therefore, the brightness of the tandem QLEDs is the sum of all the sub-LEUs when driven at the same current, which will lead to higher efficiency and a longer lifetime. For example, the over-100 cd/A inverted green tandem QLEDs and the over-21% EQE R/G/B tandem QLEDs were realized by the authors very recently [40,41]. In this regard, using the tandem architecture is a very promising way of realizing efficient and stable WQLEDs.

The all-solution-processed conventional R/G/B three-LEUs tandem WQLEDs were first realized by the authors in 2017 (Figure 4(b)) [42]. The pure white-light emission, which originated from the three R/G/B sub-LEUs, was realized (Figure 4(c)), which indicates that the three LEUs are successfully connected by the proposed ZnMgO/PEDOT:PSS ICL. The efficiency of the presented WQLEDs was very limited (CE, 4.75 cd/A), however, which is mainly attributed to the poor morphology of the ICL. This is because it is difficult to directly deposit the aqueous PEDOT:PSS onto the surface of ZnMgO because the surface of ZnMgO nanoparticles is hydrophobic. The poor morphology of ZnMgO/PEDOT:PSS leads to the low efficiency of the resultant tandem device. To address this problem, a new and efficient ICL with a ZnMgO/Al/HATCN/MoO₃ structure was further designed (Figure 4(d), (e), and...
Figure 4. R/G/B-QD tandem WQLEDs. (a) Proposed simplified schematic diagram and relative charge motion trajectory of the tandem device structure. (b) Device architecture of the R/G/B-QD tandem WQLEDs [42]. Reprinted with permission from ref. [42]. Copyright 2017, John Wiley and Sons. (c) Normalized EL spectra of the tandem WQLEDs with different driving current densities. The inset shows a photo of the WQLED when driven at 2.0 mA/cm² [42]. Reprinted with permission from ref. [42]. Copyright 2017, John Wiley and Sons. (d) Device structure of the all-solution-processed R/G/B-QD tandem WQLEDs [43]. Reprinted with permission from ref. [43]. Copyright 2018, John Wiley and Sons. (e) Normalized EL spectra of the three-unit R/G/B-QD tandem WQLEDs at different luminance levels. The inset shows a photo of the tandem WQLED at a driving current density of 16 mA/cm² [43]. Reprinted with permission from ref. [43]. Copyright 2018, John Wiley and Sons. (f) CIE coordinates of R/G/B monochromatic QLEDs and tandem WQLEDs at different luminance levels [43]. Reprinted with permission from ref. [43]. Copyright 2018, John Wiley and Sons. (g) Device architecture of the conventional R/G/B-QD tandem WQLEDs [44]. Reprinted with permission from ref. [44]. Copyright 2018, American Chemical Society. (h) Normalized EL spectra of the three-LEUs and tandem WQLEDs. The inset shows an electroluminescent photo of the tandem WQLEDs [44]. Reprinted with permission from ref. [44]. Copyright 2018, American Chemical Society. (i) Device structure and (j) energy level diagram of the R/G/B-QD tandem WQLEDs [45]. Reprinted with permission from ref. [45]. Copyright 2018, John Wiley and Sons. (k) Schematic energy level diagram showing the charge generation process caused by the electric field [45]. Reprinted with permission from ref. [45]. Copyright 2018, John Wiley and Sons. (l) Proposed schematic of FRET among the R/G/B QDs in different types of WQLEDs.

With this new ICL, efficient and color-stable WQLEDs with an EQE of 23% were demonstrated. By replacing the aqueous PEDOT:PSS with PMA (polyoxometalate phosphomolybdic acid), the morphology of the ICL of ZnO/PMA was improved, and thus, the tandem WQLEDs with a ZnO/PMA ICL exhibited a high EQE of 25%, as reported by Cao et al. (Figure 4(g) and (h)) [44]. Recently, an all-solution-processed R/G/B three-LEUs inverted tandem WQLED with an EQE of 28% was realized by Yang et al. (Figure 4(i and j))
Table 1. Performances of different types of CdSe- and Cd-free-QD-based WQLEDs.

| QD Device          | V_{out} (V) | Max. L (cd/m^2) | Max. CE (cd/A) | Max. EQE (%) | CIE   | CRI | Color stability | Ref. |
|--------------------|-------------|-----------------|----------------|--------------|-------|-----|----------------|------|
| CdSe-based         | ≤ 5         | 830             | 0.9            | 0.36         | (0.35, 0.41) | 86  | Low            | [33] |
| Mixed (R/G/B)      | 4.3         | 1440            | –              | 1.3          | (0.39, 0.40) | 69  | Low            | [34] |
| Mixed (R/G/B)      | < 5         | 23352           | 21.8           | 10.9         | (0.45, 0.33) | 75  | Low            | [35] |
| Layered (R/G/B)    | ≤ 5         | 16241           | 15.9           | 6.8          | (0.32, 0.33) | –   | Middle         | [37] |
| Layered (Y/B)      | < 5         | 36990           | 24.6           | –            | (0.32, 0.32) | –   | Middle         | [38] |
| Tandem (R/G/B)     | ∼ 14        | 4206            | 4.75           | 2.04         | (0.30, 0.44) | –   | High           | [42] |
| Tandem (R/G/B)     | 9.0         | 65690           | 55.06          | 23.9         | (0.33, 0.34) | 80  | High           | [43] |
| Tandem (R/G/B)     | ∼ 9.2       | 115000          | 60.46          | 27.4         | (0.41, 0.39) | –   | High           | [44] |
| Tandem (R/G/B)     | 11.9        | 20320           | 79.9           | 28.5         | (0.35, 0.43) | 75  | –              | [45] |
| InP-based Hybrid (R/B) | > 270   | –               | –              | (0.33, 0.34) | –     | 91  | –              | [46] |
| Hybrid (R/G/B)     | –           | 322             | –              | (0.35, 0.34) | 95    | Low | –              | [47] |
| CuIn(Ga)S-based    | Hybrid (R/B) | 10             | 450            | –            | (0.34, 0.34) | 92  | Low            | [48] |
| Hybrid (Y/B)       | ∼ 2.5       | ∼ 1500          | 0.13           | –            | (0.33, 0.32) | 90  | Middle         | [49] |
| Single (W-QDs)     | ∼ 4         | 1007            | 3.6            | 1.9          | (0.29, 0.33) | 88  | High           | [50] |
| Cds-based Single (W-QDs) | ∼ 6    | 35              | –              | 0.03         | (0.40, 0.43) | 82  | Very High      | [51] |
| CsPbBr_xCl_3-x-based | Hybrid (B/Y) | ∼ 2.9  | 350            | 0.18         | 0.07          | (0.33, 0.34) | –   | –              | [53] |

5. Cadmium-free WQLEDs

Due to the inherent toxicity of cadmium, the commercialization of the Cd-QD-based QLEDs has been hindered to a certain extent. In this circumstance, the cadmium-free QLEDs have attracted great interest due to their environment-friendliness. To date, there are many different types of emerging cadmium-free-QD-based WQLEDs, such as the InP-QD-based WQLEDs, the CuIn(Ga)S-QD-based WQLEDs, the CD-based W-LEDs, and the inorganic-perovskite-(CsPbBr_xCl_3-x)-based W-LEDs.

(1) InP-QD-based WQLEDs

The InP-QD-based QLEDs, which have similar optical and electronic properties as the Cd-QD-based QLEDs, are considered an ideal candidate for future display applications [54–57]. The performances of the InP-QD-based monochromatic QLEDs, however, such as the device efficiency, color purity, and device lifetimes, are very inferior to those of the well-developed Cd-QD-based monochromatic QLEDs [1,4,17,18,54–57]. In this circumstance, the development of InP-QD-based WQLEDs with an R/G/B multi-colored EML is hindered by the poor performances of the monochromatic devices, especially the blue-light-emission device. Therefore, the development of the InP-QD-based WQLEDs is still in the early stage and is rarely reported.

In 2012, Sun et al. demonstrated a hybrid WQLED with a high CRI of 91 by using red-light-emitting InP/ZnS QDs (Figure 5(a)), which were synthesized through a facile one-pot solvo-thermal method [46]. The white-light emission of the presented device was a combination of red-light emission from InP/ZnS QDs and...
blue- and green-light emission from poly-TPD (Figure 5(b and c)). In the same year, the same researchers developed another InP-QD-based WQLED with CIE coordinates of (0.349, 0.342) and a high CRI of 95 by using a similar device structure (Figure 5(d)) [47]. The EML of this device was fabricated by depositing a loosely packed green InP-QD layer, which could directly contact TPBi and poly-TPD. A ternary white-light emission was obtained by combining the blue-light emission from poly-TPD, the green-light emission from InP-QDs, and the red-light emission from the exciplex formed at the interface between the poly-TPD and the TPBi (Figure 5(e)).

(2) CuIn(Ga)S-QD-based WQLEDs

To date, the CuIn(Ga)S QDs have received great attention due to their inherent properties, such as their
non-toxic and low-cost raw materials and tunable band gaps (by changing the particle size or composition of the particles) [58–60]. The CuIn(Ga)S QDs usually exhibit a broad emission owing to the donor–acceptor pair or surface defect states recombination, which is not desirable for display applications [58–63]. This wide emission property, however, can be utilized to produce white light with a high CRI for lighting applications.

In 2010, a CuInS-QD-based WQLED with a high CRI of 92 was demonstrated by Xu et al. (Figure 5(f)) [48]. The white-light emission of the presented device was achieved by combining the red-light emission from CuInS QDs and the blue- and green-light emission from poly-TPD (Figure 5(g)). Very recently, Teng et al. fabricated a CuInS-QD-based WQLED by using a yellow CuInS-QD-TFB hybrid EML (Figure 5(h)), and the resultant devices exhibited a maximum luminance of 1500 cd/m², a CRI of 90, and CIE color coordinates of (0.33, 0.32) [49]. In 2016, Yang et al. reported a single CuGaS-QD-based WQLED in which the white-light emission was originated only from CuGaS QDs, without any contribution of HTL emissions (Figure 5(i–l)) [50]. As the white-light emission of this device was only from the radiative recombination of the injected carriers on the CuGaS QDs, it exhibited a very stable white-light emission regardless of the change of the driving voltage (Figure 5(m)). In addition, the presented WQLED exhibited 1007 cd/m² luminance, a high CRI of 83–88, and an EQE of 1.9%.

(3) Carbon-dot-based W-LEDs

Carbon dots (CDs), which have unique properties, such as a tunable emission color, resistance to photobleaching, intrinsic non-toxicity, and ease of bioconjugation, have also been exploited to fabricate LEDs [64,65]. Due to the complicated synthetic methods and low quantum yield, however, fundamental research on CDs was rarely conducted. In 2011, Ma et al. first reported
a CD-based white LED with a CRI of 82 by using highly luminescent CDs synthesized through a novel one-step method (Figure 6(a)) [51]. The presented CD-based W-LED exhibited a highly stable white-light emission at the applied voltage (Figure 6(b)). Rogach et al. have demonstrated stable CD-based W-LEDs, which still exhibited low luminance (90 cd/m²) even after 2 years [52]. The presented device employed ZnO nanoparticles as the ETL to enhance the current injection, leading to the white-light emission at a driving voltage of 5–9 V (Figure 6(c and d)).

4) CsPbBr$_2$Cl$_{3-x}$-based W-LEDs

The organic–inorganic perovskite-based LEDs (PeLEDs) have emerged of late as a new class of cadmium-free, color-tunable, and narrow-bandwidth LEDs for display applications, and have attracted great interest as a research topic [66–71]. Even though tremendous progress has so far been achieved with regard to the efficiency of the green PeLEDs [66–68], they are still far from being commercialized. For one thing, the efficiency levels of red and blue devices are still very low [72,73]. In addition, the stability of the PeLEDs has always been a big problem. Therefore, almost all the studies on PeLEDs have been concentrated on the development of efficient and stable monochromatic devices [66–68,71–73]. For the white device, only Yang et al. have demonstrated a hybrid W-LED with emission from CsPbBr$_x$Cl$_{3-x}$ and polymer (MEH:PPV) very recently (Figure 6(e and f)) [53]. The white-light emission of this device was the blending of the blue-light emission of the CsPbBr$_x$Cl$_{3-x}$ nanocrystals and the yellow light emission from the MEH:PPV molecules. A pure white-light emission with 350 cd/m² luminance and CIE coordinates of (0.33, 0.34) was achieved by the presented devices.

6. Summary and perspective

Great progress has been achieved of late in the device architectures of the Cd-quantum-dot (QD)-based white-light-emission quantum-dot light-emitting diodes (WQLEDs). In the early stage of the WQLED development, the white-light emission is usually achieved by combining the complementary emissions from QDs and the adjacent charge transport layers (CTLs). With the development of the device structure, the WQLEDs with a mixed-QD single emission layer (EML) were demonstrated, in which the white-light emission is originated from the red-(R)-, green-(G)-, and blue-(B)-QDs. Tremendous progress has been achieved of late in the efficiency of the WQLEDs with a mixed-QD single EML (external quantum efficiency (EQE) > 10%), but due to the close contact of the QDs, Förster resonant energy transfer (FRET) between different-colored QDs is unavoidable, which causes energy loss and limits the efficiency of the WQLEDs. To suppress FRET, WQLEDs with a multilayered QD EML have been developed, which can reduce the close contact of the different-colored QDs, leading to the suppression of FRET. It is difficult to deposit the multilayered EML, however, due to the intermixing of the adjacent QD EML when processed with the same solvent. By inserting an interlayer between the multilayered EML and the adjacent EML, the issue of intermixing can be avoided, but the charge balance is degraded, resulting in a decrease in the device efficiency. Therefore, developing a novel fabricating process to avoid the intermixing of the adjacent layer, balancing the charge injection, and suppressing FRET are demanded for the further improvement of the device performance of the aforementioned structure. Compared with the structure of the mixed-QD single EML or the multilayered QD EML, the tandem structure is more advantageous and is expected to be the dominant structure for realizing efficient and stable WQLEDs for lighting and display applications.

Cadmium-free WQLEDs have attracted great attention due to their environment-friendliness. The performances of these devices, however, are still far from the requirements of practical applications (Table 1).

Although the performances of the Cd-QD-based WQLEDs have been steadily improved, a series of issues have yet to be solved for the successful commercialization of the WQLED technology. First, the color stability of WQLEDs is still a big problem. To improve the color stability, the exciton recombination zone should be well confined within each QD EML, whereas for tandem devices, the efficiency roll-off rate of R-, G-, and B-QLEDs should be kept the same. Second, the stability of WQLEDs is rarely studied, and the lifetime of WQLEDs remains short. It is necessary to study the degradation mechanism of monochromatic (especially blue) and white QLEDs. Considering the poor stability of the blue QDs, replacing them with more stable organic blue-light emitters can be a feasible way of constructing stable hybrid organic-QD white light-emitting diodes (LEDs). Furthermore, the large-area and low-cost device fabrication techniques remain in the early stages of development. The realization of large-area WQLED devices is an important step towards lighting and display applications, but it is still challenging to realize a uniform and high-quality QD film using the commonly utilized fabrication techniques, such as spin-coating and inkjet printing. With the research efforts continuously devoted to this by the academia and industry, the efficiency, color stability, and device stability of WQLEDs can be further improved, and
the authors believe that WQLEDs can finally find application in large-area, low-cost, high-resolution full-color displays and solid-state lighting.

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