Facile synthesis of CsPbBr₃/PbSe composite clusters

Thang Phan Nguyena‡, Abdullah Ozturkb‡, Jongee Parkc, Woonbae Sohnd, Tae Hyung Leed, Ho Won Jangd and Soo Young Kima

School of Chemical Engineering and Materials Science, Chung-Ang University, Seoul, Republic of Korea; Metallurgical and Materials Engineering Department, Middle East Technical University, Ankara, Turkey; Metallurgical and Materials Engineering Department, Attilim University, Ankara, Turkey; Department of Materials Science and Engineering, Research Institute of Advanced Materials, Seoul National University, Seoul, Republic of Korea

ABSTRACT

In this work, CsPbBr₃ and PbSe nanocomposites were synthesized to protect perovskite material from self-enlargement during reaction. UV absorption and photoluminescence (PL) spectra indicate that the addition of Se into CsPbBr₃ quantum dots modified the electronic structure of CsPbBr₃, increasing the band gap from 2.38 to 2.48 eV as the Cs:Se ratio increased to 1:3. Thus, the emission color of CsPbBr₃ perovskite quantum dots was modified from green to blue by increasing the Se ratio in composites. According to X-ray diffraction patterns, the structure of CsPbBr₃ quantum dots changed from cubic to orthorhombic due to the introduction of PbSe at the surface. Transmission electron microscopy and X-ray photoemission spectroscopy confirmed that the atomic distribution in CsPbBr₃/PbSe composite clusters is uniform and the composite materials were well formed. The PL intensity of a CsPbBr₃/PbSe sample with a 1:1 Cs:Se ratio maintained 50% of its initial intensity after keeping the sample for 81 h in air, while the PL intensity of CsPbBr₃ reduced to 20% of its initial intensity. Therefore, it is considered that low amounts of Se could improve the stability of CsPbBr₃ quantum dots.

1. Introduction

Nowadays, much of the research concerning halide perovskites is focused on the new generation of solar cells, light-emitting diodes, transistors, lasers, and memristors with thin film, nanowire, and nanorod structures [1–6]. The power conversion efficiency of lead halide perovskite-based thin film photovoltaic cells has improved fast, from 3.8% to over 20% in a decade [7]. Among organic and inorganic perovskite materials, cesium lead halide has shown better stability than organic perovskite materials, suggesting great potential for use in opto-electronic devices.

Research on the morphology of perovskites shows that nano-size materials display superior properties in comparison with bulk-size materials, such as higher quantum yield, narrower emission bandwidth, and tunable color [8,9]. Recently, it was reported that cesium lead halide quantum dots have promisingly high color purity for light-emitting diodes [10,11]. Furthermore, it was shown that the growth rate, structure and size of CsPbBr₃ dots can be controlled by changing the length of carbon chains of acids and amines in ligands during synthesis [12]. This allows the possibility for finding the optimal structure and size for cesium lead halide

CONTACT Ho Won Jang hwjang@snu.ac.kr; Soo Young Kim sooyoungkim@cau.ac.kr

‡These authors contributed equally to this work.

© 2017 The Author(s). Published by National Institute for Materials Science in partnership with Taylor & Francis. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
quantum dots. However, the thermal and electrical stability of cesium lead halide quantum dots is still limited.

One particular organo-halide perovskite material, CH$_3$NH$_3$PbI$_3$, has been used as the shell of PbS quantum dots. It was reported that PbS/CH$_3$NH$_3$PbI$_3$ core/shell quantum dots can increase the performance of sensitized solar cells because CH$_3$NH$_3$PbI$_3$ covered the PbS core as a passive shell, improving the quantum efficiency and air stability [13]. Perovskite CH$_3$NH$_3$PbI$_3$ was grown to protect perovskite material from self-degradation and photostability [13]. Perovskite CH$_3$NH$_3$PbI$_3$ has been used as the shell of PbS quantum dots. The recent reports about protecting perovskite materials were summarized in Table 1 [22–27].

A nanocomposite material of CsPbBr$_3$ and PbSe was synthesized to protect perovskite material from self-enlargement during reaction. As a core material, CsPbBr$_3$ quantum dots were chosen because CsPbBr$_3$ is the most stable among cesium lead halides. It is reported that materials with low lattice mismatch could easily form the core/shell structure such as CdSe/CdS (3.9% lattice mismatch) [28] or CdSe/ZnS (12% lattice mismatch) [29]. The lattice constant of cubic phase CsPbBr$_3$ is known to be 5.87 Å and that of PbSe is reported to be 6.1 Å [30,31]. Therefore, the lattice mismatch between CsPbBr$_3$ and PbSe is approximately 4%. The same source of Pb$^{2+}$ in an organic solvent could be used to produce CsPbBr$_3$ and PbSe. Furthermore, trioctylphosphine selenide can be used as an easy source for the PbSe shell layer. It is therefore expected that CsPbBr$_3$/PbSe composites could be synthesized to improve the stability of inorganic perovskite quantum dots.

2. Experimental details

2.1. Materials

Lead bromide (PbBr$_2$) 98%, cesium carbonate (Cs$_2$CO$_3$) 98%, octadecene (ODE) 90%, oleic acid 90% technique grade (OA), and oleyl amine (OAm) 95% were purchased from Sigma-Aldrich and used without further purification.

2.2. Synthesis of CsPbBr$_3$ quantum dots

The synthesis of CsPbBr$_3$ follows the previously reported procedures [32]. 70 mg of PbBr$_2$ was loaded into a 100 mL flask along with 10 mL of ODE, 1 mL of OA, and 0.5 mL of OAm. The solution was then heated up to 120 °C under N$_2$ to completely disperse PbBr$_2$. Cesium oleate was prepared by loading 0.814 g of Cs$_2$CO$_3$ along with 30 mL of ODE and 2.5 mL of OA into a 100 mL flask. The temperature of the solution was increased to 120 °C for the completion of cesium oleate. After heating the PbBr$_2$ solution to 190 °C, 0.4 mL of cesium oleate heated at 100 °C was injected to complete the synthesis of CsPbBr$_3$ quantum dots. The mixture was cooled down in an ice water bath. Quantum dots were precipitated and washed using hexane and butanol with a 1:1 volume ratio. After that, quantum dots were dispersed into toluene for further use.

2.3. Synthesis of CsPbBr$_3$/PbSe nanocomposite

The selenide source was prepared by loading 10 mg of selenium in 0.5 mL of trioctylphosphine (TOP) and 0.5 mL of ODE. The mixture was heated up to 140 °C in 1 h. The 0.2 mL of TOPSe was quickly added into the solution of PbBr$_2$ with cesium oleate. The solution was kept at 190 °C for 1 h. Then, the color of the solution changed from light green to dark green. The materials were precipitated and washed using hexane and 2-butanol. The synthesized materials were re-dispersed in toluene for further use. In order to investigate the effect of synthesis temperature and the concentration of Se on the properties of the CsPbBr$_3$/PbSe nanocomposite, samples were produced at synthesis temperatures of 150, 170, and 190 °C, and using 0.2, 0.4, and 0.6 mL of TOP-Se to match a Cs:Se mol ratio of 1:1, 1:2, and 1:3, respectively.

2.4. Characterization

A JASCO V-670 UV-vis spectrophotometer with a xenon arc lamp and PMT-1527 Hamamatsu photomultiplier was used to measure UV-visible absorbance and photoluminescence (PL) of the materials. X-ray diffraction (XRD, D8-Advance/Brucker-AXS), field-emission scanning electron microscopy (FE-SEM, SIGMA/Carl Zeiss), and transmission electron microscopy (TEM, JEOL-2100F, Japan) were applied to measure the structures and sizes of CsPbBr$_3$ and CsPbBr$_3$/PbSe composites. Synchrotron radiation photoemission spectroscopy (SRPES) experiments were also performed in an ultrahigh-vacuum chamber (base pressure of $\sim$10$^{-10}$ Torr) at the 4D beam line of the Pohang Acceleration Laboratory. The onset of photoemission, corresponding to the vacuum level at the sample surface, was measured using an incident photon energy of 250 eV with a negative bias on the sample. The results were corrected for charging effects using Au 4f as an internal reference.

3. Results and discussion

The expected structure of CsPbBr$_3$/PbSe composite is schematically drawn in Figure 1(a). Figure 1(b)–(i) show photographs of CsPbBr$_3$/PbSe composites and pristine CsPbBr$_3$ in hexane solution under normal light ((b)–(e)) and under a UV lamp ((f)–(i)). For comparison, the pristine CsPbBr$_3$ is synthesized at 150, 170, and 190 °C from left to right as shown in Figure 1(e) and (i). The ratio
of Cs:Se in photographs of CsPbBr₃/PbSe composites is 1:1, 1:2, and 1:3 from left to right. The synthesis temperatures are 150 °C ((b), (f)), 170 °C ((c), (g)), and 190 °C ((d), (h)). The wavelength of the UV lamp was 365 nm. The colors of the composite solutions synthesized at 150 °C are all blue under UV illumination. At 170 °C, the solutions emitted light of cyan color under UV, suggesting that the light shifted to higher wavelength as the synthesis temperature increased. Composite materials synthesized at 190 °C emitted green light under UV illumination and the color of emitted light changed from green to cyan as the concentration of Se increased. These results indicate that the emission wavelength of CsPbBr₃/PbSe composites under UV illumination increased as the synthesis temperature increased. Furthermore, the increase of Se concentration in CsPbBr₃/PbSe shortened the wavelength of emitted light under UV illumination. The synthesis of perovskite quantum dots via solution methods is quite sensitive. A large size was simple to achieve due to the easy bonding of anion and cation. According to previous reports, the CsPbBr₃ quantum dot solution was cooled down immediately after finishing the reaction [32,33]. In our case, the CsPbBr₃ quantum dot solution was heated for 1 h after adding TOPSe to make CsPbBr₃/PbSe composites. However, luminescence was detected under UV illumination as shown in Figure 1. This means that the crystal structure of CsPbBr₃ was maintained even after a longer heating process and CsPbBr₃ was protected by PbSe.

To investigate the effects of the Se content of CsPbBr₃/PbSe on its optical properties, UV-vis and PL spectra were measured. Figure 2 shows (a) UV-vis absorption spectra and (b) PL spectra of CsPbBr₃ quantum dots and composites of CsPbBr₃/PbSe with different Cs:Se ratios (1:1, 1:2, and 1:3). The synthesis temperature of the CsPbBr₃/PbSe composites was fixed at 190 °C. The

### Table 1. Recent methods to protect perovskite materials.

| Perovskite     | Additional materials | Structure                          | References |
|----------------|----------------------|------------------------------------|------------|
| CsPbBr₃        | DBR mirror*          | Protective layer                   | [22]       |
| CsPbBr₃ / PbBr₃| ZnS                  | Composite                          | [23]       |
| FA-MAPbBr₃     | Photopolymer         | Protective layer                   | [24]       |
| MAPbI₃         | C₆H₅(CH₂)₂NH₃I       | Protective layer for storing       | [25]       |
| CsPbBr₃       | bis-(2,2,4-trimethylpentyl) phosphinic acid (TMPPA) | Protective solution for storing perovskite quantum dots | [26]       |
| CsPbBr₃/PbSe   | NH₃Br                | Composite                          | [27]       |
| CsPbBr₃       | PbSe                 | This work                          |            |

*DBR: Distributed Bragg reflector.
^FA: Formamidinium.
^MA: Methylammonium.

Figure 1. (a) Schematic of the expected CsPbBr₃/PbSe nanocomposite structure. Photographs of CsPbBr₃/PbSe nanocomposite in hexane solution under normal ((b)–(d)) and UV ((f)–(h)) illumination with Cs:Se ratios of 1:1, 1:2, and 1:3 synthesized at 150 °C ((b), (f)), 170 °C ((c), (g)) and 190 °C ((d), (h)) from left to right, respectively. For comparison, the photographs of pristine CsPbBr₃ under (e) normal and (i) UV illumination are also shown.
absorption peak appeared at 455 nm in CsPbBr₃ quantum dots and in CsPbBr₃/PbSe composites with a 1:1 Cs:Se ratio, which corresponds to an optical band gap of 2.38 eV as shown in the inset of Figure 2(a). In the case of CsPbBr₃/PbSe composites with a 1:2 Cs:Se ratio, the absorption peak shifts to 429 nm, indicating that the band gap is increased to 2.42 eV. A Cs:Se ratio of 1:3 shifts the absorption peak to 414 nm, further increasing the band gap to 2.48 eV. These results indicate that the addition of Se into CsPbBr₃, quantum dots modifies the electronic structure of CsPbBr₃. This result is in agreement with the PL spectra as shown in Figure 2(b). The CsPbBr₃ quantum dots emit green color with a wavelength between 500 and 550 nm. The PL spectra of CsPbBr₃/PbSe composites with a 1:1 Cs:Se ratio indicate that their cyan color consists of a blue peak at 478 nm and a green peak at 516 nm. As the Cs:Se ratio increased from 1:1 to 1:3, the PL peak shifted to 462 nm. These results indicate that the emission color of CsPbBr₃ perovskite quantum dots could be modified from green to blue by adjusting the Se ratio in composites.

In order to confirm the formation of PbSe on the surface of CsPbBr₃ quantum dots, XRD measurements were performed. Figure 3 shows the XRD patterns of CsPbBr₃ quantum dots and CsPbBr₃/PbSe composites with different Cs:Se ratios (1:1, 1:2, and 1:3). The synthesis temperature of the CsPbBr₃/PbSe composites was fixed at 190 °C. The CsPbBr₃ quantum dots show two peaks at 15.16 and 30.6°, indicating that the synthesized CsPbBr₃ quantum dots have a cubic structure with (1 0 0) and (2 0 0) planes. This result agrees well with previous reports on CsPbBr₃ quantum dots synthesized at above 140 °C [32,34,35]. In the CsPbBr₃/PbSe composite with a 1:1 Cs:Se ratio, new peaks appeared at 12.8 and 29.1° which correspond to the (1 0 0) and (2 0 0) planes of PbSe [36,37]. Furthermore, the (1 0 0) and (2 0 0) peaks of cubic CsPbBr₃ disappeared and new peaks at 14 and 16° appeared, which are assigned to the (1 0 0) and (1 0 1) planes of orthorhombic CsPbBr₃ [35]. This means that the structure of CsPbBr₃ quantum dots changed from cubic to orthorhombic due to the introduction of PbSe at the surface. In the case of the CsPbBr₃/PbSe composite with a 1:2 Cs:Se ratio, the peaks corresponding to PbSe (1 0 0) and (2 0 0) planes shifted to higher angles of 13 and 29°, respectively, suggesting that the plane distance of PbSe increased following the increase in Se. It is reported that PbSe has a cubic rocksalt structure with a lattice parameter of 6.12 Å and CsPbBr₃ has perovskite structure with a lattice parameter of 5.87 Å [30,31]. Therefore, it is considered that PbSe was compressed due to the smaller lattice parameter of CsPbBr₃ and that the lattice parameter of PbSe was restored as Se content increased. It is reported that orthorhombic phase has higher band gap than cubic phase. However, the photoluminescence is inactive in cubic-to-orthorhombic crystal transformation [26]. But, PL peak shift was found as shown in Figure 2. Therefore, band gap enlargement could be explained by Se doping. The (2 0 0) peak of CsPbBr₃ was absent in XRD spectra. However, the (1 0 0) peak of PbSe and peaks of orthorhombic CsPbBr₃ and (1 0 0) cubic CsPbBr₃ appeared in XRD patterns with weak intensity. The full width at half maximum of PbSe and CsPbBr₃ peaks also increased, indicating the size becomes smaller. Therefore, it is considered that the structure of cubic CsPbBr₃ is broken as the ratio of Se increased. This result agrees with the data of absorbance and photoluminescence as shown in Figure 2.

Figure 4 shows SRPES spectra of CsPbBr₃ quantum dots and CsPbBr₃/PbSe composite synthesized at 190 °C with a Cs:Se ratio of 1:3. The two peaks of Cs 3d[3/2] and Cs 3d[5/2] are shown at 726.1 and 740 eV, respectively. The Br 3d[3/2] and Br 3d[5/2] peaks are also shown at 69.3 and 70.4 eV, respectively. No peak change was observed in Cs 3d and Br 3d after the formation of PbSe at the surface.
of CsPbBr$_3$. In the case of the Pb 4f peak, two peaks are shown at 138.1 and 143 eV in CsPbBr$_3$, quantum dots, which correspond to Pb 4f$^{7/2}$ and Pb 4f$^{5/2}$, respectively. Additional peaks appeared at 137.5 and 142.4 eV in the CsPbBr$_3$/PbSe composite, which indicates the formation of Pb-Se bonds. These values are compatible with previous research on CsPbBr$_3$ and PbSe nanocrystals [38–40]. These results indicate that PbSe was formed well on the surface of CsPbBr$_3$, quantum dots.

The size of CsPbBr$_3$, quantum dots and CsPbBr$_3$/PbSe composite with a 1:3 Cs:Se ratio was measured using FE-SEM (Figure 5) and TEM (Figure 6). It is shown that the average size of CsPbBr$_3$, quantum dots is approximately 15 nm and that of CsPbBr$_3$/PbSe composite is approximately 20–25 nm. This suggests that PbSe is attached to the surface of CsPbBr$_3$, increasing the size by approximately 5–8 nm. The magnified images shown in the insets of Figure 5(a) and (b) indicate that CsPbBr$_3$ is mono-dispersed well and CsPbBr$_3$/PbSe forms a cluster. Figure 5(c) shows the size distribution of CsPbBr$_3$/PbSe composite clusters according to synthesis temperature. The average size of particles synthesized at 150, 170, and 190 °C is 6–8, 8–10, and 16–22 nm, respectively. These results support the conclusion that the emission wavelength of CsPbBr$_3$/PbSe composites under UV illumination increased as the synthesis temperature increased (see Figures 1 and 2). The CsPbBr$_3$/PbSe composite clusters were examined by TEM as shown in Figure 6. The (0 2 0) plane distance of CsPbBr$_3$ was measured as 0.29 nm, and the (2 0 0) plane distance of PbSe had a similar value of 0.30 nm. Therefore, it is considered that the (0 2 0) plane of CsPbBr$_3$ connects with the (2 0 0) plane of PbSe, forming the CsPbBr$_3$/PbSe composite clusters. Energy dispersive X-ray spectroscopy (EDS) mapping of Pb, Se, Br, and Cs atoms confirmed that the atomic distribution in CsPbBr$_3$/PbSe composite clusters is uniform and the composite materials were well-formed.

In order to test their stability, CsPbBr$_3$, quantum dots and CsPbBr$_3$/PbSe composites synthesized at 190 °C were dispersed in hexane and kept in air. Figure 7(a) shows the change in normalized PL as a function of time. The PL was measured every 24 h from the starting point of measurement. After 33 h, the PL intensity had degraded to around 70–80% of its initial intensity regardless of samples. After 57 h, PL values of CsPbBr$_3$/PbSe samples with Cs:Se ratios of 1:2 and 1:3 dramatically decreased to

---

**Figure 3.** X-ray diffraction patterns of bare CsPbBr$_3$ and CsPbBr$_3$/PbSe nanocomposites with Cs:Se ratios of 1:1, 1:2, and 1:3 synthesized at 190 °C. The peaks of orthorhombic CsPbBr$_3$ confirm the distortion of the lattice when forming PbSe beside the CsPbBr$_3$ quantum dots in the 1:1 Cs:Se ratio sample.

**Figure 4.** SRPES spectra of CsPbBr$_3$, quantum dots and CsPbBr$_3$/PbSe nanocomposites. The formation of PbSe peaks can be seen in the Pb 4f spectrum of the CsPbBr$_3$/PbSe nanocomposites. The Br 3d and Cs 3d peaks do not show large changes, suggesting that the perovskite structure was unchanged by the PbSe growth.
with a 1:1 Cs:Se ratio still maintained 50% of its initial intensity even after 81 h, suggesting that low amounts of Se could improve the stability of CsPbBr₃ quantum dots. Figure 7(b) shows normalized PL spectra after storage approximately 20% of its initial intensity, suggesting that PbSe could not elongate CsPbBr₃ stability. In the case of CsPbBr₃ quantum dots, the PL intensity reduced to 20% of its initial value after 81 h. However, CsPbBr₃/PbSe with a 1:1 Cs:Se ratio still maintained 50% of its initial intensity even after 81 h, suggesting that low amounts of Se could improve the stability of CsPbBr₃ quantum dots. Figure 7(b) shows normalized PL spectra after storage.
20% of their initial intensity. These results suggested that low amounts of Se could improve the stability of CsPbBr3 quantum dots. Therefore, it is considered that this synthesis method for CsPbBr3/PbSe composites could be used for other perovskite materials to increase the stability.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This research was supported in part by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) [grant number 2015K1A3A1A59073839] and in part by the Chung-Ang University Research Grants in 2016.

References
[1] Li G, Rivarola FWR, Davis NJLK, et al. Highly efficient perovskite nanocrystal light-emitting diodes enabled by a universal crosslinking method. Adv Mater. 2016;28:3528–3534.
[2] Li X, Wu Y, Zhang S, et al. CsPbX3 quantum dots for lighting and displays: room-temperature synthesis, photoluminescence superiorities, underlying origins and white light-emitting diodes. Adv Func Mater. 2016;26:2435–2445.
[3] Jeon NJ, Noh JH, Kim YC, et al. Solvent engineering for high-performance inorganic–organic hybrid perovskite solar cells. Nat Mater. 2014;13:897–903.
[4] Xiao ZG, Huang JS. Energy-efficient hybrid perovskite memristors and synaptic devices. Adv Electron Mater. 2016;2:1600100.
[5] Zhu H, Fu Y, Meng F, et al. Lead halide perovskite nanowire lasers with low lasing thresholds and high quality factors. Nat Mater. 2015;14:636–642.
[6] Chin XY, Cortecchia D, Yin J, et al. Lead iodide perovskite light-emitting field-effect transistor. Nat Commun. 2015;6:7383–7391.
[7] Lee MM, Teuscher J, Miyasaka T, et al. Efficient hybrid solar cells based on meso-superstructured organometal halide perovskites. Science. 2012;338:643–647.

Figure 7. Stability of materials in hexane solution, stored under ambient air, as evaluated by photoluminescence measurements: (a) pristine and composite perovskites compared at 9, 33, 57, and 81 h; (b) normalized photoluminescence spectra of CsPbBr3 and CsPbBr3/PbSe 1:1, 1:2, 1:3 kept for 9 and 81 h.

4. Conclusions
CsPbBr3/PbSe composite clusters were synthesized by adding TOPSe into a solution of PbBr2 with cesium oleate. As the ratio of Cs:Se increased from 1:1 to 1:3, CsPbBr3 partially transformed from cubic structure to orthorhombic structure and bonded with PbSe crystal, forming the composite cluster. The addition of Se into CsPbBr3 quantum dots modified the electronic structure of CsPbBr3, increasing the band gap from 2.38 to 2.48 eV as the Cs:Se ratio increased to 1:3. Therefore, the emission color of CsPbBr3 perovskite quantum dots was modified from green to blue by increasing the Se ratio in composites. The average size of CsPbBr3 quantum dots was approximately 15 nm and that of CsPbBr3/PbSe composite with a 1:3 Cs:Se ratio was approximately 20–23 nm. According to SEM and TEM images, CsPbBr3/PbSe composite exists in cluster form and each atom is uniformly distributed in the whole composite. The PL intensity of a CsPbBr3/PbSe sample with a 1:1 Cs:Se ratio maintained 50% of its initial intensity after keeping the sample for 81 h in air, while the PL intensity of CsPbBr3 quantum dots reduced to 20% of their initial intensity. These results suggested that low amounts of Se could improve the stability of CsPbBr3 quantum dots. Therefore, it is considered that this synthesis method for CsPbBr3/PbSe composites could be used for other perovskite materials to increase the stability.
8] Swarnkar A, Chulliyil R, Ravi VK, et al. Colloidal CsPbBr3 perovskite nanocrystals: luminescence beyond traditional quantum dots. Angew Chem Int Ed. 2015;54:15424–15428.

9] Zhang Y-X, Wang H-Y, Zhang Z-Y, et al. Photoluminescence quenching of inorganic caesium lead halides perovskite quantum dots (CsPbX3) by electron/hole acceptor. Phys Chem Chem Phys. 2017;19:1920–1926.

10] Zhang X, Lin H, Huang H, et al. Enhancing the brightness of caesium lead halide perovskite nanocrystal based green light-emitting devices through the interface engineering with perfluorinated ionomer. Nano Lett. 2016;16:1415–1420.

11] Du X, Wu G, Cheng J, et al. High-quality CsPbBr3 perovskite nanocrystals for quantum dot light-emitting diodes. RSC Adv. 2017;7:10391–10396.

12] Pan A, He B, Fan X, et al. Insight into the ligand-mediated synthesis of colloidal CsPbBr3 perovskite nanocrystals: the role of organic acid, base, and caesium precursors. ACS Nano. 2016;10:7943–7954.

13] Seo G, Seo J, Ryu S, et al. Enhancing the performance of sensitized solar cells with PbS/CH3NH3PbI3 core/shell quantum dots. J Phys Chem Lett. 2014;5:2015–2020.

14] Morassaei MS, Zinatloo-Ajabshir S, Salavati-Niasari M. Simple salt-assisted combustion synthesis of Nd2Sn2O7–SnO2 nanocomposites with different amino acids as fuel: an efficient photocatalyst for the degradation of methyl orange dye. J Mater Sci Mater Electron. 2016;27:11698–11706.

15] Zinatloo-Ajabshir S, Mortazavi-Derazkola S, Salavati-Niasari M. Simple sonothermal synthesis of Ho2O3–SiO2 nanocomposites as an effective photocatalyst for degradation and removal of organic contaminant. Ultrason Sonochem. 2017;39:452–460.

16] Zinatloo-Ajabshir S, Morassaei MS, Salavati-Niasari M. Facile fabrication of Dy2Sn2O7–SnO2 nanocomposites as an effective photocatalyst for degradation and removal of organic contaminants. J Colloid Interface Sci. 2017;497:298–308.

17] Zinatloo-Ajabshir S, Zinatloo-Ajabshir Z, Salavati-Niasari M, et al. Facile preparation of Nd5Zr2O7–ZrO2 nanocomposites as an effective photocatalyst via a new route. J Energy Chem. 2017;26:315–323.

18] Razi F, Zinatloo-Ajabshir S, Salavati-Niasari M. Preparation, characterization and photocatalytic properties of Ag2ZnIn3/AgI nanocomposites via a new simple hydrothermal approach. J Mol Liq. 2017;225:645–651.

19] Morassaei MS, Zinatloo-Ajabshir S, Salavati-Niasari M. New facile synthesis, structural and photocatalytic studies of NdOCl-Nd2SnO3–SnO2 nanocomposites. J Mol Liq. 2016;220:902–909.

20] Zinatloo-Ajabshir S, Mortazavi-Derazkola S, Salavati-Niasari M. Sono-synthesis and characterization of Ho2O3 nanomaterials via a new precipitation way for their application in full-color light-emitting diodes. Chem Mater. 2017;29:4175–4183.

21] Zinatloo-Ajabshir S, Zinatloo-Ajabshir Z, Salavati-Niasari M, Zinatloo-Ajabshir S. Nd5Zr2O7–NdO3 nanocomposites: New facile synthesis, structural and photocatalytic studies of NdOCl-Nd2Sn2O7–SnO2 nanocomposites. J Mol Liq. 2017;225:645–651.

22] Du X, Wu G, Cheng J, et al. High-quality CsPbBr3 perovskite nanocrystals for quantum dot light-emitting diodes. RSC Adv. 2017;7:10391–10396.

23] Pan A, He B, Fan X, et al. Insight into the ligand-mediated synthesis of colloidal CsPbBr3 perovskite nanocrystals: the role of organic acid, base, and caesium precursors. ACS Nano. 2016;10:7943–7954.

24] Bella F, Griffin G, Correa-Baena J-P, et al. Improving efficiency and stability of perovskite solar cells with photocurable fluoropolymers. Science. 2016;354:203–206.

25] Smith IC, Hoke ET, Solis-Ibarrondo D, et al. A layered hybrid perovskite solar-cell absorber with enhanced moisture stability. Angew Chem Int Ed. 2014;53:11232–11235.

26] Wang C, Chesman ASR, Jasieniak J. Stabilizing the cubic perovskite phase of CsPbI3 nanocrystals by using an alkyl phosphinic acid. Chem Commun. 2017;53:232–235.

27] Lou S, Xuan T, Yu C, et al. Nanocomposites of CsPbBr3 perovskite nanocrystals in an ammonium bromide framework with enhanced stability. J Mater Chem C. 2017;5:7431–7435.

28] Talapin DV, Koepp R, Götzinger S, et al. Highly emissive colloidal CdSe/CdS heterostructured of mixed dimensionality. Nano Lett. 2003;3:1677–1681.

29] Dabbousi BO, Rodriguez-Viejo J, Mikulec FV, et al. (CdSe)ZnS core-shell quantum dots: synthesis and characterization of a size series of highly luminescent nanocrystallites. J Phys Chem B. 1997;101:9463–9475.

30] Jiang LQ, Guo JK, Liu HB, et al. Prediction of lattice constant in cubic perovskites. J Phys Chem Solids. 2006;67:1531–1536.

31] Skelton JM, Parker SC, Togo A, et al. Thermal physics of the lead chalcogenides PbS, PbSe, and PbTe from first principles. Phys Rev B. 2014;89:205203.

32] Protesescu L, Yakunin S, Bodnarchuk MI, et al. Nanocrystals of caesium lead halide perovskites (CsPbX3) with X = Cl, Br, and I): novel optoelectronic materials showing bright emission with wide color gamut. Nano Lett. 2015;15:3692–3696.

33] Liang Z, Zhao S, Xu Z, et al. Shape-controlled synthesis of all-inorganic CsPbBr3 perovskite nanocrystals with bright blue emission. ACS Appl Mater Interfaces. 2016;8:28824–28830.

34] Beal RE, Slotcavage DJ, Leijtens T, et al. Caesium lead halide perovskites with improved stability for tandem solar cells. J Phys Chem Lett. 2016;7:746–751.

35] Rakita Y, Kedem N, Gupta S, et al. Low-temperature solution-grown CsPbBr3 single crystals and their characterization. Cryst Growth Des. 2016;16:5717–5725.

36] Lipovskii A, Kolobkova E, Petrikov V, et al. Synthesis and characterization of PbSe quantum dots in phosphate glass. Appl Phys Lett. 1997;71:3406–3408.

37] Yong K-T, Sahoo Y, Choudhury KR, et al. Shape control of PbSe nanocrystals using noble metal seed particles. Nano Lett. 2006;6:709–714.

38] Wang Y, Zhu Y, Huang J, et al. CsPbBr3 perovskite quantum dots-based monolithic electrosyn fiber membrane as an ultrastable and ultrasensitive fluorescent sensor in aqueous medium. J Mater Chem C. 2017;5:7431–7435.

39] Kim S, Marshall AR, Kroupa DM, et al. Air-stable and efficient PbSe quantum-dot solar cells based upon ZnSe to PbSe cation-exchanged quantum dots. ACS Nano. 2015;9:8157–8164.

40] Yanover D, Capek RK, Rubin-Brusilovski A, et al. Small-sized PbSe/PbS core/shell colloidal quantum dots. Chem Mater. 2012;24:4417–4423.

41] Van Le Q, Park M, Sohn W, et al. Investigation of energy levels and crystal structures of caesium lead halides and their application in full-color light-emitting diodes. Adv Electron Mater. 2017;3:1600448.