RESEARCH HIGHLIGHTS

Journal of Semiconductors
(2021) 42, 070201
doi: 10.1088/1674-4926/42/7/070201

Blue perovskite LEDs

Mengqi Zhang[1], Chuantian Zuo[2], Jianjun Tian[1, †], and Liming Ding[2, †]

[1]Institute for Advanced Materials Technology, University of Science and Technology Beijing, Beijing 100083, China

[2]Center for Excellence in Nanoscience (CAS), Key Laboratory of Nanosystem and Hierarchical Fabrication (CAS), National Center for Nanoscience and Technology, Beijing 100190, China

Citation: M Q Zhang, C T Zuo, J J Tian, and L M Ding, Blue perovskite LEDs[J]. *J. Semicond.*, 2021, 42(7), 070201. http://doi.org/10.1088/1674-4926/42/7/070201

Metal halide perovskite light-emitting diodes (PeLEDs) show great potential in ultra-high-definition displays, due to their narrowband emission, wide color gamut (~140%), and cost-effective solution processability[1]. Thanks to scientists' tremendous efforts, the external quantum efficiencies (EQEs) for the state-of-the-art PeLEDs emitting near-infrared and green light have reached 21.6%[2] and 23.4%[3], respectively. However, blue PeLEDs, as one of the essential technologies for perovskite-based high-resolution monitors and white lighting, are still inferior to their red and green counterparts. Blue emission is usually achieved by using dimensional engineering (quantum confinement) or composition engineering (mixed halides, e.g., mixed Br/Cl) strategies. For example, quasi-two-dimensional (2D) perovskites, nanocrystals (e.g., quantum dots, QDs) or nanoplates, give blue emission due to quantum confinement effects. However, achieving pure-blue (465–475 nm) and deep-blue (420–465 nm) light from quasi-2D perovskites is challenging[4], while ultra-small QDs and nanoplates suffer from high surface trap density and poor stability[5]. For PeLEDs based on mixed Br/Cl perovskites, the emission peak can be tuned easily, but these perovskites face the disadvantages of phase separation and deep energy-level Cl vacancies[4].

Scientists have made great efforts to develop high-performance blue PeLEDs. Dong *et al.* made sky-blue PeLEDs based on $CsPbBr_3$ QDs, in which the emission shifts from green to sky-blue as $CsPbBr_3$ changes from bulk to QDs because of quantum confinement (Fig. 1(a))[6]. They designed a bipolar shell consisting of an inner anion shell and an outer molecules shell, which can promote carrier transport and decrease trap density in QDs, thus stabilizing QDs (Fig. 1(b))[6]. The PeLEDs based on the optimized QDs gave an EQE of 12.3% with electroluminescence (EL) peak at ~480 nm, which is one of the highest value for blue PeLEDs (Fig. 1(c)). This efficiency was obtained under low current density ($<10^{-1}$ mA/cm^2) and luminance, and decreased with increasing current density (Fig. 1(c)). Chu *et al.* introduced a large cation $CH_3CH_2NH_3^+$ (EA) into quasi-2D perovskites to enlarge the bandgap, thus realizing blue emission. The PeLEDs based on quasi-2D perovskites gave an EQE of 12.1% with sky-blue EL peak at 488 nm[7]. More recently, Karlsson *et al.* developed a vapor-assisted crystallization (VAC) technique to prepare mixed halide perovskite films ($Cs_{1.2}FA_{0.3}Pb(Br_{1-x}Cl_x)_{3.5}$, x = 0.3–0.57), which mitigated local compositional heterogeneity and ion migration (Fig. 1(d)), thus obtaining stable blue emission at 490–451 nm (Fig. 1(e))[8]. The PeLEDs gave EQE of 11.0% and 5.5%, with emission peaks at 477 and 467 nm, respectively (Fig. 1(f)).

Sky-blue (480–490 nm) PeLEDs present advances in EQE (>10%) and luminance (>4000 cd/m^2), but the efficiency and luminance for pure-blue and deep-blue (420–475 nm) PeLEDs are much lower. Though the passivation strategies could reduce Cl^- vacancies in pure-blue and deep-blue mixed halide perovskite nanocrystals, leading to high PLQY and efficient PeLEDs[9], they still suffer from poor stability and low luminance. Recently, Bi *et al.* proposed a new strategy, in which acid etching and ligand exchanging were combined to yield stable $CsPbBr_3$ QDs with high PLQY (97%) and ultra-low trap-density, giving pure blue emission (465 nm) (Fig. 2(a))[10]. This strategy avoids the issues for mixed halides and yields pure blue emission. The PeLEDs based on these QDs gave pure-blue EL at 470 nm with an EQE of 4.7% (Fig. 2(b)), corresponding to the Commission Internationale de L'Eclairage (CIE) coordinates (0.13, 0.11) which meets the requirement of Rec. 2020 display standards. Notably, the device gave a luminance of 3850 cd/m^2, which is one of the highest brightness reported for pure-blue and deep-blue PeLEDs[10]. Furthermore, the PeLEDs exhibited a half-lifetime exceeding 12 h under continuous operation (Fig. 2(c)), being a record value for blue PeLEDs[10]. Dissimilarly, Wang *et al.* made efficient pure-blue PeLEDs base on mixed halide perovskite nanocrystals film[11]. They adopted dual ligands, 2-phenylethanamine bromide (PEABr) and 3,3-diphenylpropylamine bromide (DPPABr), to control the growth of $CsPbClBr_2$ nanocrystal films (Fig. 2(d)). This method can narrow down the quantum-well width distribution (Fig. 2(e)), suppressing non-radiative recombination. The PeLEDs offered an EQE of 8.8% with emission peak at 473 nm (Fig. 2(f)).

In summary, blue-emitting perovskite materials and devices have become a research hotspot in recent years. Though the EQE for sky-blue PeLEDs has exceeded 10%, the pure-blue and deep-blue PeLEDs suffer from low efficiency and luminance. And the poor stability is a bottleneck for the application of PeLEDs[12]. There is a large room for enhancing the performance of blue PeLEDs.

Acknowledgements

J. Tian thanks the National Key Research and Development Program of China (2017YFE0119700), National Natural

Correspondence to: J J Tian, tianjianjun@mater.ustb.edu.cn; L M Ding, ding@nanoctr.cn

Received 28 MARCH 2021.

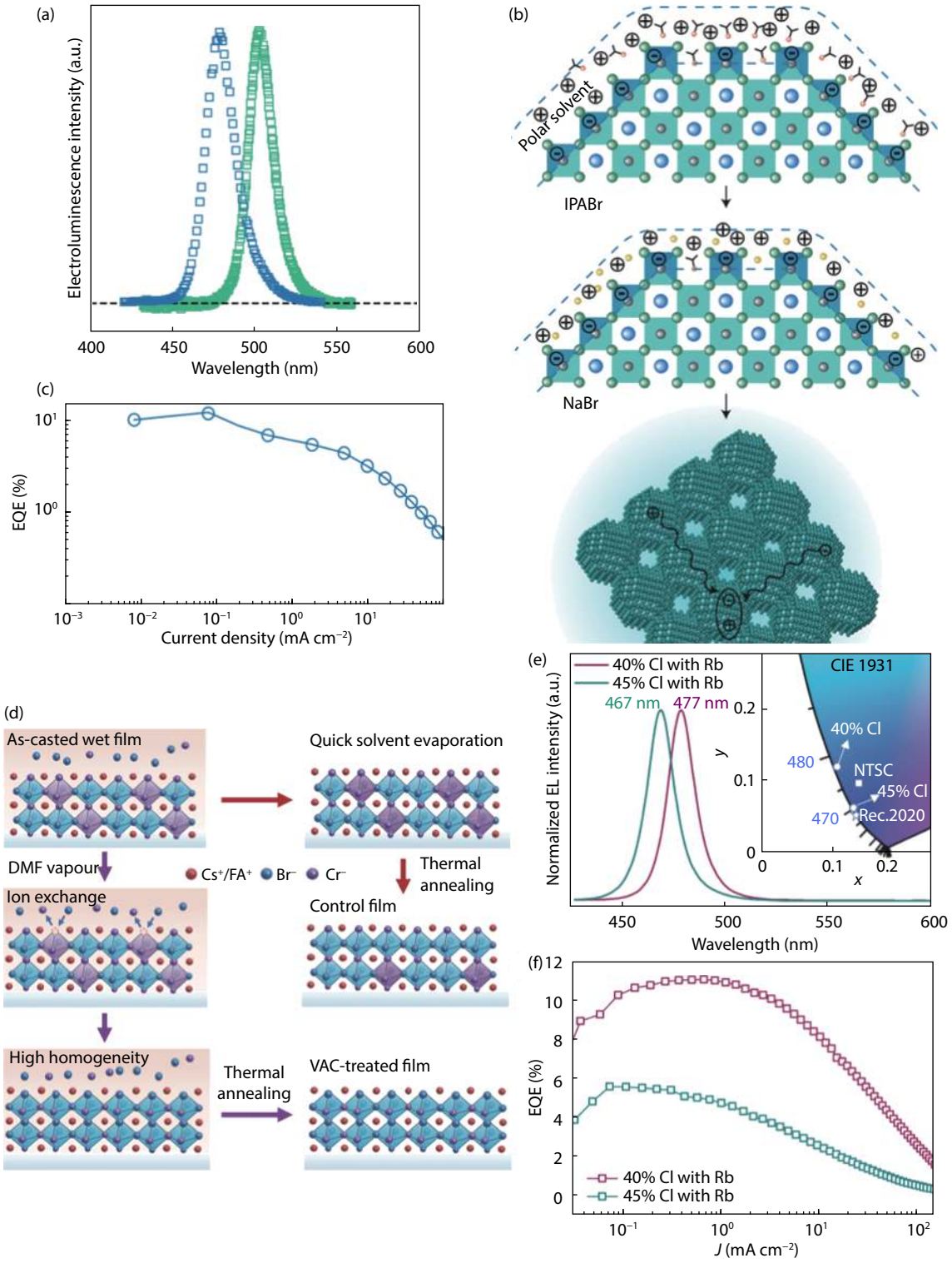

Fig. 1. (Color online) (a) EL spectra for blue PeLEDs. (b) Schematic illustration of the bipolar-shell-stabilized perovskite QDs. (c) EQE for blue-PeLEDs made with bipolar-shell-stabilized QDs. Reproduced with permission[6], Copyright 2020, Nature Publishing Group. (d) Schematic illustration of the mechanism for halide redistribution. (e) EL spectra (Left) and CIE color coordinates (Right) for VAC-treated, Rb-incorporated PeLEDs. (f) EQE for Rb-device as a function of current density. Reproduced with permission[8], Copyright 2021, Nature Publishing Group.

Science Foundation of China (51961135107, 51774034, 51772026) and Beijing Natural Science Foundation (2182039). L. Ding thanks the National Key Research and Development Program of China (2017YFA0206600) and the National Natural Science Foundation of China (51773045, 21772030, 51922032 and 21961160720) for financial support.

References

[1] Kovalenko M V, Protesescu L, Bodnarchuk M I. Properties and potential optoelectronic applications of lead halide perovskite nanocrystals. Science, 2017, 358, 745

[2] Xu W D, Hu Q, Bai S, et al. Rational molecular passivation for high-performance perovskite light-emitting diodes. Nat Photonics,

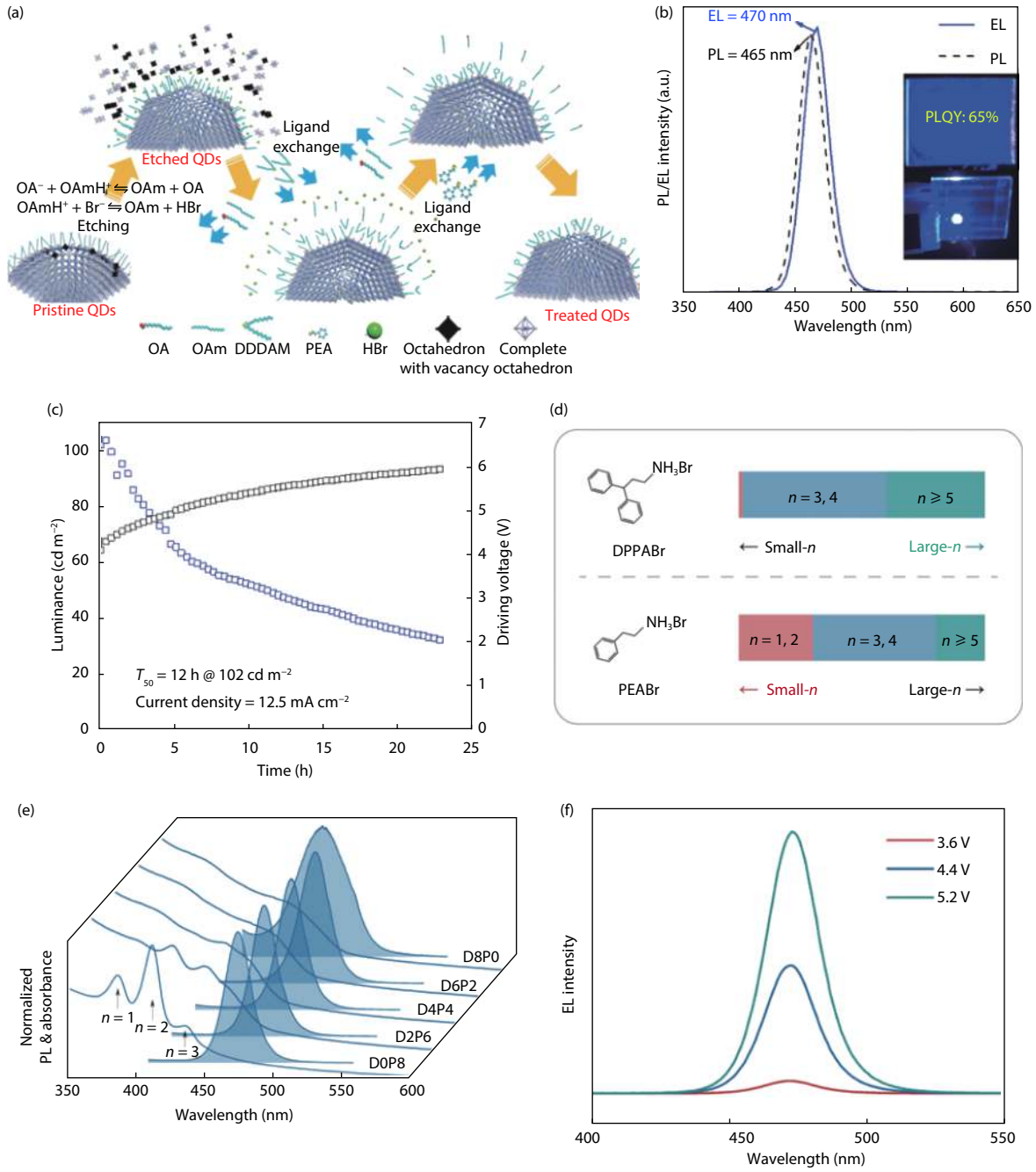

Fig. 2. (Color online) (a) Schematic illustration of ligand exchange process driven by acid etching. (b) PL for QDs films and EL for PeLEDs. (c) T_{50} for PeLEDs with an initial luminance of 102 cd m^{-2}. Reproduced with permission[10], Copyright 2021, Wiley Publishing Group. (d) Schematic diagram for DPPABr-based and PEABr-based $CsPbClBr_2$ nanocrystal films. (e) Steady-state PL and absorption spectra for $CsPbClBr_2$ films. (f) EL spectra for PeLEDs under forward biases of 3.6, 4.4, and 5.2 V. Reproduced with permission[11], Copyright 2020, Nature Publishing Group.

2019, 13, 418

[3] Kim Y H, Kim S J, Kakekhani A, et al. Comprehensive defect suppression in perovskite nanocrystals for high-efficiency light-emitting diodes. Nat Photonics, 2021, 15, 148

[4] Liu A Q, Bi C H, Guo R Q, et al. Electroluminescence principle and performance improvement of metal halide perovskite light-emitting diodes. Adv Optical Mater, 2021, 9, 2002167

[5] Bi C H, Hu J C, Yao Z W, et al. Self-assembled perovskite nanowire clusters for high luminance red light-emitting diodes. Adv Funct Mater, 2020, 30, 2005990

[6] Dong Y T, Wang Y K, Yuan F L, et al. Bipolar-shell resurfacing for blue LEDs based on strongly confined perovskite quantum dots. Nat Nanotechnol, 2020, 15, 668

[7] Chu Z M, Zhao Y, Ma F, et al. Large cation ethylammonium incorporated perovskite for efficient and spectra stable blue light-emitting diodes. Nat Commun, 2020, 11, 4165

[8] Karlsson M, Yi Z Y, Reichert S, et al. Mixed halide perovskites for spectrally stable and high-efficiency blue light-emitting diodes. Nat Commun, 2021, 12, 361

[9] Zheng X P, Yuan S, Liu J K, et al. Chlorine vacancy passivation in mixed halide perovskite quantum dots by organic pseudohalides enables efficient Rec. 2020 blue light-emitting diodes. ACS Energy Lett, 2020, 5, 793

[10] Bi C H, Yao Z W, Sun X J, et al. Perovskite quantum dots with ultralow trap density by acid etching-driven ligand exchange for high luminance and stable pure-blue light-emitting diodes. Adv Mater, 2021, 33, 2006722

[11] Wang C H, Han D B, Wang J H, et al. Dimension control of in situ

fabricated $CsPbClBr_2$ nanocrystal films toward efficient blue light-emitting diodes. Nat Commun, 2020, 11, 6428

[12] Jiang Y Z, Cui M H, Li S S, et al. Reducing the impact of Auger recombination in quasi-2D perovskite light-emitting diodes. Nat Commun, 2021, 12, 336

Mengqi Zhang received BE in Central South University in 2015 and ME in University of New South Wales in 2020. She is currently a PhD candidate at University of Science and Technology Beijing under the supervision of Professor Jianjun Tian. Her work focuses on perovskite quantum dots synthesis and related optoelectronic devices.

Chuantian Zuo received his PhD in 2018 from National Center for Nanoscience and Technology (CAS) under the supervision of Professor Liming Ding. Then he did postdoctoral research in CSIRO, Australia. Currently, he is an assistant professor in Liming Ding Group. His research focuses on innovative materials and devices.

Jianjun Tian received his PhD from University of Science and Technology Beijing (USTB) in 2007. In 2011–2012, he worked at the University of Washington. Now he is a professor at USTB. He was nominated as the Director of Functional Materials Institute, USTB, in 2015. His research focuses on the development of quantum dots and perovskite materials for optoelectronic applications.

Liming Ding got his PhD from University of Science and Technology of China (was a joint student at Changchun Institute of Applied Chemistry, CAS). He started his research on OSCs and PLEDs in Olle Inganäs Lab in 1998. Later on, he worked at National Center for Polymer Research, Wright-Patterson Air Force Base and Argonne National Lab (USA). He joined Konarka as a Senior Scientist in 2008. In 2010, he joined National Center for Nanoscience and Technology as a full professor. His research focuses on functional materials and devices. He is RSC Fellow, the nominator for Xplorer Prize, and the Associate Editors for Science Bulletin and Journal of Semiconductors.