

Organic Semiconducting Ligands Passivated CsPbBr₃ Nanoplatelets for Blue Light-Emitting Diodes

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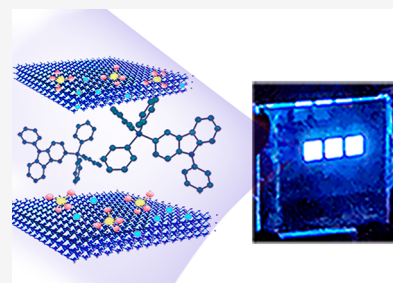
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ABSTRACT: Metal halide perovskite nanocrystals have shown tremendous potential for application in light-emitting diodes (LEDs) due to their unique and remarkable optoelectronic properties. Here, we report the development of CsPbBr₃ nanoplatelets (NPLs) with surface passivation by organic semiconducting ligands for blue LEDs. The use of two organic salts, triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium sulfate (TPPcarz₂SO₄) and triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium bromide (TPPcarzBr), as surface treatment agents allows for the preparation of 300 nm size CsPbBr₃ NPLs with a blue emission peaked at 455 nm and a photoluminescence quantum efficiency (PLQE) of 82%. Moreover, the charge-transporting TPPcarz⁺ units improve the conductivity of thin films based on CsPbBr₃ NPLs and the band edge alignments for blue LEDs. As a result, blue LEDs based on these CsPbBr₃ NPLs exhibit high external quantum efficiencies (EQEs) of up to 4.15%, a maximum luminance of 1511 cd m⁻², and a half-lifetime of 50 min (at 100 cd/cm²).



Metal halide perovskites have attracted tremendous interest as next-generation light-emitting materials for their remarkable optical properties, including narrow band emissions with low full width at half maximum (fwhm), up to near-unity photoluminescence quantum efficiencies (PLQEs), and exceptional color tunability covering the whole visible spectral region from deep blue to the near-infrared.^{1,2} Electroluminescence devices or light-emitting diodes (LEDs) based on metal halide perovskites (PeLEDs) have been heavily investigated as an alternative LED technology in recent years with their external quantum efficiencies (EQEs) approaching those of organic and quantum dot-based LEDs.^{3–5} Like existing LED technologies, achieving efficient and stable blue PeLEDs is one of the most challenging tasks. To date, the overall performance of blue PeLEDs is far behind those of near-infrared, red, and green ones.^{6–9}

To achieve blue PeLEDs, strategies involving synthetic control of composition and dimensionality of metal halide perovskites have been developed over the past few years for the preparation of blue-emitting perovskite layers.¹⁰ For instance, mixed halide perovskites containing controlled ratios of Br and Cl can exhibit blue emission with highly tuned peak wavelengths. However, the spectral instability of mixed halide perovskites is inevitable due to ion migration and phase segregation under electrical fields.¹¹ Reducing the dimension-

ality with the realization of quantum size effects on metal halide perovskites represents another effective method for color tuning. Quantum confined metal halide perovskite nanocrystals (NCs), such as 2D nanoplatelets (NPLs) and 0D quantum dots, as well as quasi-2D perovskites have been developed for the fabrication of blue PeLEDs, which exhibit significantly better spectral stability than those based on mixed halide perovskites.^{12–17} Recently, we reported a facile synthetic approach for the preparation of blue-emitting CsPbBr₃ NPLs with treatment by an organic sulfate, 2,2-(ethylenedioxy) bis(ethylammonium) sulfate (EDBESO₄), which exhibit remarkably enhanced PLQE (85%) and stability as compared to pristine CsPbBr₃ NPLs (PLQE of 28%) coated with oleylammonium.¹⁸ Using EDBESO₄-treated CsPbBr₃ NPLs as emitters, we have demonstrated blue PeLEDs with excellent spectral stability. However, the inferior charge injection and

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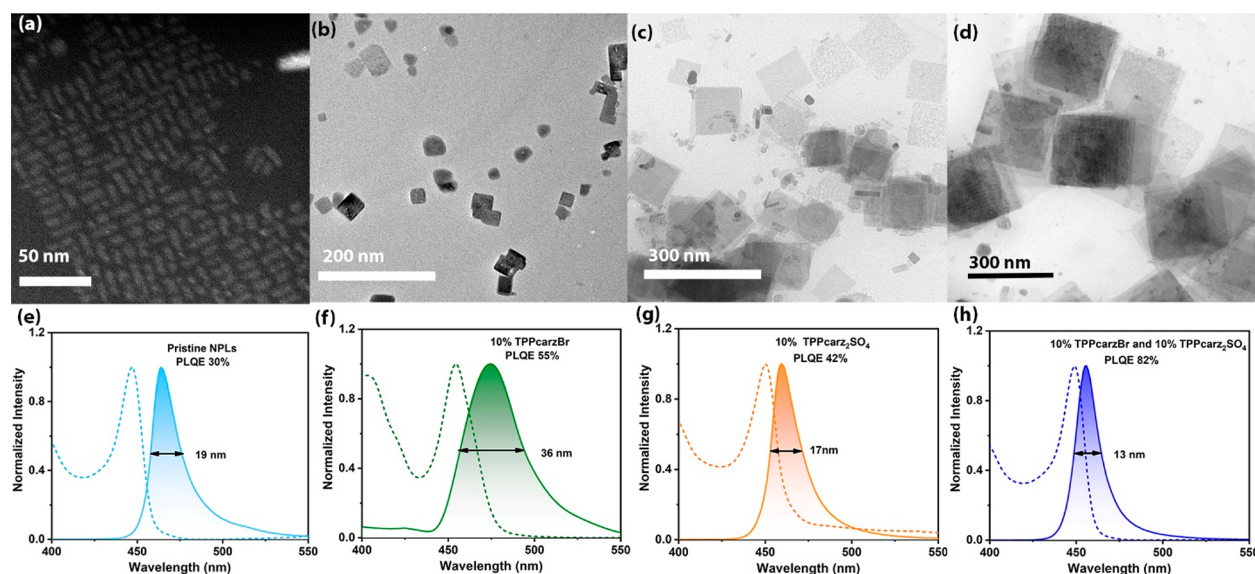


Figure 1. TEM images (a–d) and corresponding absorption and emission spectra (e–h) of CsPbBr₃ nanocrystals obtained with different ratios of the capping ligands: (a and e) without any TPPcarzBr or TPPcarz₂SO₄; (b and f) TPPcarzBr/oleylamine = 0.1:1; (c and g) TPPcarz₂SO₄/oleylamine = 0.1:1; (d and h) TPPcarzBr/TPPcarz₂SO₄/oleylamine = 0.1:0.1:1.

transport in these blue PeLEDs have limited the device performance with EQEs of less than 2%.

In this work, we have developed large size CsPbBr₃ NPLs with surface passivation by organic semiconducting ligands in addition to oleylammonium to address charge injection and transport issues. By using triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium sulfate (TPPcarz₂SO₄) and triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium bromide (TPPcarzBr) for surface treatment, CsPbBr₃ NPLs with a thickness of 3 units of PbBr₆^{4−} octahedra (around 2 nm) and lateral size of up to 300 nm have been synthesized for the first time. Solution-processed thin films based on TPPcarz₂SO₄ and TPPcarzBr treated CsPbBr₃ NPLs exhibit a narrow band blue emission peaked at 455 nm with PLQEs of up to 82% and good stability. More importantly, TPPcarz⁺, as an energetically aligned conductive ligand, has enabled improvement of charge mobility by orders of magnitude, which prevented charge accumulation with balanced charge injection at the interfaces, circumventing the key bottleneck of low efficiency and inferior stability of PeLEDs based on CsPbBr₃ NPLs. When employing these large size CsPbBr₃ NPLs in PeLEDs, a maximum luminance of 1511 cd m^{−2} and an EQE of 4.15% were achieved, respectively, which are the best values reported to date for pure blue PeLEDs based on CsPbBr₃ NPLs.

Several colloidal synthesis methods have been reported for the preparation of blue-emitting CsPbBr₃ NPLs, including ligand-assisted reprecipitation, hot-injection synthesis, and ligand-assisted ultrasonication.^{10,19} To the best of our knowledge, most blue-emitting CsPbBr₃ NPLs developed to date have small sizes of tens of nanometers wide and are surface passivated by insulating organic ligands,^{13,20} which are not ideal for their applications in optoelectronic devices. Replacing insulating organic ligands with conjugated and conductive ligands to improve charge transport properties has been demonstrated for perovskite NCs with green and red emissions, but not blue-emitting NPLs.^{21–23} The main challenges of producing blue-emitting CsPbBr₃ NPLs passivated by organic semiconducting ligands are twofold: (i) The quantized emission and fusion issue of anisotropic

CsPbBr₃ NPLs make it difficult to modulate their surface environments without affecting their optical properties. (ii) For the large bandgap of CsPbBr₃ NPLs with a deep valence band, it is not trivial to identify surface passivation ligands with appropriate band structures.²⁴ Based on our previous work,^{25,26} we investigated the potential of two organic semiconducting salts, TPPcarz₂SO₄ and TPPcarzBr, as surface passivation agents for blue-emitting CsPbBr₃ NPLs. New CsPbBr₃ NPLs were synthesized following a modified method with TPPcarz₂SO₄ and TPPcarzBr mixing with insulating oleylamine, which was used to induce directional growth and form dimensional confinement of CsPbBr₃ NPLs.^{27,28} Detailed synthetic procedures can be found in the [Supporting Information](#).

To minimize the amount of insulating oleylammonium cations on the surfaces of CsPbBr₃ NPLs, while maintaining the uniform thicknesses of NPLs, the amounts of TPPcarz₂SO₄ and TPPcarzBr were delicately modulated by changing their feed molar ratios to oleylamine in the precursor solutions. **Figure 1** shows the transmission electron microscopy (TEM) images of CsPbBr₃ NPLs prepared by using different synthetic conditions and their corresponding optical properties. Rectangle-shaped CsPbBr₃ NPLs with a lateral size of 5–20 nm were obtained using a reported method without the addition of any TPPcarzBr or TPPcarz₂SO₄ (hereafter referred to as pristine CsPbBr₃ NPLs as shown in **Figure 1a**).^{27,28} As expected, pristine CsPbBr₃ NPLs exhibit a blue emission peaked at 465 nm with an fwhm of 19 nm and a PLQE of 30% (**Figure 1e**). The other three CsPbBr₃ NPLs were obtained by adding 10% TPPcarzBr, 10% TPPcarz₂SO₄, and 10% TPPcarzBr/10% TPPcarz₂SO₄ to the precursor solutions. For the case of adding 10% TPPcarzBr, nonuniform CsPbBr₃ NPLs with larger sizes were obtained (**Figure 1b**), which exhibit a red-shifted and broadened blue emission peaked at 475 nm with an fwhm of 36 nm and a PLQE of 55% (**Figure 1f**), as a result of reduced extent of quantum confinement. For the case of adding 10% TPPcarz₂SO₄, CsPbBr₃ NPLs with large lateral sizes of around 130 nm were obtained (**Figure 1c**), suggesting that SO₄^{2−} can increase the Ostwald ripening process. As

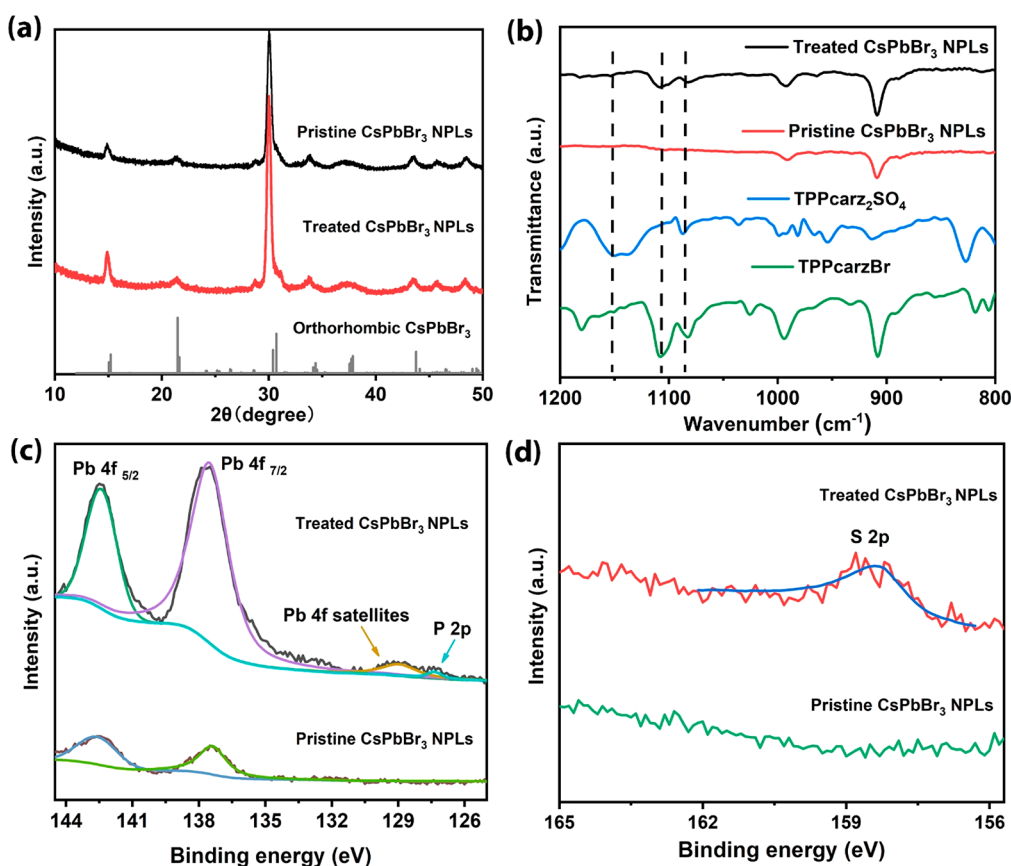


Figure 2. (a) XRD patterns of pristine CsPbBr₃ NPLs and treated CsPbBr₃ NPLs. The reference for orthorhombic CsPbBr₃ is PDF Card No. 01-085-6500. (b) FTIR spectra of treated CsPbBr₃ NPLs, pristine CsPbBr₃ NPLs, TPPcarzBr, and TPPcarz₂SO₄. (c) XPS spectra corresponding to Pb 4f and P 2p of treated CsPbBr₃ NPLs and pristine CsPbBr₃ NPLs. (d) XPS spectra of S 2p for treated CsPbBr₃ NPLs and pristine CsPbBr₃ NPLs.

compared to the pristine CsPbBr₃ NPLs, CsPbBr₃ NPLs prepared with the addition of 10% TPPcarz₂SO₄ exhibit a similar blue emission with a smaller fwhm of 17 nm and a higher PLQE of 42%. Finally, for the case of adding both 10% TPPcarzBr and 10% TPPcarz₂SO₄, highly uniform CsPbBr₃ NPLs with the largest lateral sizes of up to 300 nm were obtained (Figures 1d and S1). A blue emission peaked at 455 nm (a thickness of 3 units of PbBr₆⁴⁻ octahedra around 2 nm) with a high PLQE of 82% and a remarkably low fwhm of 13 nm is achieved for these CsPbBr₃ NPLs.¹⁹ The corresponding spectral curves for the calculation of PLQEs are shown in Figure S2.

The effects of the addition of both TPPcarzBr and TPPcarz₂SO₄ on the morphological and photophysical properties of CsPbBr₃ NPLs are multifold. First, for the bulkiness and unique charge distribution, TPPcarz⁺ can provide steric or electrostatic stabilization to increase the lateral size of the CsPbBr₃ NPLs. The similar way of tuning the lateral size of perovskite NPLs by varying the ratio of short and long ligands has been reported previously.²⁹ Second, SO₄²⁻ can bind uncoordinated Pb²⁺ to passivate the surface defects and suppress the coalescence of CsPbBr₃ NPLs.³⁰ Third, the presence of Br⁻ from TPPcarzBr could reduce Br⁻ vacancies on CsPbBr₃ NPLs, resulting in enhanced PLQEs.²⁰ Provided that CsPbBr₃ NPLs treated by both TPPcarzBr and TPPcarz₂SO₄ exhibit the desired structural and optical properties, we have focused on them (referred to as treated

CsPbBr₃ NPLs) for more detailed studies and used them for the fabrication of pure blue PeLEDs.

To confirm the composition and structure of treated CsPbBr₃ NPLs, powder X-ray diffraction (PXRD) was performed with the results shown in Figure 2a. The structures of both pristine and treated CsPbBr₃ NPLs are assigned to the *Pbnm* space group, corresponding to orthorhombic CsPbBr₃ (PDF# 01-085-6500). The treated and pristine NPLs have the tendency to self-assemble into stacked superlattices on the substrate, as evidenced by the periodic diffraction shown in the small-angle X-ray scattering pattern (Figure S3). The distance (*d*-spacing) between organic ligand layers within the stacking NPLs was calculated to be around 27 Å ($2\theta = 3.3^\circ$), which agrees well with the previously reported value.³¹ Fourier transform infrared (FTIR) spectroscopy and X-ray photoelectron spectroscopy (XPS) measurements were performed to verify the presence of multiple ions (TPPcarz⁺, SO₄²⁻, and Br⁻) on the surfaces of the CsPbBr₃ NPLs. As shown in Figure 2b, the vibration peaks at 1107 and 1082 cm⁻¹ for the phenyl groups in TPPcarz⁺ are detected in treated CsPbBr₃ NPLs, confirming the interactions between TPPcarz⁺ and CsPbBr₃ NPLs. The characteristic broad peak at around 1150 cm⁻¹, attributed to the triply degenerate ν_3 band of SO₄²⁻, could also be found in purified treated CsPbBr₃ NPLs. XPS measurements were performed on thin films based on purified pristine and treated CsPbBr₃ NPLs to reveal the changes of the surface state with the addition of two organic salts (Figure 2c,d). A higher intensity of the Pb 4f peak was recorded for treated

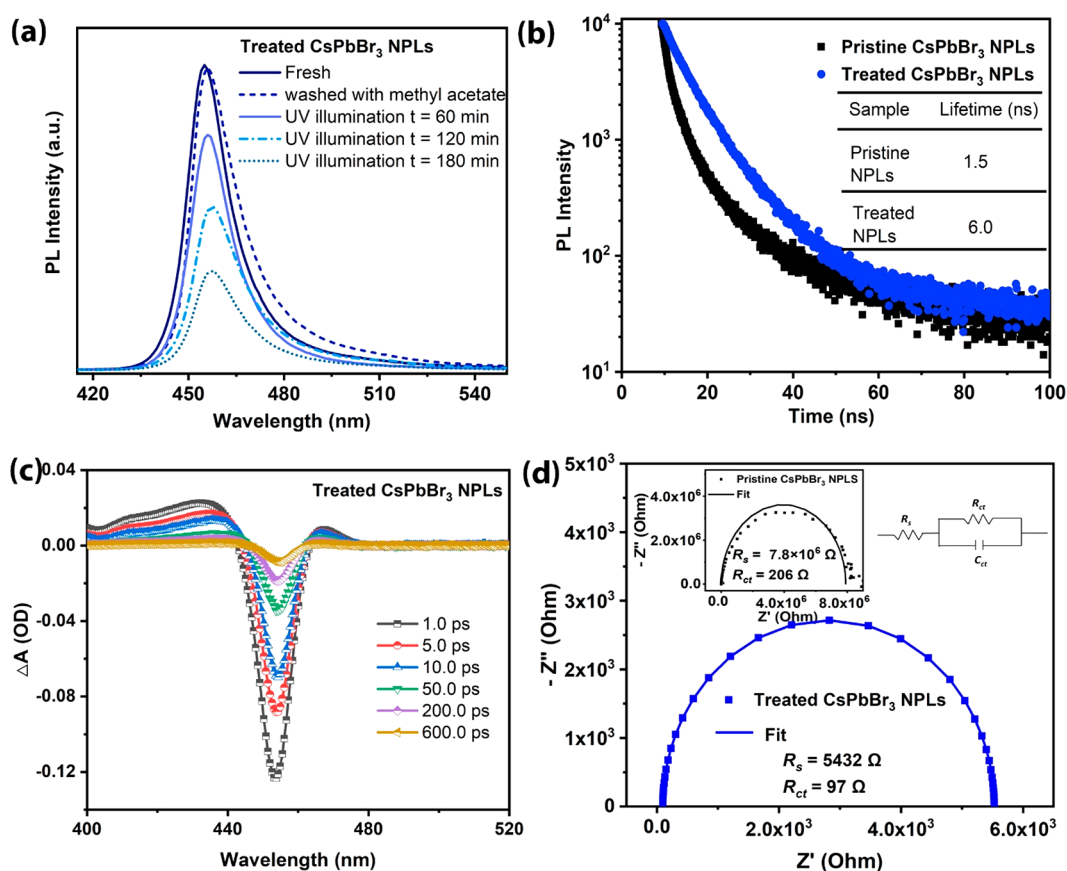


Figure 3. (a) PL spectra of thin films based on treated CsPbBr₃ NPLs washed with methyl acetate and under continuous UV illumination. (b) Time-resolved PL decay curves and lifetimes of pristine CsPbBr₃ NPLs and treated CsPbBr₃ NPLs. (c) TA spectra of treated CsPbBr₃ NPLs recorded at different pump–probe decay times with the excitation wavelength of 380 nm. (d) Nyquist plots of devices based on treated CsPbBr₃ NPLs (inset shows Nyquist plots of devices based on pristine CsPbBr₃ NPLs).

CsPbBr₃ NPLs than for pristine CsPbBr₃ NPLs, which is likely due to the less insulating organic ligands on the surfaces. In treated CsPbBr₃ NPLs, the features of phosphorus (127.3 eV) in the P 2p spectrum region confirm the presence of TPPcarz⁺. The high conductivity of TPPcarz⁺ causes the changes of electronic and chemical environments for Pb²⁺ with a Pb 4f satellite peak appearing at a binding energy 128.9 eV.³² The changes of surrounding environments for Pb²⁺ are also evidenced by the narrower Pb 4f peak in treated CsPbBr₃ NPLs, as a result of fewer Pb–oleate interactions in treated CsPbBr₃ NPLs than in pristine CsPbBr₃ NPLs.²⁰ The appearance of sulfur in the S 2p spectrum at 158.3 eV provides strong evidence for the existence of SO₄^{2−} in treated CsPbBr₃ NPLs. The accurate elemental composition of treated CsPbBr₃ NPLs was quantified by X-ray fluorescence (XRF). XRF spectra of P and S collected from the purified treated CsPbBr₃ NPLs were shown in Figure S4a,b. From the corresponding calibration curves of P³⁺, S⁶⁺, Cs⁺, Pb²⁺, and Br[−] (Figure S5), the quantitative molar ratio of these elements was determined as P: S: Cs: Pb: Br = 0.22:0.20:0.46:1:4.26. The ratio values obtained for pristine CsPbBr₃ NPLs were Cs: Pb: Br = 0.61:1:3.79.³³ The XRF results further confirm the surface passivation of CsPbBr₃ NPLs by TPPcarz⁺, SO₄^{2−}, and Br[−], which are stable after the purification process.

To utilize synthesized CsPbBr₃ NPLs for solid-state electronic devices, it is essential to obtain thin films with sufficient uniformity and smoothness. Spin coating of CsPbBr₃ NPL solutions in octane was carried out to prepare thin films

on cleaned glass substrates (details in Experimental Section in the Supporting Information). Atomic force microscopy (AFM) was used to characterize the morphology of spun cast thin films, with results shown in Figure S6. Thin films based on pristine CsPbBr₃ NPL show rough and uneven coverage with a root-mean-square roughness R_q of 1.89 nm, which is likely due to the dissociation of surface ligands and accumulation of NPLs. In contrast, thin films based on treated CsPbBr₃ NPLs are more uniform and smooth with an R_q of 0.21 nm, which is attributed to the relatively high viscosity of the treated CsPbBr₃ NPL solution and excellent stable dispersion of CsPbBr₃ NPLs.²⁵ The optoelectronic properties and stability of thin films based on treated CsPbBr₃ NPLs were also fully characterized. As shown in Figure 3a, thin films based on treated CsPbBr₃ NPLs before and after washing with antisolvent exhibit almost the same emission spectra, suggesting that treatment by TPPcarzBr and TPPcarz₂SO₄ can reduce defect sites and avoid coalescence of NPLs during the purification and spin-coating process. The PLQEs of thin films based on treated CsPbBr₃ NPLs were determined to be up to 82%. The photostability of thin films based on treated CsPbBr₃ NPLs was tested under continuous UV irradiation (365 nm, 40 mW/cm²), which shows only a small intensity reduction after 60 min and no shift in the emission peak after 180 min (Figure 3a). In contrast, thin films based on pristine CsPbBr₃ NPLs exhibit much lower PLQEs with additional red-shifted emission peaks, as a result of the formation of surface defects and coalescence due to the loss of highly dynamic

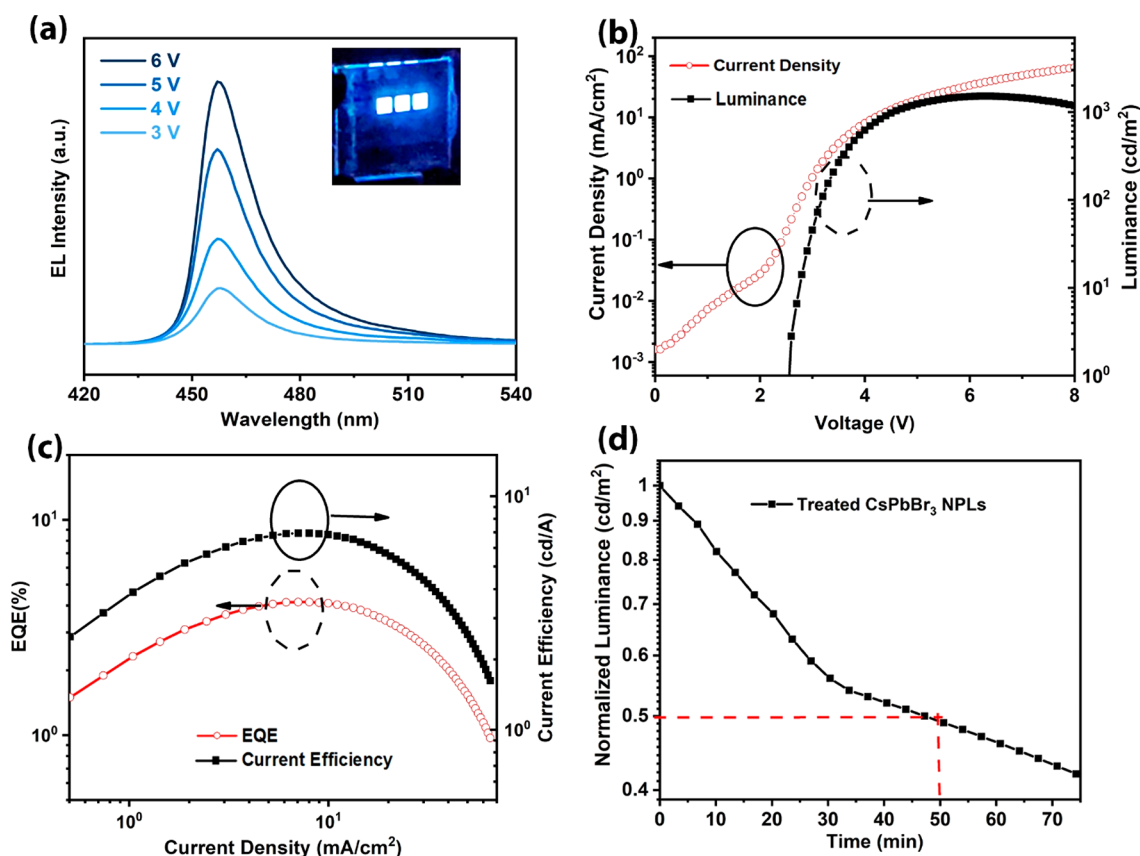


Figure 4. (a) EL spectra at different bias voltages for the device based on treated CsPbBr₃ NPLs. (b) Current density–voltage–luminance (*J–V–L*) plots for the device based on treated CsPbBr₃ NPLs. (c) EQE–current density–current efficiency plots for the device based on treated CsPbBr₃ NPLs. (d) Half-lifetime (T_{50}) of PeLEDs based on treated CsPbBr₃ NPLs at an initial luminance of ~ 100 cd m⁻².

oleylammonium ligands during the purification process (Figure S7a).³⁴

Time-resolved PL decay curves for thin films based on pristine and treated CsPbBr₃ NPLs are shown in Figure 3b. A longer PL decay lifetime of 6.0 ns was recorded for thin films based on treated CsPbBr₃ NPLs relative to the pristine CsPbBr₃ NPLs (1.5 ns), presumably due to nonradiative recombination pathways through surface defects being suppressed by treatment with two organic salts. The low density of surface defects can be further validated by a small Urbach tail for the thin films based on treated CsPbBr₃ NPLs.^{20,35} A smaller Urbach energy of 15 meV was recorded for thin films based on treated CsPbBr₃ NPLs than that of thin films based on pristine CsPbBr₃ NPLs of 41 meV (Figure S7b). Transient absorption (TA) measurements were conducted to further reveal the ultrafast exciton dynamic processes in thin films based on treated and pristine CsPbBr₃ NPLs. Thin films based on treated CsPbBr₃ NPLs are found to exhibit a bleach peak at 455 nm, corresponding to excitons formed in $n = 3$ metal halide quantum wells (QWs) (Figure 3c).³⁶ In contrast, multiple bleach peaks at 460–530 nm are shown in thin films based on pristine CsPbBr₃ NPLs (Figure S8a). The redshift of bleach peaks with the delay time indicates a distribution of metal halide QWs with different thicknesses and merging of the NPLs into bulk perovskites during the measurement.¹⁹

The conductivity of thin films based on treated and pristine CsPbBr₃ NPLs was examined by electrochemical impedance spectroscopy (EIS). Nyquist plots and the parameters of charge transport resistance (R_{ct}) and the series resistance (R_s)

have been characterized using an appropriate equivalent circuit as shown in Figure 3d. Both R_{ct} and R_s decrease significantly for thin films based on treated CsPbBr₃ NPLs as compared to those of thin films based on pristine CsPbBr₃ NPLs, from 206 to 97 Ω , and from 7.8×10^6 Ω to 5432 Ω , respectively, indicating a much higher conductivity of thin films based on treated CsPbBr₃ NPLs. Interfacial charge transfer was further investigated by electron-only and hole-only devices via current density–voltage (*J–V*) traces (Figure S8b). It was found that both electron and hole currents in thin films based on treated CsPbBr₃ NPLs are pronouncedly enhanced compared to those of thin films based on pristine CsPbBr₃ NPLs. The charge carrier mobilities of thin films based on treated and pristine CsPbBr₃ NPLs were then measured by using space-charge-limited currents (SCLCs) (Figure S9). Hole and electron mobilities of 8.7×10^{-5} and 5.9×10^{-5} cm² V⁻¹ s⁻¹ were obtained for thin films based on treated CsPbBr₃ NPLs, which are significantly higher than those of thin films based on pristine CsPbBr₃ NPLs (1.3×10^{-6} cm² V⁻¹ s⁻¹ for hole mobility, 5.1×10^{-6} cm² V⁻¹ s⁻¹ for electron mobility). The densities of hole and electron traps of pristine and treated CsPbBr₃ NPLs films can be calculated using the equation $N_{(e/h)} = (2V_{TFL}\epsilon_r\epsilon_0)/(eL^2)$, where $N_{(e/h)}$ is the trap density for electron or hole, respectively; V_{TFL} is trap-filled limiting voltage, e is the elementary charge, and d is the film thickness; ϵ_r and ϵ_0 are the dielectric constant and vacuum permittivity, respectively. As expected, the hole and electron trap densities of treated CsPbBr₃ NPL films (2.98×10^{17} and 1.10×10^{17} cm⁻³) are notably lower than those of pristine CsPbBr₃ NPLs

films (7.93×10^{17} and $5.93 \times 10^{17} \text{ cm}^{-3}$), which further confirms the effective passivation by TPPcarz₂SO₄ and TPPcarzBr. In addition to increased conductivity, the introduction of TPPcarz⁺ on treated CsPbBr₃ NPLs was found to be beneficial for the energy level alignment to promote charge injection when they are used as emitting layer in blue PeLEDs. The energy level diagram for a simple blue PeLED based on treated CsPbBr₃ NPLs is shown in Figure S11a. The band edge values for TPPcarz⁺ were obtained through UV absorption and cyclic voltammetry for TPPcarzBr and TPPcarz₂SO₄ (Figure S10a,b),³⁷ while the values for ITO, PEDOT:PSS, poly(TPD), blue CsPbBr₃ NPLs, and TPBi were obtained from the literature.³⁸ All of these results suggest that bipolar TPPcarz⁺ could facilitate the injection and transport of both electrons and holes.

The thin films based on treated CsPbBr₃ NPLs were used as emitting layer to fabricate blue PeLEDs composed of ITO/poly(ethylenedioxythiophene):polystyrenesulfonate (PEDOT:PSS)/poly(N, N'-bis(4-butylphenyl)-N,N'-bisphenylbenzidine) (poly-TPD)/CsPbBr₃ NPLs/1,3,5-Tris (1-phenyl-1H-benzimidazol-2-yl) benzene (TPBi)/LiF/Al. The electroluminescence (EL) spectra with an emission peak at 455 nm at different voltages are shown in Figure 4a. A low turn-on voltage ($\sim 2.6 \text{ V}$) is achieved, likely due to the superior conductivity of thin films based on treated CsPbBr₃ NPLs. The champion devices produce an EQE of 4.15%, a maximum luminance of 1511 cd m^{-2} , and a current efficiency of 8.2 cd A^{-1} at 6.3 V (Figure 4b and c), the highest values achieved for blue PeLEDs based on CsPbBr₃ NPLs to date. The EQE histogram of 30 devices is shown in Figure S11b, suggesting the excellent reproducibility of these devices with an average EQE of 3.9%. Moreover, the device shows a T_{50} lifetime of 50 min, which is 2.5 times longer than that of the recent best PeLEDs based on NPLs (Figure 4d).³³ Table S1 summarizes the performance parameters of devices based on the pristine, TPPcarz₂SO₄, and TPPcarzBr treated NPLs for comparison.

In summary, we have developed large size CsPbBr₃ NPLs passivated by a combination of three ions of TPPcarz⁺, SO₄²⁻, and Br⁻ for the first time. The treated large size CsPbBr₃ NPLs exhibit significantly improved optical and electronic properties compared to conventional small size CsPbBr₃ NPLs passivated only by long alkyl chain insulating ligands. Narrow blue emission peaked at 455 nm with a fwhm of 13 nm and a PLQE of 82% is achieved for these large CsPbBr₃ NPLs, presumably due to their high uniformity and aspect ratio. Partially replacing long alkyl chain insulating ligands with organic semiconducting ligands for the surface passivation of CsPbBr₃ NPLs also enables efficient charge injection and transport, when they are used as an emitting layer in blue PeLEDs, which exhibit high EQEs of up to 4.15% and a half-lifetime of 50 min (at 100 cd/cm^2). Our work further emphasizes the importance of surface modification and morphological control of perovskite nanocrystals to achieve desired optoelectronic properties for device applications, which paves a new path toward the realization of their full potential.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsenerylett.3c01576>.

Experimental Section: chemicals; preparation of triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium bromide

(TPPcarzBr) and triphenyl (9-phenyl-9H-carbazol-3-yl) phosphonium sulfate (TPPcarz₂SO₄); synthesis of pristine and treated CsPbBr₃ NPLs; Ppurification of colloidal NPLs; fabrication and testing of PeLEDs; Materials Characterization: TEM image and the histogram of the NPLs lengths; X-ray fluorescence spectra; AFM images; PL spectra; TA spectra; SCLC measurements; absorption spectra; histogram of maximum EQE measured from 30 devices; half-lifetime of PeLEDs (PDF)

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Notes

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