Opto-Electronic
Advances

ISSN 2096-4579 CN 51-1781/TN

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Citation: He JH. High-performance warm white LED based on thermally stable all inorganic perovskite quantum dots. *Opto-Electron Adv*, **6**, 230022(2023).

https://doi.org/10.29026/oea.2023.230022

Received: 10 February 2023; Accepted: 28 February 2023; Published online: 8 March 2023

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March 2023, Vol. 6, No. 3

DOI: 10.29026/oea.2023.230022

High-performance warm white LED based on thermally stable all inorganic perovskite quantum dots

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All inorganic $CsPbBr_3$ quantum dots (QDs) are regarded as excellent candidates for next-generation emitters due to their high photoluminescence quantum yield (PLQY) and defect tolerance. However, the poor stability and degraded luminescent performance may impede their further commercialization because of the separation of conventional ligands from the QDs surfaces. Recently, Zang replaced the regular oleic acid with 2-hexyl-decanoic acid (DA), which possesses higher binding energy on the QDs surfaces, to act as ligands of QDs, exhibiting PLQY of 96% and excellent stabilities against ethanol and water. WLEDs with DA-modified $CsPbBr_3$ QDs achieved improved thermal stability, a color rendering index of 93, a power efficiency of 64.8 lm/W and a properly correlated color temperature value of 3018 K, implying their prominent applications in solid-state lighting and displays.

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It is well known that more than 20% of global electronic energy is consumed by lighting and displays every year[1], which is identified as the major challenge of reduced carbon release[2]. Thus, it is quite urgent to develop efficient light sources to save massive amounts of electric power[3]. As a kind of potential solid-state light source, white light-emitting diodes (WLEDs) have received substantial attention due to their high power efficiency and eco-friendly. Conventional WLEDs' white emission originates from rare-earth phosphors excited by blue or ultraviolet LED chips[4]. However, the supply shortage of rare-earth phosphors and complex manufacturing processes hinder the large-scale and commercial applications of conventional WLEDs. In addition, their development suffers from the highly correlated color temperature (CCT) and low color rendering index (CRI), in which the cold white emission may hurt the naked eyes of humans and cause a chromatic issue. To meet the requirement of high-performance warm WLEDs, researchers pay more attention to the exploration of emitting materials with facile preparation and high PLQYs[5].

Due to the high PLQY and low-temperature solution processability, the inorganic $CsPbBr_3$ perovskite quantum dots (QDs) have been regarded as the promising candidate for emitters of efficient warm WLEDs[6,7]. Despite the rapid advances of $CsPbBr_3$ QDs, their commercial application in efficient warm WLEDs has been impeded, which is resulted from the poor stability of $CsPbBr_3$ QDs induced by the separation of conventional oleic acid (OA) ligands from the QDs surfaces. The separation of OA ligands is attributed to the weak binding between the ligands and QDs surfaces[8]. As a result, the study and design of novel ligands binding strongly to the QDs surfaces enhances the stability and luminescent

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Received: 10 February 2023; Accepted: 28 February 2023; Published online: 8 March 2023

efficiency of both emitters and WLEDs.

In the recent work published in *Opto-Electronic Advances,* DOI: 10.29026/oea.2022.200075, Prof. Zhigang Zang et al. propose a facile strategy to introduce 2-hexyldecanoic acid (DA) ligands to replace conventional OA ones[9]. The DA ligands exhibit larger binding energy than that in OA ligands (ΔE = 0.202 eV), indicating the strong binding of DA ligands to the QDs surfaces. The reduced separation of DA ligands from QDs is found to decrease surface defects, resulting in increased PLQYs of QDs up to 96% but unchanged crystal structure and PL spectra[10]. Furtherly, the DA ligands binding on QDs enable to isolate the QDs from others, suppressing the interaction of QDs[11]. Consequently, the aggregation and PL quenching of QDs are reduced, ascribed to the improved stability in solvents and enhanced luminescent performance, respectively.

The transient PL spectra and atomic force microscopy characterization can prove and clarify them. Compared with $CsPbBr_3$ QDs with OA ligands, the ligand-modified QDs with DA possess enhanced optoelectronic properties and stability against water and ethanol. They are employed as emitters in WLEDs[12]. The authors fabricated warm WLEDs combining the green DA-$CsPbBr_3$ and red AgInZnS QDs with broad spectra on blue chips[13], exhibiting a high CRI of 93, a proper CCT of 3018 K and a high power efficiency of 64.8 lm/W. This stand out among the reported WLEDs. The excellent thermal stability of operating WLEDs indicates the vital role of DA-$CsPbBr_3$ QDs and the prominent potentials of the fabricated WLEDs in applications of solid-state lighting and display[14].

In this article, the authors focus on the critical challenge of inorganic perovskite $CsPbBr_3$ QDs[15]. The ligand modification process is schematically shown in Fig. 1. They propose a ligand-modified strategy to solve the formidable issue of poor stability[16]. The DA ligands are utilized to replace the conventional OA ligands, in which the shorter lengths and di-branched chains of DA play a vital role in strong binding to the QDs surface[17]. As a result, the DA ligands can not only fill the surface defects of QDs but also isolate the QDs from others, enhancing the PLQY and suppressing the aggregation of QDs[18]. With the DA-ligand modification, the DA-$CsPbBr_3$ QDs exhibit excellent luminescent properties and enhanced stability against water and ethanol. The introduction of novel DA ligands is a "one stone and two birds" strategy, which can enhance the performance of $CsPbBr_3$ QDs directly without changing the original preparation process, crystal structures and PL spectra of QDs[10]. Applying the modified QDs to efficient warm WLEDs indicates the attractive role of ligand modification[19]. It suggests that it is a typical and effective method to promote the commercial development of inorganic perovskite quantum dots[20].

The authors are building on the research of Prof. Hao-Chung Kuo, Prof. Zhong Chen et al[21]. The excellent brightness, low energy consumption, and ultra-high resolution of micro-light-emitting diodes (micro-LEDs) are significant advantages[22]. However, the large size of traditional inorganic phosphors and the number of side defects have restricted the practical applications of small sized micro-LEDs[23]. Recently, QD and non-radiative energy transfer (NRET) have been proposed to solve existing problems. QDs possess nanoscale dimensions and high luminous efficiency, and they are suitable for NRET because they are able to nearly contact the micro-LED chip[24]. The NRET between QDs and micro-LED chip

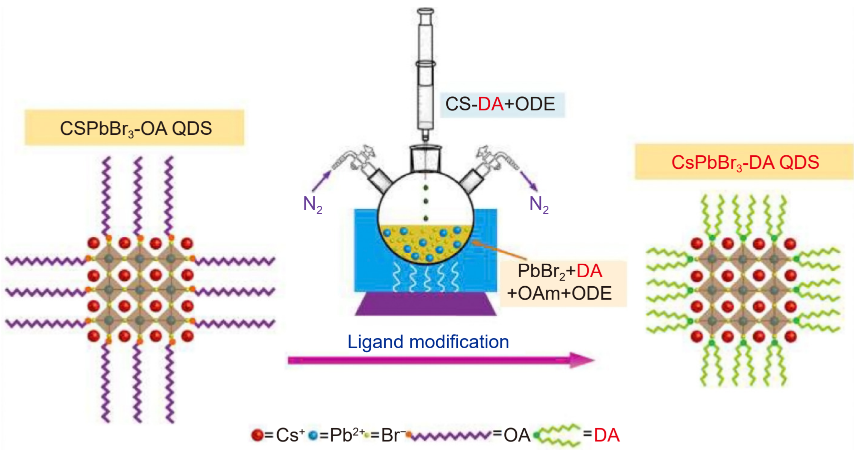

Fig. 1 | The schematic illustration of the surface in the $CsPbBr_3$ QDs with ligand modification process.

further improves the color conversion efficiency (CCE) and effective quantum yield (EQY) of full-color micro-LED devices. In their review, they discussed the NRET mechanism for QD micro-LED devices, and then nano-pillar LED[25], nano-hole LED[26], and nano-ring LED in details[27]. These structures are beneficial to the NRET between QD and micro-LED, especially nano-ring LED. Finally, the challenges and future envisions have also been described.

Display technology has gone through countless changes and penetrated every corner of our life. As a display technology, light-emitting diode (LED) has attracted attention due to its low cost, easy fabrication, and energy conservation[28]. In 2000, the technology strategy of micro-LEDs was put forward for the first time at the Texas Tech University, which signified that LED light sources had entered the era of micro display[29]. Compared with traditional LED screen display technologies such as mini-LED, organic-LED, etc., the micro-LEDs have the following advantages: high brightness, high luminous efficiency, low energy consumption, quick reaction, high contrast, self-illumination, long service life, ultra-high resolution, and good color saturation[30].

Similarly, the work of Prof. Jeongyong Kim et al[31], supports the work of Zang et al. MXene ($M_{n+1}X_n$) is an emerging class of layered two-dimensional (2D) materials[32], which are derived from their bulk-state MAX phase ($M_{n+1}AX_n$, where M: early transition metal, A: group element 13 and 14, and X: carbon and/or nitrogen)[33]. MXenes have found wide-ranging applications in energy storage devices, sensors, and catalysis, owing to their high electronic conductivity and wide range of optical absorption. However, the absence of semiconducting MXenes has limited their applications related to light emission[33]. Research has shown that QDs derived from MXene (MQDs) not only retain the properties of the parent MXene, but also demonstrate significant improvement on light emission and quantum yield (QY). The optical properties and photoluminescence (PL) emission mechanisms of these light-emitting MQDs have not been comprehensively investigated[34]. Recently, work on light-emitting MQDs has shown good progress[35], and MQDs exhibiting multi-color PL emission along with high QY have been fabricated[36]. The synthesis methods also play a vital role in determining the light emission properties of these MQDs[37]. The review provided an overview of light-emitting MQDs and their synthesis methods, optical properties, and applications in various optical, sensory, and imaging devices. The future prospects of light-emitting MQDs are also discussed to provide an insight that helps to further advance the progress on MQDs.

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Acknowledgements

The author acknowledges the financial support by the City University of Hong Kong (9380107 and 7005943).

Competing interests

The authors declare no competing financial interests.