Sensitized Yb$^{3+}$ Luminescence in CsPbCl$_3$ Film for Highly Efficient Near-Infrared Light-Emitting Diodes

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Near-infrared (NIR) light emitting diodes (LEDs) with the emission wavelength over 900 nm are useful in a wide range of optical applications. Narrow bandgap NIR emitters have been widely investigated using organic compounds and colloidal quantum dots. However, intrinsically low charge mobility and luminescence efficiency of these materials limit improvement of the external quantum efficiency (EQE) of NIR LEDs, which is far from practical applications. Herein, a highly efficient NIR LED is demonstrated, which is based on an energy transfer from wide bandgap all inorganic perovskite (CsPbCl$_3$) to ytterbium ions (Yb$^{3+}$) as an NIR emitter doped in the perovskite crystalline film. High mobility of electrically excited carriers in the perovskite crystalline film provides a long carrier diffusion and enhances radiative recombination of an emission center due to minimized charge trapping losses, resulting in high EQE value in LEDs. The NIR emission of Yb$^{3+}$ at around 1000 nm is found to be sensitized by CsPbCl$_3$ thin film with a photoluminescence quantum yield over 60%. The LED based on Yb$^{3+}$-doped CsPbCl$_3$ film exhibits a high EQE of 5.9% with a peak wavelength of 984 nm, achieved by high carrier transporting ability and effective sensitized emission property in the solid-film structure.

Near-infrared (NIR) light emitting diodes (LEDs) enable a wide range of applications including night-vision devices, optical communication, biomedical imaging, and medical treatments. The NIR emitters based on organic compounds (including metal complexes) and colloidal quantum dots (QDs) have been widely investigated. However, LED using these materials lack in sufficient level of external quantum efficiency (EQE) substantially due to low carrier mobility and trap-assisted carrier recombination in the materials. And also, intrinsically low luminescence efficiency leaves these NIR emitting materials far from practical applications. In organic compounds, photoluminescence quantum yield (PLQY) decreases with increase in emission wavelength due to the energy gap law, mainly a consequence of increased thermal-vibration coupling with rapid excited state quenching. Therefore, organic NIR LEDs, especially with emission wavelengths over 900 nm, exhibit poor performance with EQE less than 0.5%. In the case of inorganic colloidal QDs, which are emerging as promising LED materials in view of their tunable luminescence, high quantum efficiency in NIR emission can be obtained with materials prepared by solution process. For instance, lead chalcogenide QDs such as PbS and PbSe exhibit PLQYs greater than 50% in a medium of solution. Nevertheless, solid-state films of colloidal QDs for optical device applications undergo strong luminescence self-quenching due to interdot coupling leading to carrier trapping and exciton dissociation that competes with radiative recombination. Although some attempts to prevent self-quenching in films, such as incorporation into a polymer matrix and capping with organic ligands or inorganic shells, have been reported, such thick and low conductive polymer films require high external voltage for LED operation that increases power consumption.

Lead halide perovskites exhibit significant potential for applications in LEDs because of their high color purity and a narrow full-width at half-maximum (FWHM) over the entire visible light spectrum, as well as their low-cost solution processing without high-temperature treatments. After halide perovskite LEDs was first reported in 2014 by Tan et al., mixed Pb–Sn halide perovskites LEDs which could yield efficient NIR emissions from 850 to 950 nm with the best EQE of 5.0% at 917 nm while Sn-based perovskite materials suffer from
fast degradation in ambient conditions due to the oxidation of Sn⁴⁺ to Sn⁷⁺. Highest EQE of NIR-LED has been obtained by Vasilopoulou et al. who synthesized colloidal QDs of Ag₅S@SiO₂ embedded in an organo lead halide perovskite matrix. With batch-to-batch variability of monodispersed QDs in device performance, EQE could reach 16.98% with peak emission at 1397 nm, which is 100 times higher than that of a device without using the perovskite matrix.

In this report, we show a method to enhance EQE of NIR emitting device, not based on QDs but using a solution-processed film of all-inorganic perovskite (CsPbCl₃) both as a sensitizer to NIR-emitting ytterbium ions (Yb³⁺) and a high-mobility material, to the level close to 6%. As compared with QDs or organic semiconductor-based LEDs, a bulk crystalline film of perovskite provides a long carrier diffusion length and enhances radiative recombination of an emission center due to minimized charge trapping losses, resulting in higher EQE value in LEDs.

Yb³⁺ shows a NIR emission band at around 1000 nm assigned to the ²F₉/₂→²F₇/₂ transition of the inner-shell 4f orbitals, which has been recognized as attractive materials for optoelectronic application in NIR region such as LEDs, lasing, and displays. However, light absorption ability of Yb³⁺ itself is significantly smaller (ε = 1–100 dm³ mol⁻¹ cm⁻¹) than that of organic dyes (ε = 10⁵–10⁶ dm³ mol⁻¹ cm⁻¹) because the electronic transitions of lanthanide ions are electric dipole forbidden (Laporte forbidden) transitions. To enhance NIR emission of Yb³⁺, sensitization, namely energy transfer from suitable donors with high absorption coefficient (as in this study) in colloidal nanocrystals (e.g., Cd or Pb chalcogenide) and in the form of Yb³⁺ complexes with organic ligands, have been attempted so far. Unfortunately, their NIR PLQYs were still much small (<10%) compared to visible light emitting analogues, which prevents practical applications for NIR optoelectronic devices.

It was recently found that photoluminescence of Yb³⁺ in nanocrystals of CsPbCl₃ can exhibit a quantum yield over 100% due to quantum cutting type sensitization mechanism by using CsPbCl₃ as a wide band gap sensitizer. This phenomenon suggests possibility to design an NIR-emitting device based on sensitization of Yb³⁺ with CsPbCl₃. Here, we report successful fabrication of a highly efficient NIR-emitting device using a solution-processed crystalline film of CsPbCl₃ as a sensitizer and Yb³⁺ as an emitter doped into CsPbCl₃, forming a composition of Yb³⁺-doped CsPbCl₃ (Yb³⁺:CsPbCl₃). Ensuring high charge carrier mobility and balanced charge injection in the film form of solid-state sensitizer, LED based on the Yb³⁺:CsPbCl₃ film enabled intense NIR emission at 984 nm with significantly enhanced EQE of 5.9%, which is the new type NIR LEDs without using QDs.

The Yb³⁺-doped CsPbCl₃ thin film was fabricated by a multi-step solution-process (see the Experimental Section for details of film preparations). 1 mM PbCl₂ in dimethyl sulfoxide (DMSO) containing YbCl₃ at 0.01–0.1 wt% was spin-coated onto a SnO₂ coated quartz substrate. After being dried at 90 °C for 15 min, 0.07 mL CsCl methanol solution was spin-coated onto Yb³⁺-doped PbCl₂ film and continually heated at 250 °C for 5 min. This process was repeated for five times to obtain a 120-nm-thick perovskite thin film. As displayed in Figure 1a inset image, the film is highly transparent (93% transmittance as shown in Figure S1 in the Supporting Information) to show the logo printed on the substrate. Stoichiometric range of Yb³⁺ is 1.0–9.1 mol% in CsPbCl₃, which is determined by the solution stoichiometry. Further doping Yb³⁺ prevents a film formation of CsPbCl₃. In Figure 1a, X-ray diffraction (XRD) patterns of undoped CsPbCl₃ and Yb³⁺ doped CsPbCl₃ (Yb³⁺(9.1 mol%):CsPbCl₃) films show diffraction peaks at 15.8°, 22.5°, 26.6°, 32.1°, 35.9°, 39.4°, and 46.0°, assigned to (100), (110), (111), (200), (210), (211), and (220) crystal planes of CsPbCl₃, respectively, which confirms the formation of cubic-phase perovskite crystal without detectable crystalline impurities. Here, we found that 0D CsPbCl₃ phase increased when PbCl₂ film slowly reacted with CsCl solution (Figure S2, Supporting Information) which strongly affects the luminescent property of the film as described later. Negligible shifts of the XRD reflections are observed with Yb³⁺ doping in this concentration range. On the other hand, X-ray photoelectron spectroscopy (XPS) measurements revealed chemical interactions between CsPbCl₃ and Yb³⁺. As shown in Figure 1b, CsPbCl₃ exhibits Cl 2p XPS band at 197.9 eV, which is broadly observed in a higher energy side by doping Yb³⁺. The higher energy band, which essentially implies reduced electron density on chlorine ions, corresponds to Cl⁻ bonded to Yb³⁺. It means that a part of Pb⁺⁺ was replaced to Yb³⁺. It is supported by the result that Yb 4d XPS bands were slightly shifted to a lower energy side in CsPbCl₃ compared with YbCl₃.

Figure 2a shows photoluminescence (PL) and the excitation spectra of CsPbCl₃ and Yb³⁺:CsPbCl₃ film. The undoped CsPbCl₃ film shows a band-edge excitonic emission at 415 nm with the emission lifetime of 23.8 ns (Figure S3a, Supporting Information). The photoluminescence quantum yield of CsPbCl₃ film is less than 0.1% due to lower exciton binding energy in perovskite crystalline films than that in low dimensional nanocrystals. It is noteworthy that this emission from CsPbCl₃ (415 nm) is completely quenched by doping of Yb³⁺ at 9.1 mol% to CsPbCl₃. On excitation of CsPbCl₃ at 320 nm, CsPbCl₃:Yb³⁺ film exhibits strong emission at 984 nm, which is assigned to the ²F₉/₂→²F₇/₂ transitions of Yb³⁺. Such strong NIR luminescence is hardly observed by direct excitation of Yb³⁺ at 980 nm even using a strong diode laser (~430 W cm⁻²). The excitation spectrum monitored at 984 nm matches the absorption spectrum of CsPbCl₃. These results indicate that the NIR luminescence of Yb³⁺ is effectively enhanced by the energy transfer from CsPbCl₃ to Yb³⁺ even in the polycrystalline film structure. The lifetime of this emission from Yb³⁺ in CsPbCl₃ is estimated as a single emission component of 1.68 ms (Figure S3b, Supporting Information), indicating that Yb³⁺ is uniformly dispersed in CsPbCl₃ film. The stoichiometry of cesium lead halides, CsPbCl₃ or Cs₄PbCl₆, is important for the energy transfer process to Yb³⁺. It is known that a crystal structure of Cs₄PbX₆ phase is very different from that of CsPbX₃, resulting in the large bandgaps and strong excitonic absorption for Cs₄PbCl₆. Cs₄PbCl₆ film obtained in this study shows a broad emission band around 350 nm with the lifetime of 1.14 ns (Figures S3a and S4, Supporting Information). This emission from Cs₄PbCl₆ is still observed in Yb⁺⁺:Cs₄PbCl₆ while the emission intensity of Yb⁺⁺ is negligibly small (Figure S4, Supporting Information), which means that the energy transfer from Cs₄PbCl₆ to Yb⁺⁺ hardly occurs. In Yb⁺⁺:CsPbCl₆, the NIR emission intensity increased
with increasing Yb\(^{3+}\) concentration from 1 mol\% to 9.1 mol\% with respect to Pb\(^{3+}\) (Figure 2b). The absolute PLQY measured using an integrating sphere increased from 31.0\% up to 62.3\% (Figure 2c). Although a condensed film structure generally causes nonradiative relaxation processes of photoexcited materials due to the surface and lattice defects as compared with nanocrystals, we could observe the highest NIR PLQY over 60\% with the thin film structure as achieved by the efficient energy transfer with a quantum-cutting process.

We fabricated a perovskite NIR LED using the highest emissive Yb\(^{3+}\)(9.1 mol\%):CsPbCl\(_3\), employed in a device structure: transparent conducting oxide (TCO) glass/SnO\(_2\) (10 nm)/8-quinolinolato lithium (Liq) (=2 nm)/Yb\(^{3+}\):CsPbCl\(_3\), or CsPbCl\(_3\) (120 nm)/polyN, N'-bis(4-butylphenyl)-N, N'-bis(phenyl)benzidine (poly-TPD)/poly(3,4-etylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) (60 nm)/Au (80 nm) (see the Experimental Section for details of device fabrications). Figure 3a displays cross-sectional view of the device structure observed by scanning electron microscopy (SEM). The energy diagram of the perovskite LED is shown in Figure 3b. The valence bands of CsPbCl\(_3\) and Yb\(^{3+}\):CsPbCl\(_3\) were estimated by ultraviolet photoelectron spectroscopy (UPS) in air atmosphere (Figure S5, Supporting Information), in which the energy position of CsPbCl\(_3\) is slightly lowered by doping of Yb\(^{3+}\). The conduction band levels were determined by Tauc plot analysis with a bandgap of 3.0 eV (Figure S6, Supporting Information). SnO\(_2\) nanoparticles were used as the electrotransport/hole-blocking layer (ETL/HBL). Liq was deposited on the SnO\(_2\) coated cathode to accelerate the electron injection from SnO\(_2\) to the perovskite layer. CsPbCl\(_3\) and Yb\(^{3+}\):CsPbCl\(_3\) emissive layers are then formed on the SnO\(_2\)/Liq layer. PEDOT:PSS and poly-TPD work as a hole-transport/electron-blocking layer. Finally, Au (80 nm) was evaporated on the top as the anode. To estimate charge injection balance, we measured the current density versus voltage (J–V) characteristics of electron-injection-only device (TCO/SnO\(_2\)/Liq/Yb\(^{3+}\):CsPbCl\(_3\)/Au and TCO/SnO\(_2\)/Yb\(^{3+}\):CsPbCl\(_3\)/Au) and hole-injection-only device (TCO/Yb\(^{3+}\):CsPbCl\(_3\)/poly-TPD/PEDOT:PSS/Au) (Figure S7, Supporting Information).
Supporting Information). According to the J–V results, more balanced charge injection occurs due to an improvement of electron injection by inserting a thin Liq layer between SnO2 and CsPbCl3, which was supported by observation of very weak electroluminescence in the Liq-free device. Figure 4a shows the J–V curves of the complete devices. The turn-on voltage of the Yb3+:CsPbCl3 device is shifted to the higher side as compared with that of the CsPbCl3 device as a result of an increase in the hole injection barrier between poly-TPD and perovskite layers.

In the CsPbCl3 based device, weak electroluminescence is broadly observed around 400 nm and 670 nm (Figure S8, Supporting Information), which assigned to a direct transition

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**Figure 2.** a) Photoluminescence (solid line) and the excitation (dotted line) spectra of CsPbCl3 film (blue) and Yb3+(9.1 mol%):CsPbCl3 film (red) (λex = 300 nm, λdet = 415 nm (CsPbCl3), and 984 nm (Yb3+:CsPbCl3)). b) Concentration dependence of Yb3+ on photoluminescence spectra (Yb3+ concentrations are defined as [Yb3+]/([Yb3+]+[Pb2+])). c) NIR PLQYs plotted as a function of Yb3+ molar concentration.

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**Figure 3.** a) Cross-sectional SEM image of the Yb3+:CsPbCl3 based LED. b) Energy diagram of the charge transfer materials in LED.
from the conduction band to the valence band (CB→VB) in CsPbCl₃ and a transition from the conduction band of CsPbCl₃ to the HOMO level of PEDOT:PSS, namely CB(CsPbCl₃)→HOMO(PEDOT:PSS), respectively. The weak intensity of electroluminescence from CsPbCl₃ (EQE is not detected in our system) is because of the excition dissosiation with high charge transport in the perovskite crystalline film. The Yb³⁺:CsPbCl₃ based device showed a strong NIR electroluminescence at 984 nm under an applied voltage of 2 V, as shown in Figure 4b, while no luminescence was observed in the visible wavelength region. It suggests that the energy transfer from electrically excited CsPbCl₃ to Yb³⁺ effectively occurs as well as the case of photoexcitation, which is enhanced by effective carrier diffusion to an emission center composed of Yb³⁺ partially replaced in a CsPbCl₃ lattice.

The irradiance–voltage curve of Yb³⁺:CsPbCl₃ device is shown in Figure 4c. The Yb³⁺:CsPbCl₃ device has a low turn-on voltage of ≈1.6 V, which was enabled by the high-mobility of perovskite film and the efficient carrier injection from HTL and ETL, yielding a high irradiance at 3100 μW cm⁻² at 3.6 V. The EQE value of the Yb³⁺:CsPbCl₃ device reaches a maximum of 5.9% at 0.827 mA cm⁻² (Figure 4d) which is the highest EQE ever reported for thin film type NIR LEDs capable of emission beyond 900 nm [30]. The NIR electroluminescence half-life time (T₅₀) in air condition under applying a constant current (0.827 mA cm⁻²) has reached 58 h (Figure S9, Supporting Information). We confirm that highly performance for NIR LEDs is achieved by constriction of the unprecedented NIR emissive system composed of the perovskite thin film and Yb³⁺.

In conclusions, we have demonstrated the fabrication of highly NIR luminescent CsPbCl₃ perovskite films doped with Yb³⁺ and the bright NIR LEDs based on it. Yb³⁺:CsPbCl₃ film shows a strong NIR luminescence through the efficient energy transfer from perovskite to Yb³⁺, leading to accomplishment of the highest NIR PLQY, over 60%, in thin-film structures. The Yb³⁺:CsPbCl₃ based LEDs also exhibit a bright electroluminescence around 1000 nm with EQEs up to 5.9%, which was achieved by high carrier transporting ability and effective sensitized emission property in the solid-film structure. The material and method of the Yb³⁺:perovskite-based NIR LEDs reported here open up its applications to night-vision devices, optical communication, biomedical imaging, and medical treatments.

Experimental Section

Perovskite Film Preparation: The perovskite film was fabricated by a multistep solution-process. 1 m PbCl₂ (Sigma-Aldrich) in DMSO containing YbCl₃ (Sigma-Aldrich) at a stoichiometric range of 0–9.1 mol% was spin coated onto glass substrates (quartz for optical measurements and TCO for LED device) at 3000 rpm for 30 s. After being dried at 90 °C for 15 min, 0.07 m CsCl methanol solution was spin coated onto PbCl₂ film at 3000 rpm for 30 s and continuously heated at 250 °C for 5 min. This process was repeated for five times to obtain the ideal perovskite films. The obtained perovskite films were rinsed...
with isopropanol and dried 250 °C again for 5 min. The Cs$_5$PbCl$_3$ phase was obtained when PbCl$_2$ film slowly reacted with CsCl solution by spin coating at 2000 rpm for 30 s.

**Device Fabrication:** Transparent conducting oxide (TCO, an ITO–ATO composite) glass (15 Ω sq$^{-1}$, Geomatic Co., Ltd.) was cleaned sequentially with acetone, isopropanol, and deionized water by putting them under sonication for 10 min in each of the solvents, and then dried by blowing N$_2$ gas. The TCO glass was finally treated under oxygen plasma for 10 min. The SnO$_2$ blocking layer was coated on TCO glass by spin-coating a diluted aqueous solution of SnO$_2$ nanoparticle (15% in H$_2$O colloidal dispersion, Alfa Aesar) with an absolute photoluminescence quantum yield measurement system (AC-3, Riken Keiki Co., Ltd.).

**Characterizations:** XRD patterns were measured by D8 DISCOVER (BrukerAXS K. K.) with Cu Kα radiation under the operation condition of 40 kV, 40 mA to determine the crystal structure of perovskite. XPS was performed using a Kratos Atlas Ultra delay-line detector equipped with a monochromatic Al Kα X-ray source (1486.6 eV). SEM measurements were performed with SU8000 (Hitachi High-Technologies Co.) to check the thickness and morphology of the layers. Ionization potential ultraviolet photoelectron spectroscopy (UPS) in the air was estimated by a photoemission yield spectrometer (AC-3, Riken Keiki Co., Ltd.). Photoluminescence spectra were recorded on FP-8600 spectrometer (JASCO Corporation). PLOY for NIR emission was measured using an absolute photoluminescence quantum yield measurement system (Quantaurus-QY plus, Hamamatsu Photonics K. K.).

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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Note: A typo was corrected in the constant current applied in the experiments presented in Figure 4 and Figure S9 on 19 February 2020 after original online publication.

**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

energy transfer, lead halide perovskites, light-emitting diodes, near-infrared, Ytterbium

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[1] Y. J. Pansare, S. Hejazi, W. J. Faenza, R. K. Prud’homme, Chem. Mater. 2012, 24, 812.
[2] F. Ding, Y. Zhan, X. Lub, Y. Sun, Chem. Sci. 2018, 9, 4370.
[3] I. L. Medintz, H. T. Uyeda, E. R. Goldman, H. Mattoussi, Nat. Mater. 2005, 4, 435.
[4] A. Zampetti, A. Minotto, F. Cacialli, Adv. Funct. Mater. 2019, 29, 1807623.
[5] D.-H. Kim, A. D’Aléò, X.-K. Chen, A. D. S. Sandanayaka, D. Yao, L. Zhao, T. Komino, E. Zaborova, G. Canard, Y. Tsuchiya, E. Choi, J. W. Wu, F. Fages, J.-L. Brédas, J.-C. Ribierre, C. Adachi, Nat. Photonics 2018, 12, 98.
[6] K. T. Ly, R.-W. C. Cheng, H.-W. Lin, Y.-J. Shiau, S.-H. Liu, P.-T. Chou, C.-S. Tsao, Y.-C. Huang, Y. Chi, Nat. Photonics 2017, 11, 63.
[7] H. Xiang, J. Cheng, X. Ma, X. Zhoua, J. J. Chrumaa, Chem. Soc. Rev. 2013, 42, 6128.
[8] K. N. Bourdakos, D. M. N. M. Dissanayake, T. Lutz, S. R. P. Silva, R. J. Curry, Appl. Phys. Lett. 2008, 92, 90.
[9] Y. Shirasagi, G. J. Supran, M. G. Bavendi, V. Bulović, Nat. Photonics 2013, 7, 13.
[10] H. Wijaya, D. Darwan, X. Zhao, E. W. Y. Ong, K. R. G. Lim, T. Wang, L. J. Lim, K. H. Khoo, Z.-K. Tan, Adv. Funct. Mater. 2019, 29, 1906483.
[11] J. V. Caspar, T. J. Meyer, J. Phys. Chem. 1983, 87, 952.
[12] G. Qian, Z. Zhong, M. Luo, D. Yu, Z. Zhang, Z. Y. Wang, D. Ma, Adv. Mater. 2009, 21, 111.
[13] J. R. Sommer, R. T. Farley, K. R. Graham, Y. Yang, J. R. Reynolds, J. Xue, K. S. Schanche, ACS Appl. Mater. Interfaces 2009, 12, 274.
[14] P. Murto, A. Minotto, A. Zampetti, X. Xu, M. R. Andersson, F. Cacialli, E. Wan, Adv. Optical Mater. 2016, 4, 2068.
[15] G. M. Akselrod, M. C. Weidman, Y. Li, C. Argyropoulos, W. A. Tisdale, M. H. Mikkelsen, ACS Photonics 2016, 3, 1741.
[16] M. Greben, A. Fucikova, J. Valenta, J. Appl. Phys. 2015, 117, 144306.
[17] O. E. Seminon, J. C. Johnson, J. M. Luther, A. G. Midgett, A. J. Nozik, M. C. Beard, J. Phys. Chem. Lett. 2010, 1, 2445.
[18] H. Du, C. Chen, R. Krishnan, T. D. Krauss, J. M. Harbold, F. W. Wise, M. G. Thomas, J. Silcox, Nano Lett. 2002, 2, 1321.
[19] Z. Oleksandriv, V. Sjöerd, H. Edward, H. Sargent, ACS Nano 2013, 7, 5282.
[20] P. Moroz, G. Liyanage, N. N. Kholmicheva, S. Yakunin, U. Rijal, P. Uprety, E. Bastola, B. Mellott, K. Subedi, L. Sun, M. V. Kovalenko, M. Znakov, Chem. Mater. 2014, 26, 4256.
[21] N. Greenham, X. Peng, A. Alivisatos, Phys. Rev. B 1996, 54, 17628.
[22] J. S. Steckel, S. Cee-Sullivan, V. Bulovic, M. G. Bavendi, Adv. Mater. 2003, 15, 1862.
[23] Q. V. Le, H. W. Jang, S. Y. Kim, Small Methods 2018, 2, 1700419.
[24] Z.-K. Tan, R. S. Moghadam, M. L. Lai, P. Docampo, R. Higler, F. Deschler, M. Price, A. Sadhana, L. M. Pazos, D. Credgington, F. Hanusch, T. Bein, H. J. Snaith, R. H. Friend, Nat. Nanotechnol. 2014, 9, 687.
[25] W. Xu, Q. Hu, S. Bai, C. Bao, Y. Miao, Z. Yuan, T. Borzda, A. J. Barker, E. Tyukalova, Z. Hu, M. Kawecki, H. Wang, Z. Yan, X. Liu, X. Shi, K. Uvdal, M. Fahlman, W. Zhang, M. Duchamp, J.-M. Liu, A. Petrozza, J. Wang, L.-M. Liu, W. Huang, F. Gao, Nat. Photonics 2019, 13, 418.

[26] K. Lin, J. Xing, L. N. Quan, F. P. G. Arquer, X. Gong, J. Lu, L. Xie, W. Zhao, D. Zhang, C. Yan, W. Li, X. Liu, Y. Lu, J. Kirman, E. H. Sargent, Q. Xiong, Z. Wei, Nature 2018, 562, 245.

[27] T. Chiba, Y. Hayashi, H. Ebe, K. Hoshi, J. Sato, S. Sato, Y.-J. Pu, S. Ohisa, J. Kido, Nat. Photonics 2018, 12, 681.

[28] B. Zhao, S. Bai, V. Kim, R. Lamboll, R. Shivanna, F. Auras, J. M. Richter, L. Yang, L. Dai, M. Alsari, X.-J. She, L. Liang, J. Zhang, S. Lilliu, P. Gao, H. J. Snaith, J. Wang, N. C. Greenham, R. H. Friend, D. Di, Nat. Photonics 2018, 12, 783.

[29] M. L. Lai, T. Y. S. Tay, A. Sadhanala, S. E. Dutton, G. Li, R. H. Friend, Z.-K. Tan, J. Phys. Chem. Lett. 2016, 7, 2653.

[30] W. Qiu, Z. Xiao, K. Roh, N. K. Noel, A. Shapiro, P. Heremans, B. P. Rand, Adv. Mater. 2019, 31, 1806105.

[31] M. Vasilopoulos, H. P. Kim, B. S. Kim, M. Papadakis, A. E. K. Gavim, A. G. Macedo, W. J. Silva, F. K. Schneider, M. A. M. Teridi, A. G. Coutsolelos, A. R. M. Yusoff, Nat. Photonics 2020, 14, 50.

[32] X. Gong, Z. Yang, G. Walters, R. Comin, Z. Ning, E. Beauregard, V. Adinolfi, O. Voznyy, E. H. Sargent, Nat. Photonics 2016, 10, 253.

[33] S. V. Eliseeva, J.-C. G. Bünzli, Chem. Soc. Rev. 2010, 39, 189.

[34] J.-C. G. Bünzli, C. Piguet, Chem. Soc. Rev. 2005, 34, 1048.

[35] A. de Bettencourt-Dias, R. A. Tigaa, J. Mater. Chem. C 2018, 6, 2814.

[36] R. Martín-Rodríguez, R. Geitenbeek, A. Meijerink, J. Am. Chem. Soc. 2013, 135, 13668.

[37] S. E. Creutz, R. Fainblat, Y. Kim, M. C. De Siena, D. R. Gamelin, J. Am. Chem. Soc. 2017, 139, 11814.

[38] S. Kishimoto, T. Nakagawa, T. Kawai, Y. Hasegawa, Bull. Chem. Soc. Jpn. 2011, 84, 148.

[39] a) B. S. K. Chong, E. G. Moore, Inorg. Chem. 2018, 57, 14062.

b) J.-Y. Hu, Y. Ning, Y.-S. Meng, J. Zhang, Z.-Y. Wu, S. Gao, J.-L. Zhang, Chem. Sci. 2017, 8, 2702.

[40] Y. Ning, J. Tang, Y.-W. Liu, J. Jing, Y. Sun, J.-L. Zhang, Chem. Sci. 2018, 9, 3742.

[41] T. J. Milstein, D. M. Kroupa, D. R. Gamelin, Nano Lett. 2018, 18, 3792.

[42] J. Almutlaq, J. Y. Omar, F. Mohammed, O. M. Bakr, J. Phys. Chem. Lett. 2018, 9, 4131.

[43] X. Zhang, Y. Zhang, X. Zhang, W. Yin, Y. Wang, H. Wang, M. Lu, Z. Li, Z. Gu, W. W. Yu, J. Mater. Chem. C 2018, 6, 10101.

[44] M. Nikl, E. Mihokova, K. Nitsch, K. Polak, M. Rodova, M. Dusek, G. P. Pazzi, P. Fabeni, L. Salvini, M. Gurioli, Chem. Phys. Lett. 1994, 220, 14.

[45] G. H. Ahmed, J. K. El-Demellawi, J. Yin, J. Pan, D. B. Velusamy, M. N. Hedhili, E. Alarousu, O. M. Bakr, H. N. Alshareef, O. F. Mohammed, ACS Energy Lett. 2018, 3, 2301.

[46] Q. A. Akkerman, A. L. Abdelhady, L. J. Manna, Phys. Chem. Chem. Lett. 2018, 9, 2326.

[47] Y. Zhang, B. Fan, Y. Liu, H. Li, K. Deng, J. Fan, Appl. Phys. Lett. 2018, 112, 183101.

[48] M. Nikl, E. Mihokova, K. Nitsch, Solid State Commun. 1992, 84, 1089.

[49] S. R. Forrest, D. D. C. Bradley, M. E. Thompson, Adv. Mater. 2003, 15, 1043.