A novel approach for designing efficient broadband photodetectors expanding from deep ultraviolet to near infrared

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Abstract
Broadband photodetection (PD) covering the deep ultraviolet to near-infrared (200–1000 nm) range is significant and desirable for various optoelectronic designs. Herein, we employ ultraviolet (UV) luminescent concentrators (LC), iodine-based perovskite quantum dots (PQDs), and organic bulk heterojunction (BHJ) as the UV, visible, and near-infrared (NIR) photosensitive layers, respectively, to construct a broadband heterojunction PD. Firstly, experimental and theoretical results reveal that optoelectronic properties and stability of CsPbI₃ PQDs are significantly improved through Er³⁺ doping, owing to the reduced defect density, improved charge mobility, increased formation energy, tolerance factor, etc. The narrow bandgap of CsPbI₃:Er³⁺ PQDs serves as a visible photosensitive layer of PD. Secondly, considering the matchable energy bandgap, the BHJ (BTP-4Cl: PBDB-TF) is selected as to NIR absorption layer to fabricate the hybrid structure with CsPbI₃:Er³⁺ PQDs. Thirdly, UV LC converts the UV light (200–400 nm) to visible light (400–700 nm), which is further absorbed by CsPbI₃:Er³⁺ PQDs. In contrast with other perovskites PDs and commercial Si PDs, our PD presents a relatively wide response range and high detectivity especially in UV and NIR regions (two orders of magnitude increase that of commercial Si PDs). Furthermore, the PD also demonstrates significantly enhanced air- and UV-stability, and the photocurrent of the device maintains 81.5% of the original one after 5000 cycles. This work highlights a new attempt for designing broadband PDs, which has application potential in optoelectronic devices.

Introduction
Photodetectors (PDs) are the technical functional components for capturing and converting ultraviolet (UV) to near-infrared (NIR) photons into electronic outputs. The broadband optical detection ability, especially from UV to NIR range, is critical for applications including medical monitoring, video imaging, optical communication, and civil engineering. Generally, the commercial silicon PDs present the relatively broad wavelength response range from 400–1100 nm, but usually suffer from high cost and low detectivity, especially in the UV region. Solution-processable broadband PDs based on soluble materials have numerous advantages of low cost, simple preparation, and high sensitivity, which has become the next generation of new detectors. Encouragingly, solution-processable metal halide perovskites process outstanding characteristics of large absorption coefficient, long diffusion length, low trapping density, and high photoluminescent quantum efficiency (PLQY), which have shown unprecedented radical progress for various optoelectronic devices, including solar cells (SCs), light-emitting diodes (LEDs), and photodetectors (PDs). Among them, all-inorganic...
perovskite quantum dots (ABX₃, A = Cs; B = Pb, Ge, Sn; X = Cl, Br, I) (PQDs) have attracted extensive interest in broadband PDs, owing to their wide-range tunability of bandgap, large absorption cross-section, high carrier mobility, etc. Especially, CsPbI₃ PQDs process narrow bandgap of 1.73 eV, becoming a candidate for broadband PDs. For example, Tian et al. fabricated 2-aminoethanethiol (AET)/CsPbI₃ PQDs composite-based PDs device, exhibiting a high responsivity of 105 mA W⁻¹ and the detection wavelength covering the visible light. However, its spectrum covers mainly the blue to visible light range (400–700 nm), short of UV response and NIR absorption, due to the insensitivity to UV light and limitation of the bandgap. In addition, they also encounter relatively high trap density, poor carrier mobility, and high susceptibility to moisture and UV light, generating phase transition from cubic to orthorhombic phase. The above issues severely limit its photodetection of broadband response spectrum with high stability and responsivity.

To overcome the challenges mentioned above, much efforts have been made to improve the stability and responsivity, and to expand the spectral response range of perovskite-based PDs. A number of metal ions (e.g., Zn²⁺, Cr³⁺, Nd³⁺, Er³⁺, Ce³⁺) doping have been proved to be a promising way to boost the optical and electrical performance of perovskite materials, including the decrease of trap density and the improvements of carrier mobility, stability, and photoluminescence quantum yield (PLQY). Meanwhile, the strategy of integrating perovskite with NIR absorption materials (e.g., organic bulk heterojunction (BHJ)), lead sulfide quantum dots, etc.) was attempted to expand the spectral response range of PDs to the NIR region. For example, Chen et al. achieved broadband photodetectors with high NIR external quantum efficiency of over 70% in organic-inorganic perovskite/BHJ hybrid. Nevertheless, such PD has low responsivity in the UV region and relatively poor stability of organic-inorganic perovskite.

The scheme of luminescent conversion was proven to be an effective route to enlarge the response to the UV by absorbing and converting UV to visible photons and further being captured by PD. The luminescent conversion films consisting of Cr³⁺, Ce³⁺, Yb³⁺ tridoped CsPbCl₃ PQDs or carbon dots were explored to boost the UV response of silicon PDs. As a class of excellent luminescent conversion materials, luminescent concentrator (LC) consists of transparent polymer sheets doped with luminescent species that can be employed as a nonimaging optical device that collects and concentrates light energy. It has been widely applied in photovoltaic cells or optical communications to largely improve the power conversion efficiency.

In this work, we represent the design and fabrication of a novel type of hybrid PDs based on ultraviolet (UV) luminescent concentrators (LC) and doped PQDs and an organic bulk heterojunction, which can realize efficient photodetection in the whole range of 200–1000 nm. The device integrates a tridoped PQDs (CsPbCl₃:Cr³⁺,Ce³⁺, Mn²⁺) photoluminescent layer to harvest and converts UV light to visible, a CsPbI₃:Er³⁺ layer to realize the photoelectric conversion of visible light, and an organic bulk heterojunction to extend photoelectric response to NIR light. In such a device, CsPbI₃:Er³⁺ PQDs was explored as the visible photoelectric layer. Doping of Er³⁺ largely improved the radiative transition rate of the perovskite excitons and structure stability, altered charge carrier transport of CsPbI₃ QDs, thus leading to performance enhancement considerably. In CsPbCl₃:Cr³⁺,Ce³⁺, Mn²⁺ based LC, Mn²⁺ ions convert the UV to red lights, locating within the optimum regions of CsPbI₃:Er³⁺ based PD, and simultaneously, Cr³⁺ and Ce³⁺ doping significantly improve PLQY of the PQDs and enhance light-harvesting of UV light for PQDs due to the coupling of 5d states of Ce³⁺ with the PQDs, extremely in the deep UV (DUV) region. In addition, an organic BHJ (BTP-4Cl:PBDB-TF) with an absorption extending 1000 nm was adopted as NIR photoelectric layer to integrate with CsPbI₃:Er³⁺ layer. Taking all advantages above, the present PDs realize the spectral response spanning from 200 to 1000 nm and demonstrated detectivity reaching 10¹² Jones.

**Results**

Figure 1a and S1 illustrates the structure and the cross-sectional scanning electron microscopy (SEM) images of the broadband PDs, which consists of CsPbCl₃:Cr³⁺,Ce³⁺, Mn²⁺ PQDs doped polymethyl methacrylate LC (Cr/Ce/Mn-LC)/ITO/SnO₂:Ti₃C₂/CsPbI₃:Er³⁺ PQDs/PBDB-TF: BTP-4Cl(BHJ)/Ag. Firstly, the SnO₂:Ti₃C₂ ETL (~50 nm) was spin-coated on ITO substrate and then annealed at 150 °C for 15 min. The CsPbI₃:Er³⁺ PQDs with a thickness of 450 nm were fabricated on the ETL modified ITO glass by spin-coating. Then the organic BHJ of PBDB-TF: BTP-4Cl as an NIR photosensitive layer was deposited on top of the CsPbI₃:Er³⁺ PQDs film. Finally, the Cr/Ce/Mn-LC was positioned at the ITO side to construct the UV-Visible-NIR PD. The mixture of BHJ can absorb the low-energy NIR photons and effectively passivate the defects in the perovskite film and improve carrier transport and collection (Fig. 1b). As demonstrated in Fig. 1c, CsPbI₃:Er³⁺ PQDs has good absorption in the range of 350–700 nm, BHJ exhibits light absorption in the range of 700–1000 nm, and the CsPbI₃:Er³⁺ PQDs/BHJ film shows the absorption band from 350 to 1000 nm. Differently, the detected lights with a wavelength within 200–400 nm, are completely absorbed by Cr/Ce/Mn-LC and converted to 400–700 nm, which are further absorbed by CsPbI₃:Er³⁺ PQDs. Finally, combining UV-Visible-NIR absorption of...
Cr/Ce/Mn-LC and CsPbI₃:Er³⁺ PQDs and BHJ, the fabricated PDs can exhibit a wide photodetection range from 200 to 1000 nm.

Firstly, the visible sensitive materials of CsPbI₃ and CsPbI₃:Er³⁺ PQDs with different Er³⁺ doping concentrations (0–9.7%) were synthesized through the modified hot-injection method. As revealed in a transmission electron microscope (TEM) and high-resolution TEM (HRTEM) images (Fig. 2a and S2), the cubic-shaped and uniform CsPbI₃ PQDs are successfully obtained with and without Er³⁺ doping. The average diameter of pristine CsPbI₃ PQDs is determined to be 11.4 nm, which gradually decreases to 10.9, 10.7, 10.3, and 9.9 nm with different Er³⁺ doping concentrations (1.2, 4.6, 7.7, and 9.7%), respectively (Fig. S3). The doping amounts of Er³⁺ in the CsPbI₃ PQDs were ascertained by the inductively coupled plasma optical emission spectrometry (ICP-OES) (Table S1). Meanwhile, the lattice constant of the (100) plane of the CsPbI₃:Er³⁺ (7.7%) PQDs is (6.1 Å), smaller than that of CsPbI₃ PQDs (6.3 Å). This can be attributed to the lattice contraction of PQDs induced by partly replacing the Pb²⁺ (~119 pm) with the doping Er³⁺ ions (~88.1 pm). The X-ray diffraction (XRD) patterns evidence that CsPbI₃:Er³⁺ PQDs has the same cubic structure as CsPbI₃ PQDs, and the diffraction peaks of (100) and (200) planes shift toward higher diffraction angle after Er³⁺ doping (Fig. S4). The energy-dispersive X-ray (EDX) mapping images reveal that all the elements (Cs, Pb, I, and Er) exist in CsPbI₃:Er³⁺ PQDs (Fig. S5). The X-ray photoelectron spectra (XPS) of pristine CsPbI₃ and CsPbI₃:Er³⁺ PQDs in Fig. 2b and S6 demonstrate that the peaks of Cs 3d, Pb 4f, and I 3d are identified in both two samples, and two additional peaks are observed appearing at 167.6 and 172.1 eV in CsPbI₃:Er³⁺ PQDs, which can be assigned to the 4d signal of Er³⁺. The lattice contraction of CsPbI₃ PQDs happens induced by partly replacing the Pb²⁺ (~119 pm) with the smaller sized Er³⁺ (~88.1 pm), leading to the shrinking of PbI₆ octahedron with shortening of Pb-I bond and enhancing the interaction. Thus, the binding energy of Pb²⁺ 4f in PQDs shifts with Er³⁺...
doping, while remains unchanged for I− 3d and Cs+ 3d. Combined with the HRTEM (Fig. 2a) and XRD results (Fig. S5), we can deduce that Er3+ ions are successfully incorporated into the CsPbI3 PQDs and occupy the lattice position of Pb2+ ions. Similar results were reported in the previous literatures19,47,48.

Figure 2c shows the absorption and emission spectra of CsPbI3 and CsPbI3:Er3+ PQDs. The absorption peak at 681 nm can be observed, attributed to the intrinsic exciton transition of CsPbI3 PQDs. With increasing Er3+ doping concentration, the absorption peak of CsPbI3 PQDs gradually shifts from 681 to 672 nm, and the bandgap of PQDs increases from 1.73 eV (CsPbI3 PQDs) to 1.81 eV (CsPbI3: 9.7% Er3+ PQDs), as represented in Fig. S7. This can be mainly attributed to the lattice contraction by substituting Pb2+ ions with Er3+ ions (Supplementary Note 1), as observed in Fig. 2a. Similarly, the emission peak of CsPbI3 PQDs gradually blue shifts from 697 to 687 nm with increasing Er3+ doping. Interestingly, the PLQY of PQDs rapidly increases after Er3+ doping, from 52% for CsPbI3 PQDs to 93% for CsPbI3: Er3+ (7.7%) PQDs (Fig. 2d). Correspondingly, the trap density of CsPbI3 PQDs is estimated to be 1.18 × 1017 cm−3, which quickly decreases to 1.6 × 1016 cm−3 for CsPbI3: Er3+ (7.7%) PQDs (Fig. S8 and Supplementary Note 2).

Meanwhile, the carrier densities are evaluated as 1.404 × 1019 cm−3 for CsPbI3 PQDs and 1.621 × 1019 cm−3 for CsPbI3: Er3+ (7.7%) PQDs. It is found that the effect reduces the trap density and increases the carrier densities of PQDs after Er3+ doping, similar to the previous literatures49,50.

The Er3+ doping concentration dependence of PL lifetimes (τ) and transition rates of CsPbI3 and CsPbI3:Er3+ PQDs were measured (Fig. 2e and S9). It can be observed that the PL lifetimes gradually decrease from 168 ns of CsPbI3 PQDs to 69 ns of CsPbI3:Er3+ (9.7%) PQDs. The radiative rates (kτ) and nonradiative rates (knr) of CsPbI3 and CsPbI3:Er3+ PQDs were calculated in Table S2 according to the following equations: kτ = PLQY/τ, and knr = (1-PLQY)/τ. Compared to the CsPbI3 PQDs, the kτ of CsPbI3:Er3+ (7.7%) PQDs increases about 3.5-folds and the knr of CsPbI3:Er3+ (7.7%) PQDs decreases about 3.5-folds. It suggests that the Er3+ doping can boost the radiative decay rate, reduce the trap density and enhance the PLQY of PQDs. The increase of the radiative decay rate in CsPbI3:Er3+ (7.7%) PQDs can be proved by the decreased power index as a function of the excitation power density (Fig. S10)51.

The role of Er3+ in the electrical conductivity of PQDs films were studied using I−V curves of the ITO/PQDs
Ag devices (Fig. 2f and Supplementary Note 3). It can be seen that the conductivity ($\sigma$) of pristine CsPbI$_3$ PQDs is $1.2 \times 10^{-6}$ S cm$^{-1}$, which increases to $5.2 \times 10^{-6}$ S cm$^{-1}$ for CsPbI$_3$:Er$^{3+}$ (7.7%) PQDs. The built-in potential ($V_b$) values of CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ (7.7%) PQDs based devices are estimated to be 0.85 and 0.93 V by the Mott–Schottky analysis (Fig. 2g and Supplementary Note 4). A larger built-in potential value means an enhanced driving force for the separation of photo-generated carriers as well as an extended depletion region for efficient suppression of electron-hole recombination, which is favorable for carrier separation, transport, and extraction$^{52-54}$. The built-in potential ($V_b$) values of CsPbI$_3$:Er$^{3+}$ PQDs is larger than that of CsPbI$_3$ PQDs, realizing the more effective separation of photogenerated carriers after Er$^{3+}$ doping.

It should be highlighted that incorporating Er$^{3+}$ ions into CsPbI$_3$ PQDs demonstrates significantly enhanced air- and UV-stability, which is of great importance for practical applications$^{55,55,56}$. The PL intensity of CsPbI$_3$:Er$^{3+}$ (7.7%) PQDs still maintains above 97 and 67% of its initial value after 30 days of storage and 10 h UV light radiation, but the PL of CsPbI$_3$ PQDs almost disappears after 5 days storage and 8 h UV light radiation (Fig. 2h and Figs. S11, S12). The thermal stability of CsPbI$_3$ PQDs is also improved remarkably after Er$^{3+}$ doping, which PL intensity remains 87% after annealing at 390 K, and no PL is recorded for CsPbI$_3$ PQDs after annealing at 350 K. Considering the better conductivity, the CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ PQDs are further treated with ethyl acetate to remove the original long-chain ligands of oleic acid (OA) and oleylamine (OAm) of PQDs$^{57,58}$. The CsPbI$_3$:Er$^{3+}$ PQDs demonstrate outstanding air- and UV-stability (Fig. S13).

We next performed density functional theory (DFT) calculations aimed at understanding the origin of Er$^{3+}$ doping-induced changes in structural and photophysical properties of CsPbI$_3$ PQDs. Electronic structures and formation energy of intrinsic vacancy defects for Cs, Pb and I (labeled as VCs, VPb and VI) of CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ PQDs.

Fig. 3 Density functional theory calculations of CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ PQDs. a, b Band structure and DOS of CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ PQDs. c, d Calculated formation energy of intrinsic vacancy defects for Cs, Pb and I (labeled as VCs, VPb and VI) of CsPbI$_3$ and CsPbI$_3$:Er$^{3+}$ PQDs. e, f Calculated phase diagrams of cubic CsPbI$_3$ (8 fu/cell) and CsErI$_3$ (8 fu/cell) with internal symmetry breaking. The pink polygons indicate the stable regions of the single-phase of cubic CsPbI$_3$ and CsErI$_3$.
structure and density of states (DOS) of pure cubic CsPbI₃ (2 × 2 × 2 supercell, 8fu/cell) with direct bandgap 1.72 eV and internal symmetry breaking. The 1 5p and Pb 6s orbital mainly contribute to the valance band maximum (VBM), and Pb 6p and I 5p dominate the conduction bands minimum (CBM). As shown in Fig. 3b, the bandgap of CsPbI₃:Er³⁺ is larger than pristine CsPbI₃, and the band edge states of CsPbI₃:Er³⁺ (8 fu/cell) does change (i.e., VBM and CBM), presenting the bandgap increase to 1.82 eV. We also theoretically calculated the formation energy of intrinsic vacancy defects of Cs, Pb, and I (labeled as VS, VPb, and VI) in pure cubic CsPbI₃ and CsPbI₃:Er³⁺ (64 fu/cell) by using PBEsol functional and 2 × 2 × 2 k-grid. As illustrated in Fig. 3c, d and Tables S3, S4, the intrinsic vacancies in CsPbI₃ are shallow defects with relatively smaller formation energy, which shows larger formation energy in CsPbI₃:Er³⁺, leading to the reduced trap density after Er³⁺ doping, similar to the experimental results in Fig. 2d. Generally, the defects can act as carrier traps, resulting in nonradiative recombination, whereas fewer defects largely preserve the bulk electronic band structure and can improve the optoelectronic properties of PQDs. Table 1 lists the formation energy of ternary compounds to the corresponding binary compounds by DFT. The calculated formation energy ΔHₚ of CsPbI₃:Er³⁺ reveals that the reaction spontaneously occurs starting from binary precursors because of the exothermic reaction.

| Compound | Phase | ΔHₚ (eV/atom) |
|----------|-------|---------------|
| CsPbI₃  | Cubic (8fu/cell) | 0.015         |
| CsPbI₃:Er³⁺ | Cubic (8fu/cell) | 0.019         |
| CsErI₃  | Cubic (8fu/cell) | 0.047         |
| Cs₂ErI₃ | Hexagonal (2fu/cell) | 0.050        |
doped CsPbCl₃ PQDs. It presents that the absorption peak of CsPbCl₃ PQDs locates at 400 nm ascribed to the excitonic transition, and slightly shifts to a shorter wavelength after Cr³⁺,Mn²⁺,Ce³⁺ doping into CsPbCl₃ PQDs. Interestingly, the absorption of Cr³⁺,Mn²⁺,Ce³⁺ doped CsPbCl₃ PQDs increases remarkably at the range of 200–300 nm, which can be assigned to the high states of 5d of Ce³⁺, similarly to the previous literature. As displayed in Fig. 4f, one emission band (417 nm) in CsPbCl₃ and CsPbCl₃:Cr³⁺ PQDs is observed, while two emission peaks in CsPbCl₃:Cr³⁺, Mn²⁺, and CsPbCl₃:Cr³⁺,Mn²⁺,Ce³⁺ PQDs are identified, appearing at 415 and 590 nm, respectively, corresponding to exciton emission of PQDs and °T₁−A₁ transition of Mn²⁺. The Mn²⁺ emission originates from the energy transfer from PQDs to Mn²⁺ ions, evidenced by the decreased decay lifetimes of excitation emission in CsPbCl₃:Cr³⁺ PQDs after Mn²⁺ doping (Fig. S20). Surprisingly, the PLQY of CsPbCl₃:Cr³⁺, Mn²⁺, Ce³⁺ PQDs is measured to be 93.5%. According to the previous literature, such high PLQY (Fig. 4f) are mainly due to the reduced non-radiative decay rate after Cr³⁺ doping, the boosted energy transfer from PQDs to Mn²⁺ ions and the enhanced UV absorption after Ce³⁺ doping. The energy transfer mechanism of CsPbCl₃:Cr³⁺, Mn²⁺, Ce³⁺ PQDs is presented in Fig. 4g. Importantly, the doping with Cr³⁺, Mn²⁺,Ce³⁺ can also largely improves the stability of CsPbCl₃ PQDs, in which the PL intensity remains around 93% after 30 days (Fig. S21). In virtue of high conversion efficiency from UV to visible lights, the CsPbCl₃:Cr³⁺, Mn²⁺,Ce³⁺ PQDs are embedded into a PMMA polymer matrix to form a Cr/Ce/Mn-LC (inset of Fig. 4h). The Cr/Ce/Mn-LC demonstrates the similar emission spectra with CsPbCl₃:Cr³⁺, Mn²⁺,Ce³⁺ PQDs (Fig. 4h and S22) and high transparency to visible lights (Fig. S23). The face emission of the PLQY Cr/Ce/Mn-LC is 20.03%, which is lower than the edge emissions (61.47%) due to the total internal reflection to the edges in the LC (Fig. S24). Such Cr/Ce/Mn-LC processes the high efficiency and transparency, can be severed as a photoluminescent converter to boost the UV response of PD.

Figure 5a shows the charge generation and transport mechanism of the broadband PDs with the response range spanning from UV to NIR lights, in which PQDs straightforward absorb the visible lights, the BHJ layer captures the NIR lights, Cr/Ce/Mn-LC converts the UV lights (200–400 nm) to visible lights (400–700 nm) further absorbing by PQDs. The photocurrent– time (I–t) response curves based on the ITO/ETL/CsPbI₃ PQDs/Ag (S1), ITO/ETL/CsPbI₃:Er³⁺ (7.7%) PQDs/Ag (S2), ITO/
ETL/CsPbI₂: Er³⁺ (7.7%) PQDs/BHJ/Ag (S3) and Cr/ Ce/ Mn-LC/ITO/ETL/CsPbI₂: Er³⁺ (7.7%) PQDs/BHJ/Ag (S4) under the 260, 460, and 860 nm with an incident light intensity of 0.5 mW cm⁻² are recorded in Fig. 5b. The photocurrents reach 0.89, 0.68, and 0.32 mA of S4 PD, while they are only 0.098 mA, 1.4 µA, and 0.01 µA of S1 PD under 460, 860, and 260 nm, respectively. Compared with S1 PD, the photocurrents of S4 PD enhance ninefold for 460 nm, 485-fold for 860 nm, and 3.2 × 10⁴ folds for 260 nm. The improvement of photocurrent at 460 nm mainly originates from that the Er³⁺ doping into CsPbI₂ PQDs resulting in increased carriers mobility, and accelerated carriers transport (Fig. 2). BHJ hybridization not only significantly boosts the photocurrent of 860 nm owing to the direct NIR absorption, but also contributes to the slight increase of photocurrent at 460 nm (S3) due to the inhibited electron-hole pair recombination at the interfaces of CsPbI₂: Er³⁺ (7.7%) PQDs/BHJ film. The huge enhancement of photocurrent at 260 nm (S4) is on account of Cr/ Ce/ Mn-LC. In order to further demonstrate highly light emission efficiency of the Cr/ Ce/ Mn-LC on the side edge, the photocurrent–time (I–t) response curves based on the Cr/ Ce/ Mn-LC face and the edge of S4 PDs at 260 nm illumination with an incident light intensity of 0.5 mW cm⁻² are recorded in Figs. S25, 26. It can be seen that the photocurrent of Cr/ Ce/ Mn-LC surface is 0.092 mA, which increases to 0.32 mA for the side edge of S4 PDs. The improvement of photocurrent at 260 nm mainly originates from the waveguide structure and the highly improved light collecting efficiency⁷⁰. Moreover, the photocurrent response of PDs using PMMA: CsPbCl₃: Cr³⁺, Mn²⁺, Ce³⁺ luminescent conversion layer (0.105 mA) is also lower than that of Cr/ Ce/ Mn-LC (0.32 mA). In the luminescent conversion layer, the direction of visible emissions are random under UV illumination, and only the emission photons which irradiate on the PD can be utilized. But in the Cr/ Ce/ Mn-LC, most of the emission photons can be traveled to the edge side attached to PD. Thus, the improvement of photocurrent in Cr/ Ce/ Mn-LC mainly originates from the waveguide structure and the highly improved light (400–700 nm) concentrate efficiency. The dark currents of the S2–S4 PDs are lower than that of the pristine PD device by one to two orders of magnitude, suggesting the defect sites of PQDs are effectively passivized by Er³⁺ doping and BHJ hybridization (Fig. S27), consistently with the results in Figs. 2, 4a–d⁴⁶,⁷¹. In line with the decreased dark current of S3 and S4 PDs, the θ coefficients in the S3 and S4 PDs (θ = 0.763 and 0.767) have better linearity than the pristine PD (θ = 0.698), following
the power-law $I \sim P^\theta$, where $I$ and $P$ represent the photocurrent and the incident light power intensity (Fig. S28). Figs. 5c, d and S29 display the detectivity ($D^*$), external quantum efficiency (EQE), and photoresponsivity ($R$) of S1–S4 PDs. These three parameters satisfy the following equations:

1. \[ R = \frac{I_{ph} - I_d}{P S} \]  
2. \[ D^* = \sqrt{\frac{S}{2eI_d}} \]  
3. \[ EQE = \frac{Rhc}{\lambda e} \]

where $I_{ph}$ and $I_d$ are the photocurrents under the illumination of light and in the dark, $P$ and $S$ are the input light power density and the effective irradiated area, $h$ and $c$ are the Planck’s constant and the speed of light, $\lambda$ and $e$ are the incident light wavelength and the elementary charge. The pristine S1 PD presents the low $D^*$, EQE, and $R$ in the whole region. These values are largely boosted in the visible region in S2–S4 PDs, and simultaneously, its responses expand to NIR (S3 PD) and UV (S3 and S4 PD) regions. The $R$, EQE, and $D^*$ of S4 PDs are $266.2$, $439.8$, and $326 \text{ mA/W}$; $89.13$, $91.84$, and $47.12\%$; $1.14 \times 10^{12}$ Jones, $2.46 \times 10^{12}$ Jones, $1.82 \times 10^{12}$ Jones at $260$, $460$, and $860$ nm light detection, respectively. Compared with S1 PD, owing to the contribution of Er$^{3+}$ doping, the BHJ film, and Cr/Ce/Mn-LC, the $D^*$ of S4 PDs improves $1.2 \times 10^4$ folds, $1.24 \times 10^2$ folds, and $5.7 \times 10^3$ folds at $260$, $460$, and $860$ nm lights, which increases two to four orders than that of the pristine PDs. Moreover, the S4 PDs exhibits a fast response time ($R_t$) of hundreds of microseconds (Fig. S30). The long-term stability of the S1–S4 PDs was further studied. As displayed in Fig. 5e, the S2–S4 PDs maintain about 82% of the initial photocurrent, while the photocurrent of the S1 device dropped to 0% after 60 h, owing to the outstanding stability of PQDs by Er$^{3+}$ doping. The UV stability of the S1–S4 devices in Fig. 5f illustrates that the stability of S2–S4 PDs are large improved, especially, S4 PD represents the best UV light stability, maintaining above 86% of the initial photocurrent after 10 h UV illumination, but it degrades to 0% for pristine PD within 7 h. The reason for those improvements in the air- and UV- stability are mainly attributed to the role of Er$^{3+}$ doping, BHJ hybridization, and the buffer layer of Cr/Ce/Mn-LC in the device. Notably, the photocurrent of the PD is repeatable even after five thousand cycles (Fig. S31), confirming the excellent reversibility of this photodetector. Compared to the previous broadband perovskite PDs (Table 2), our device exhibits excellent performance with a relatively wide response, high responsivity, and detectivity, especially in UV and NIR regions, and good stability, which exceeds the results of the previous reports.

**Discussion**

In this work, unique broadband PDs with the response range of 200–1000 nm and the $D^*$ value reaching of $1.14 \times 10^{12}$ at 260 nm and $2.46 \times 10^{12}$ at 460 nm, and $1.85 \times 10^{12}$ at 860 nm based on doped PQDs and an organic bulk heterojunction and Cr/Ce/Mn-LC were reported. Several new contributions for developing broadband PDs in this work should be highlighted. Firstly, CsPbI$_3$:Er$^{3+}$ PQDs serve as a visible photosensitive layer of PD, and the performance improves two orders that of

| Materials | $D^*$ (Jones) | $R_t$ (μs) | Wavelength | EQE  | Ref. |
|-----------|--------------|------------|------------|------|-----|
| CH$_3$NH$_3$PbI$_3$Cl$_x$ | – | 6.5/5.0 | 400–800 | 80% | 2 |
| TiO$_2$ nanorods/MAPbI$_3$ heterojunction | $7.8 \times 10^{10}$ | $10^8$ | 300–800 | – | 11 |
| MAPbI$_3$ | $10^{11}$ | 2200/4000 | 265–800 | – | 55 |
| PEO/CS/PbI$_3$ | $9.7 \times 10^{12}$ | – | 400–600 | 57.1% | 12 |
| OTPD/MAPbI$_3$ | $7.4 \times 10^{12}$ @680 nm | – | 300–780 | 80% | 5 |
| NiO$_2$/MAPbI$_3$/PCBM /PBTT-Th:IEICO-4F | $\sim 10^{10}$ | 500/510 | 340–940 | 80%/70% | 35 |
| PFHT/PDPP3T/ CsPbBr$_3$/SnO$_2$ | $1.2 \times 10^{13}$ | 92/193 | 300–950 | – | 7 |
| PEDOT:PS/PbS/CsPbCl$_3$ | $5.78 \times 10^{10}$ | – | 350–1100 | – | 32 |
| Au/PbS/CsPbCl$_3$ | $3.29 \times 10^{13}$ | $2.7 \times 10^7/4.2 \times 10^8$ | 300–1100 | 10% | 33 |
| Cr/Ce/Mn-LC/ITO /ETL/ Er$^{3+}$ doped CsPbI$_3$ PQDs /BHJ/Ag | $2.46 \times 10^{12}$ @ 460 nm | 350/300 | 200–1000 | 91.8% | Our work |

According to Table 2, our device exhibits excellent performance with a relatively wide response, high responsivity, and detectivity, especially in UV and NIR regions, and good stability, which exceeds the results of the previous reports.
pristine PDs at the wavelength of 400–700 nm. Experimental and theoretical results demonstrate that the highly improved optoelectronic properties, such as low trap density, high charge mobility, and PLQY, excellent stability through Er$^{3+}$ doping, lead to the great performance of PD. Secondly, the hybridization of CsPbI$_3$:Er$^{3+}$ PQDs / BHJ successfully expands the response of PDs to the NIR region, due to the NIR light-absorbing of low bandgap organic BHJ film. Thirdly, the high efficiency (PQLY = 93.5%) and strong absorption ability of Cr$^{3+}$, Mn$^{2+}$, Ce$^{3+}$ doped CsPbI$_3$ PQDs are incorporated into PMMA to form a Cr/Ce/Mn-LC. The Cr/Ce/Mn-LC is employed as a UV photosensitive layer of PDs to highly enhanced UV response of PDs. Furthermore, the air- and UV-stability of broadband PDs are also significantly boosted. The performance of our PD is much better than that of other perovskite PDs and commercial Si PDs. Overall, this work presents a novel strategy to obtain a broadband PD with excellent performance.

**Materials and methods**

**Materials**

Cs$_2$CO$_3$ (99.9%), 1-octadecene (ODE, 90%), oleic acid (OA, 85%), oleylamine (OAm, 70%), PbI$_2$ (99.99%), ErI$_3$ (99.99%), PbCl$_2$ (99.99%), CrCl$_3$ (99%), MnCl$_2$ (99%), toluene, and ethyl acetate (99%) were purchased from Sigma-Aldrich and were used as starting materials without further purification.

**Synthesis of Cs-oleate**

About 0.8 g Cs$_2$CO$_3$ was added into a mixture of 30 mL of ODE and OA (2.5 mL) and then heated to 150 °C and the white powder was completely dissolved. The mixture was then kept at 120 °C.

**Synthesis of CsPbI$_3$ PQDs**

PbI$_2$ (0.3 mmol), OAm (1.5 mL), OA (1.5 mL), and ODE (10 mL) were added to a 50-mL three-neck round-bottom flask and were evacuated and refilled with N$_2$, followed by heating the solution to 120 °C for 1 h. The temperature of the solution was then increased to 180 °C for 10 min. Then, the Cs-oleate (1 mL) was swiftly injected into the solution. After 10 s, the solution was cooled in an ice bath. The CsPbI$_3$ PQDs were precipitated and then centrifuged, followed by dissolution in toluene.

**Synthesis of Er$^{3+}$ doped CsPbI$_3$ PQDs**

PbI$_2$ (0.3 mmol) and ErI$_3$ (0.15 mmol) were loaded into round-bottom flask with OAm (1.5 mL), OA (1.5 mL), and ODE (10 mL). It was continued heated at 120 °C for 2 h and refilled with N2. Then the solution was increased to 230 °C. Then, the Cs-oleate (1 mL) was swiftly injected into the solution. After 10 s, the solution was cooled in an ice bath. Finally, the CsPbI$_3$:Er$^{3+}$ (7.7 %) PQDs were precipitated and then centrifuged, followed by dissolution in toluene.

**Synthesis of Cr$^{3+}$,Ce$^{3+}$,Mn$^{2+}$ doped CsPbCl$_3$ PQDs**

PbCl$_2$ (0.5 mmol), CrCl$_3$ (0.3 mmol), CeCl$_3$(0.2 mmol), and MnCl$_2$ (0.2 mmol) were loaded into round-bottom flask with OAm (1.5 mL), OA (1.5 mL), and ODE (15 mL). The following steps were the same with the synthesis of the Er$^{3+}$ doped CsPbI$_3$ PQDs.

**Fabrication of Cr/ Ce /Mn–LC**

About 0.8 g PMMA (MW ~350000) was dispersed in 5 mL toluene by sonication, to which 2.5 mL toluene solution of CsPbCl$_3$: Cr$^{3+}$ (8.3%),Ce$^{3+}$ (3.2%),Mn$^{2+}$ (9.3%) PQDs were added. The mixture was sealed and stirred overnight to obtain a homogenous slurry. The slurry was centrifuged at 2000 rpm and the supernatants were used for LC fabrication. The above supernatants were dropped onto borosilicate glass substrates and LC was fabricated by spin-coating.

**Syntheses of BHJ film**

The PBDB-TF:BTP-4Cl (1:1.2) was dissolved in chloroform. The mixture was heated and stirred at 60 °C for 5 h to obtain an organic active layer solution. The solvent additive of 1-chloronaphthalene (CN) (0.5%) was added half an hour before the organic active layer solution deposition. For the hybrid PDs, the PBDB-TF:BTP-4Cl solution was spin-coated on a perovskite layer at 1800 rpm for 60 s and subsequently annealed at 80 °C for 10 min.

**Device fabrication**

ITO-coated glass substrates were etched with zinc powder and HCl to define the electrode patterns and washed in deionized water, acetone, and ethanol for 20 min, respectively. The ultraviolet ozone was used to remove the organic residues of the ITO surface. To fabricate the compact SnO$_2$:Ti$_3$C$_2$ layer, the SnO$_2$:Ti$_3$C$_2$ colloid solution by water to the concentration of 2.14 wt% was spin-coated on ITO substrates at 5000 rpm for 30 s and then annealed at 150 °C for 30 min. The Er$^{3+}$ doped CsPbI$_3$ PQDs film was fabricated on the SnO$_2$:Ti$_3$C$_2$ layer by spin-coating at 600 rpm for 6 s and 4000 rpm for 40 s, respectively. The PBDB-TF in chlorobenzene (CB) (400 μL) at various concentrations was dropped on a substrate at 20 s before the end of the spinning process. After that, the PBDB-TF:BTP-4Cl solution was spin-coated on a perovskite layer at 1800 rpm for 60 s and subsequently annealed at 80 °C for 10 min. The Ag electrode was deposited by thermal evaporation to complete the device fabrication. Then, the edge surface of Cr/Ce/ Mn-LC with an edge size of 0.1 × 0.04 cm was attached and fixed to the ITO layer of PD with an area of 0.1 × 0.1 cm. When UV light radiation on the face of Cr/Ce/
Mn-LC, then the emitted 400–700 nm light is coupled out of the edge surface into the ITO of PDs. The visible and NIR lights directly pass through the ITO and reach the PD. Because the Cr/Ce/Mn-LC only occupies a part of the surface of the ITO layer and has high transparency for photons with a longer wavelength (>410 nm), which would not affect the light collection of PD.

**Characterization**

UV/vis-NIR absorption spectra were measured with a Shimadzu UV-3600PC UV/vis-NIR scanning spectrophotometer in the range from 200 to 2500 nm. Patterns were recorded in thin-film mode on a Bruker AXS D8 diffractometer using Cu Karadiation (λ = 1.54178 Å). Atomic Force Microscope (AFM) was performed using a DI Innova AFM (Bruker) in light tapping mode. The morphology of the products was recorded with a Hitachi H-8100IV transmission electron microscope (TEM) under an acceleration voltage of 200 kV. The samples were pumped using a laser system consisting of a tunable optical parameter oscillator (OPO, Continuum Precision II 8000) with a pulse duration of 10 ns, a repetition frequency of 10 Hz, and a line width of 4–7 cm⁻¹. A visible photomultiplier (350–850 nm) combined with a double-grating monochromator were used for spectral collection. The X-ray photoelectron spectroscopy (XPS) was carried out in a Kratos Axis Ultra DLD spectrometer equipped with a monochromatic Al Kα X-ray source (hv = 1486.6 eV) operated at 150 W with a multichannel plate, and a delay line detector under 1 atm vacuum. A photomultiplier combined with a monochromator was used for dynamics signal collection of 365 nm Xe lamp. The typical PLQY in such a system is estimated as follows:

\[
\text{PLQY} = \frac{N_{\text{em}}}{N_{\text{abs}}} = \frac{\int I_{\text{sample}}(\lambda) - I_{\text{ref}}(\lambda) \, d\lambda}{\int E_{\text{ref}}(\lambda) - E_{\text{sample}}(\lambda) \, d\lambda}
\]

where \(N_{\text{em}}\) and \(N_{\text{abs}}\) are the numbers of emission and absorption photons of samples. \(I_{\text{sample}}\) and \(E_{\text{sample}}\) present the spectral intensity of the emitted light and excitation light of samples, and \(I_{\text{ref}}\) and \(E_{\text{ref}}\) is the spectral intensity of the emitted light and excitation light for a reference cuvette containing neat toluene. The monochromatic light was from a Newport Oriel 200TM. The Mott–Schottky curves via capacitance-voltage measurements of CsPbI₃:Er³⁺ PQDs are obtained by a Princeton electrochemical workstation (Parstat Mc Princeton Instruments Co., Ltd., USA). The Xe lamp (LSB-X150AUV 200–2500 nm, Zolix) with the spectral range from 200 to 2500 nm equipped with a monochromator (Omni-λ3007i, Zolix) was used to generate the monochromatic light to conduct the spectral response measurements. Actually, the intensity of the Xe lamp is weak in the region of 200–300 nm, thus we must correct it before the measurement.

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**Conflict of interest**

The authors declare no competing interests.

**Supplementary information**

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**References**

1. Li, D. Y. et al. Plasmonic photonic crystals induced two-order fluorescence enhancement of blue perovskite nanocrystals and its application for high-performance flexible ultraviolet photodetectors. Adv. Funct. Mater. 28, 1804429 (2018).
2. Li, F. et al. Ambipolar solution-processed hybrid perovskite phototransistors. Nat. Commun. 6, 8238 (2015).
3. Lin, Q. Q. et al. Near-infrared and short-wavelength infrared photodiodes based on dye-perovskite composites. Adv. Funct. Mater. 27, 1702485 (2017).
4. Chen, B. et al. Large electrostrictive response in lead halide perovskites. Nat. Mater. 17, 1020–1026 (2018).
5. Fang, Y. J. & Huang, J. S. Resolving weak light of sub-picowatt per square centimeter by hybrid perovskite photodetectors enabled by noise reduction. Adv. Mater. 27, 2804–2810 (2015).
6. Gong, M. G. et al. High-performance all-inorganic CsPbCl₃ perovskite nanocrystal photodetectors with superior stability. ACS Nano 13, 1772–1783 (2019).
7. Cao, F. R. et al. Self-powered UV-NIR photodetector based on conjugated-polymer/CsPbI₃ nanowire array. Adv. Funct. Mater. 29, 1900756 (2019).
8. Zhao, Y. et al. Sensitive and stable tin-lead hybrid perovskite photodetectors enabled by double-sided surface passivation for infrared upconversion detection. Small 16, 2001534 (2020).

9. Shao, D. L. et al. A high performance UV-visible dual-band photodetector based on an inorganic Cs2SnI6 perovskite/ZnO heterojunction structure. J. Mater. Chem. C 8, 1819–1825 (2020).

10. Liu, C. Y. et al. Silicon/2D-material photodetectors from near-infrared to mid-infrared. Light.: Sci. Appl. 10, 123 (2021).

11. Zhou, H. et al. Self-powered, ultraviolet-visible perovskite photodetector based on TiO2 nanorods. RSC Adv. 6, 6026–6028 (2016).

12. Bao, C. et al. High performance and stable all-inorganic metal halide perovskite-based photodetectors for optical communication applications. Adv. Mater. 30, 1839422 (2018).

13. Tian, W. et al. Low-dimensional nanomaterial/Si heterostructure-based photodetectors. InfoMat 1, 140–163 (2019).

14. Li, L. et al. Ferroelectricity-induced performance enhancement of V-doped ZnO/Si photodetector by direct energy band modulation. Nano Energy 65, 104046 (2019).

15. Livache, C. et al. A colloidal quantum dot infrared photodetector and its use for intraband detection. Nat. Commun. 10, 2125 (2019).

16. Yang, C. et al. MAPbI3 single crystals free from hole-trapping centers for enhanced photodetectivity. ACS Energy Lett. 4, 2579–2584 (2019).

17. Luo, P. et al. PbSe quantum dots sensitized high-mobility Bi2O2Se nanosheets for high-performance and broadband photodetection beyond 2 μm. ACS Nano 13, 9028–9037 (2019).

18. Jing, X. L. et al. Enhanced photoluminescence and photoresponsiveness of Eu3+ ions-doped CsPbCl3 perovskite quantum dots under high pressure. Adv. Funct. Mater. 31, 2100930 (2021).

19. Kroupa, D. M. et al. Quantum-cutting ytterbium-doped CsPbCl3–BrPbI2 perovskite thin films with photoluminescence quantum yields over 190%. ACS Energy Lett. 3, 2390–2395 (2018).

20. Shao, L. et al. Broadband ultraviolet photodetectors based on cesium doped lead-free Cs2MnBr3 metal halide nanocrystals. ACS Sustain. Chem. Eng. 9, 4980–4987 (2021).

21. Shen, X. Y. et al. Zn-alloyed CsPbI3 nanocrystals for highly efficient perovskite light-emitting devices. Nano Lett. 19, 1552–1559 (2019).

22. Bi, C. H. et al. Improved stability and photodetector performance of CsPbI3 perovskite quantum dots by ligand exchange with aminothioether. Adv. Funct. Mater. 29, 1902446 (2019).

23. Liu, Q. B. et al. Epitaxial growth of CsPbBr3-PbS vertical and lateral heterostructures for visible to infrared broadband photodetection. Nano Res. 14, 3879–3885 (2021).

24. Protesescu, L. et al. Nanocrystals of cesium lead halide perovskites (CsPbX3, X = Cl, Br, and I) novel optoelectronic materials showing bright emission with wide color gamut. Nano Lett. 15, 3692–3696 (2015).

25. Lu, M. et al. Simultaneous strontium doping and chlorine surface passivation of Mn-doped CsPbI3 perovskite quantum dots by nickel chloride. Adv. Mater. 32, 2000449 (2020).

26. Portnoi, M. et al. Thermally stable copper(I)-doped cesium lead halide perovskite quantum dots with strong blue emission. J. Phys. Chem. Lett. 10, 943–952 (2019).

27. Dong, Y. R. et al. Trivalent-neodymium additive modulated MAPbBr3 perovskite nucleation and growth: ultrawide processing window for one-step fabrication of efficient light-emitting perovskites. Adv. Electron. Mater. 6, 2000449 (2020).

28. Duan, Z. H. et al. Broad-band photodetectors based on copper indium diselenide quantum dots in a methylammonium lead iodide perovskite matrix. ACS Appl. Mater. Interfaces 12, 35201–35210 (2020).

29. Zhong, L. H. et al. Trap state passivation by rational ligand molecule engineering toward efficient and stable perovskite solar cells exceeding 23% efficiency. Adv. Energy Mater. 11, 2100529 (2021).

30. Chen, X. et al. Europium ions doped WO3 nanorods for dual interfacial modification facilitating high efficiency and stability of perovskite solar cells. Nano Energy 80, 105664 (2021).

31. Laban, W. A. & Etgar, L. Depleted hole conductor-free lead halide iodide perovskite solar cells through samarium doped CsPbI2Br perovskite. ACS Appl. Mater. Interfaces 12, 35201–35210 (2020).

32. Patil, J. V., Mali, S. S. & Hong, C. H. Boosting the stability of fully-inorganic perovskite solar cells and efficient light-emitting diode. Nano Energy 81, 105615 (2019).

33. Wang, Y. et al. Surface ligand management aided by a secondary amine enables increased synthesis yield of CsPbI3 perovskite quantum dots and high photovoltaic performance. Adv. Mater. 32, 2000449 (2020).

34. Shao, D. L. et al. Synthesis and photoluminescence kinetics of Ce5+–doped CsPbI3 QDs with near-unit PLQY. Nano Res. 14, 3352–3357 (2021).

35. Liu, J. M. et al. Sm3+–doped CsPbI3 NCs glass: a luminescence material for potential use in lighting engineering. Ceram. Int. 45, 22688–22693 (2019).

36. Jiang, F. et al. Trap-mediated energy transfer in Er-doped cesium lead halide perovskite. J. Phys. Chem. Lett. 11, 3320–3326 (2020).

37. Yong, Z. J. et al. Doping-enhanced short-range order of perovskite nanocrystals for near-ultraviolet luminescence quantum yield. J. Am. Chem. Soc. 140, 9942–9951 (2018).

38. Zhao, X. H. et al. Vertically stacked PEDOT/PSS/PbS/CsPbCl3 for flexible optoelectronic devices. J. Alloy. Compd. 866, 158997 (2021).

39. Li, K. et al. Vertically stacked Au/PbS/CsPbI3 phototransistors for plasmon-enhanced high-performance broadband photodetection. ACS Appl. Electron. Mater. 2, 4080–4086 (2020).

40. Zhao, X. H. et al. Enhanced photodetection of perovskite nanoplatelet devices by vertically stacked PEDOT:PSS/PbS/CsPbCl3 architecture. Mater. Lett. 290, 129467 (2021).
59. Wróbel, J. et al. Thermodynamic and mechanical properties of lanthanum–magnesium phases from density functional theory. J. Alloy. Compd. 512, 296–310 (2012).

60. Kang, J. & Wang, L. W. High defect tolerance in lead halide perovskite CsPbBr3. J. Phys. Chem. Lett. 8, 489–493 (2017).

61. Chen, B. B. et al. A large-scale synthesis of photoluminescent carbon quantum dots: a self-exothermic reaction driving the formation of the nanocrystalline core at room temperature. Green. Chem. 18, 5127–5132 (2016).

62. Kim, J. et al. Hydrophobic stabilizer-anchored fully inorganic perovskite quantum dots enhance moisture resistance and photovoltaic performance. Nano Energy 75, 104985 (2020).

63. Ding, H. et al. Growth, patterning and alignment of organolead iodide perovskite nanowires for optoelectronic devices. Nanoscale 7, 4163–4170 (2015).

64. Yang, B. et al. Ultrasensitive and fast all-inorganic perovskite-based photodetector via fast carrier diffusion. Adv. Mater. 29, 1703758 (2017).

65. Xue, J. J. et al. A small-molecule “charge driver” enables perovskite quantum dot solar cells with efficiency approaching 13%. Adv. Mater. 31, 1900111 (2019).

66. Li, D. Y. et al. Cerium-doped perovskite nanocrystals for extremely high-performance deep-ultraviolet photoelectric detection. Adv. Optical Mater. 9, 2100423 (2021).

67. Liu, H. W. et al. CsPbX3 halide perovskite quantum dots with high Mn substitution ratio. ACS Nano 11, 2239–2247 (2017).

68. Zhou, D. L. et al. Cerium and ytterbium codoped halide perovskite quantum dots: a novel and efficient downconverter for improving the performance of silicon solar cells. Adv. Mater. 29, 1704149 (2017).

69. Zhou, D. L. et al. Impact of host composition, codoping, or tridoping on quantum-cutting emission of ytterbium in halide perovskite quantum dots and solar cell applications. Nano Lett. 19, 6904–6913 (2019).

70. Luo, X. et al. Quantum-cutting luminescent solar concentrators using ytterbium-doped perovskite nanocrystals. Nano Lett. 19, 338–341 (2019).

71. Zou, C. et al. A highly sensitive UV-vis-NIR all-inorganic perovskite quantum dot phototransistor based on a layered heterojunction. Adv. Optical Mater. 6, 1800324 (2018).

72. Li, C. L. et al. Ultrafast and broadband photodetectors based on a perovskite/organic bulk heterojunction for large-dynamic-range imaging. Light. Sci. Appl. 9, 31 (2020).