Janus CsPbBr₃–AgBiS₂ Heteronanocrystals for High-Efficiency Photodetectors

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Cite This: Nano Lett. 2025, 25, 4393–4400

Cite This: Nano Lett. 2025, 25, 4393–4400

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ABSTRACT: Heteronanocrystals (HNCs) composed of colloidal lead halide perovskites and chalcogenides always offer unique photoelectric properties. Nevertheless, synthesizing perovskite– chalcogenide HNCs has been a tough challenge due to their completely different growth dynamics. Here, we present an effective strategy to synthesize Janus CsPbBr₃–AgBiS₂ HNCs by in situ growth of CsPbBr₃ NCs on prepared AgBiS₂ quantum dot (QDs). The assynthesized HNCs show a large range of absorption characteristics from visible to near-infrared (NIR) wavebands. Femtosecond transient absorption (TA) spectroscopy reveals the transfer of both electron and hole from CsPbBr₃ to AgBiS₂. The enhanced absorption



range and exciton dissociation in 150 °C HNCs leads to photoconductors with drastically improved responsivity (R of 183.8 A W⁻¹) and specific detectivity (D^* of 5.0 × 10¹⁴ Jones). This work not only provides a reliable method for combining ionic CsPbBr₃ and covalent AgBiS₂ but also has great potential for future practical applications, such as an NC (QD) solar cell.

KEYWORDS: heteronanocrystals, CsPbBr₃ NCs, AgBiS₂ QDs, photodetector

ll-inorganic lead halide (CsPbX₃, X = Cl, Br, and I) **A**perovskite nanocrystals (NCs) with extraordinary properties, including high photoluminescence quantum yield (PLQY), high absorption coefficient, narrow emission spectrum, and tunable bandgaps, have emerged as a promising semiconductor material for widespread technological applications.¹ When it comes to the applications in a solar cell or photodetector, an enormous challenge that needs to be solved is the trade-off between slowing the degradation of the perovskite active layer and maintaining the photoconducting behavior.¹ The effects of ligand blocking and quantum confinement reduce the separation efficiency of the photogenerated electron-hole in CsPbX₃ NCs, and such recombination loss is one of the primary energy loss pathways in a single junction photovoltaic/photoelectric devices.² Thus, photovoltaic/photoelectric devices of perovskite NCs have yet to demonstrate photosensitivity or photoelectric conversion efficiency (PEC) beyond other systems (such as polycrystalline thin-film). For traditional II-VI group NCs, the commonly used strategy is ligand engineering (e.g., ligand exchange), that is, replacing organic capping ligands with short chain ligands.³ However, in the case of perovskite NCs, ligand exchange processes may cause decomposition in the crystalline structure due to its intrinsic chemical instability. Beyond the ligand engineering, another effective method to overcome this above-mentioned obstacle is building a heterointerface between perovskite NCs and other functional materials (such

as chalcogenide) to form a heterostructure, thereby achieving passivation of surface defects, slowing carrier relaxation, and increasing carrier extraction efficiency.

The frequently used heterostructure of CsPbX₃ NCs in a 3D matrix (such as an AlO_x matrix⁴ and metal organic frameworks⁵) with its overly large size of hundreds of nanometers to micrometers always results in a loss of colloidal stability and solution processability, and the poor electrical conductivity also limits their application. The nanoscale heterojunction in heteronanocrystals (HNCs) that is composed of one perovskite NC coupled with another NC, e.g., perovskite NCs/ oxides HNCs (SiO₂, Al₂O₃, etc., however, with poor electrical conductivity),^{6–9} perovskite NCs/metal-nanoparticles (Au,¹⁰ Pt,^{11,12} Pd,¹³ and Bi(0)¹⁴), and perovskite NCs/chalcogenide HNCs (PbS/PbSe,^{15–19} ZnS,²⁰ CdS,^{21,22} Pb₄S₃Br₂,^{23–25} Pb₄S₃Cl₂,²⁶ and Pb_xBi_yS₂,^{27,28} etc.) have many advantages: (i) they endow advanced functionalities in wave function engineering and surface passivation beyond single-component perovskites; (ii) they offer good solution dispersibility for the liquid-phase device casting process;¹⁵ (iii) they offer ultrafast

Received:December 24, 2024Revised:March 1, 2025Accepted:March 3, 2025Published:March 4, 2025





Scheme 1. Synthetic Process of CsPbBr₃-AgBiS₂ HNCs



Figure 1. Structural analysis of $CsPbBr_3-AgBiS_2$ HNCs, $CsPbBr_3$ NCs, and $AgBiS_2$ QDs. (a) TEM image of 150 °C HNCs. (b,c) HRTEM image and (d) EDS mapping of an individual 150 °C HNC. (e) HRTEM image of three 150 °C HNCs. (f) TEM image of 160 °C HNCs. (g) HRTEM image of an individual 160 °C HNC. (h) HRTEM image of the control $CsPbBr_3$ NCs. (i) HRTEM image of $AgBiS_2$ QDs. In our experiment, a growth time of 3 min was selected to explore the photoelectric property of the HNCs.

10 nm

transfer of carrier between CsPbX₃ and chalcogenide (e.g., the hot charge transfer from CsPbBr₃ to PbSe in CsPbBr₃–PbSe HNCs¹⁹). Moreover, the emerging lattice epitaxial CsPbX₃based HNCs further amplify these advantages,^{11–14,18,19,22–27} which can minimize the junction resistance. Different from monophase NCs, HNCs such as the traditional CdSe/ CdS,^{29–31} CdSe/CdS/ZnS,³² CdSe/CdTe,³³ PbS/CdS,³⁴ InP/ZnSe/ZnS,³⁵ Cu_{2-x}S/PbS,³⁶ and Cu_{2-x}S/CuInS₂ NCs,³⁷ with Janus, core–shell, or other structures, have attracted intensive investigation for their greater freedom in tailorability or property optimization. Similarly, HNCs of CsPbX₃ NCs with other functional materials have also been a new design

5 nm

20 nm

paradigm toward advanced material properties and device performance. However, the synthesis of HNCs often presents many problems due to the completely different growth dynamics between CsPbX₃ and chalcogenide.

10 nm

For the selection of another functional material, heterostructures of perovskite coupled with chalcogenide have been proven to have potential application value. Sargent et al. reported a series of bulk-phase perovskite-PbS heterostructures, including PbS QDs in MAPbI₃ matrix,³⁸ PbS QDs in CsPbBr_xI_{3-x} matrix,³⁹ and PbS QDs in layered MAPbBrI₂.⁴⁰ Although the above-mentioned heterostructures are not at the nanoscale, the improvement in carrier extraction and transport



Figure 2. XRD, XPS, and spectroscopic measurements of different samples. (a) XRD patterns, (b) high-resolution XPS spectra of Ag 3d, (c) high-resolution XPS spectra of Bi 4f & S 2p, (d) steady-state PL spectra, and (e) UV-visible absorption spectra of different samples. For all the graphs, different samples are distinguished as different colors of $AgBiS_2$ QDs (red line), 150 °C HNCs (blue line), 160 °C HNCs (green line), and CsPbBr₃ NCs (black line).

is noticeable. In contrast to traditional chalcogenide QDs, AgBiS₂ QDs possess an exceptionally high absorption coefficient $(10^5 \text{ to } 10^3 \text{ cm}^{-1})$, which endows them with outstanding light-harvesting efficiency.⁴¹ When it comes to AgBiS₂ QDs coupled with perovskite NCs to form a heterojunction, they are theoretically able to work in a collaborative fashion. This synergy enables the effective regulation of the charge separation and transport pathways. Nevertheless, to the best of our knowledge, there has been no report yet on the heterojunction formed by combining perovskite NCs with AgBiS₂ QDs. Herein, we report for the first time the synthesis of perovskite/ternary metal chalcogenide (CsPbBr₃–AgBiS₂) HNCs with a high colloidal stability. Due to the narrow band gap (1.1 eV) of AgBiS₂, HNCs exhibited a wide absorption range covering the visible region to the near-infrared (NIR) region. Transient absorption (TA) spectra reveal the charge transfer from $CsPbX_3$ to $AgBiS_{24}$ which is derived from the difference in both the conduction band (CB) and valence band (VB). The highly efficient light energy harvesting of HNCs leads to a photoconductor with drastically improved responsivity (R, 183.8 A W^{-1}) and specific detectivity (D^* , 5.0 × 10¹⁴ Jones), holding promise for ultrasensitive photodetection.

The Schlenk technique was employed for synthesis of $AgBiS_2$ QDs, which followed a previous report with modifications⁴² and was also utilized in our recent report (Figure S1).⁴³ Details appear in the experimental procedures in the Supporting Information. The synthesis used preformed CsPbBr₃ nanoclusters as precursors for CsPbBr₃ NCs, and presynthesized AgBiS₂ QDs (~5 mg) were dispersed in the reaction solution before CsPbBr₃ nanocluster injection (Scheme 1). For all of the synthesis, we utilized CsPbBr₃ nanoclusters with an excitonic peak at around 400 nm (Figure S2), which was similar to a previous report by Pradhan and coworkers.⁴⁴ Manna and co-workers demonstrated the feasibility of synthesis of CsPbBr₃–Pb₄S₃Br₂ Janus HNCs by using these CsPbBr₃ nanoclusters.²³ We determined the mass ratio of AgBiS₂ QDs and CsPbBr₃ NCs as ~1:2, in order to ensure an adequate supply of AgBiS₂ QDs and CsPbBr₃ NCs in the

reaction mixture can be calculated as \sim 2:1, as shown in Supplementary Text: Part-1). The HNCs with three different growth times (1, 3, and 5 min) have a similar trend of absorption spectra, showing a rapid growth process (Figure S3 and Supplementary Text: Part-2).

Transmission electron microscopy (TEM) images of HNCs synthesized at 150 °C (named 150 °C HNCs) reveal uniform HNCs with nanoscale CsPbBr3 domains coupled with spherical AgBiS₂ QDs (Figure 1a), and a Janus construction can be observed. The average sizes of CsPbBr₃ and AgBiS₂ domains are 14.3 \pm 2 and 10.1 \pm 2 nm, respectively. The HRTEM image of a randomly selected 150 °C HNC presents a distinct contrast ratio between two domains (Figure 1b). The lattice fringe spacing of 0.29 and 0.28 nm can be ascribed to the (200) planes of CsPbBr₃ (domain 1 with dark color) and the (200) plane of AgBiS₂ (domain 2 with light color), respectively (Figure S4). In order to further distinguish the component and distribution of elements in different domains, we obtained the selected-area overlapped HRTEM (Figure 1c) and energy dispersive spectroscopy (EDS) mapping (Figure 1d). As shown in EDS mapping, the distribution patterns of the Br element and Ag element show that components of domains 1 and 2 are CsPbBr3 and AgBiS2, respectively. We also obtained the detailed EDS mappings of all possible elements (Figure S5), in which Cs, Pb, and Br elements (ratio of 0.8:1:3.2) are mainly distributed on domain 1, while Ag, Bi, and S elements (ratio of 0.9:1:2.0) are mainly distributed on domain 2, showing this individual HNC with a Janus heterostructure with suitable proportions in respective domains. The HRTEM image containing three HNCs shows a noticeable contrast change in the two domains for each HNC, which is consistent with the above analysis (Figure 1e).

The reaction temperature is a key parameter for formation of heterostructure and size tuning (more discussion in Supplementary Text: Part-2). For a low reaction temperature, such as 140 °C, the probability of heterostructure formation is significantly reduced (Figure S6). Higher reaction temperatures (e.g., ≥ 160 °C) resulted in HNCs with a larger size in CsPbBr₃ domain (17.1 ± 4 nm) yet a similar size in AgBiS₂ domain (10.1 ± 2 nm), which is because the pre-prepared



Figure 3. TA spectra of 150 °C HNCs and CsPbBr₃ NCs. (a) TA spectra of CsPbBr₃ NCs. (b) The exciton bleach recovery kinetics of CsPbBr₃ NCs. The spectra were normalized based on the ΔA related to CsPbBr₃ bleach. (c) PL spectra (unnormalized) of 150 °C HNCs (blue line) and CsPbBr₃ NCs (black line). (d) TA spectra of 150 °C HNCs. TA spectra of 150 °C HNCs with different ordinate rangse (e) from -1.3 to 0.3 mOD and (f) from -0.05 to 0.01 mOD. In this analytic process, TA spectra with 0.2 ps (black line), 0.5 ps (red line), 0.5 ns (blue line), and 3.6 ns (green line) were selected. (g) Normalized ΔA of 150 °C HNCs and CsPbBr₃ NCs at 0.5 ps, 0.5 ns, and 3.6 ns. (h) The CsPbBr₃ and AgBiS₂ exciton bleach recovery kinetics of 150 °C HNCs. The spectra were normalized based on the ΔA related to CsPbBr₃ bleach (black line) and AgBiS₂ bleach (blue line). (i) Schematic type I band alignment in the HNCs.

AgBiS₂ QDs with a fixed size were used in the synthetic process (Figure 1f). The irregular morphology of the CsPbBr₃ domain in some of the HNCs can be ascribed to the higher reaction kinetics and faster growth rate for a higher reaction temperature. The interconnecting heterointerface can be observed in the HRTEM image of an individual 160 °C HNC (Figure 1g and S7). The selected-area fast Fourier transformed (FFT) patterns from CsPbBr₃ and AgBiS₂ domains in the HRTEM image of an individual 160 °C HNC show that CsPbBr3 and AgBiS2 are viewed along the [001] and [110] directions, respectively (Figure S8). The disordered degree of size and morphology of the CsPbBr₃ domain increased for reaction temperature >160 °C, and the colloidal stability (clarity of solution) decreased with the increase of reaction temperature (Figure S9). For comparison, we prepared CsPbBr₃ NCs with the similar edge lengths as those of the CsPbBr₃ domains in 150 °C HNCs (Figure 1h). From the TEM image of the control CsPbBr₃ NCs, the size of CsPbBr₃ NCs can be counted as 13.2 ± 2 nm (Figures S10). Figure 1i shows the TEM image of uniform AgBiS₂ QDs with an average diameter of \sim 9.5 nm (statistical number of QDs > 300). The synthesis of HNCs was carried out by using AgBiS₂ QDs with the same size.

The powder X-ray diffraction (XRD) patterns of different samples are presented in Figure 2a, and detailed XRD information is shown in Figure S11. Characteristic peaks for 150 °C HNCs (blue line) and 160 °C HNCs (green line) incorporate features from both components. The characteristic peak (200) of $AgBiS_2$ shifts toward a higher angle direction for HNCs ($\approx 32^{\circ}$) compared to the AgBiS₂ QDs ($\approx 31^{\circ}$), which results from the formation of the heterointerface. X-ray photoelectron spectroscopy (XPS) was further used to examine the elemental composition of different samples. Figure S12 presents the XPS spectrum for a survey scan of four samples, with all peaks labeled. A doublet corresponding to Ag $3d_{3/2}$ (374.4 eV) and Ag $3d_{5/2}$ (368.4 eV) was observed for AgBiS₂ QDs (red line in Figure 2b).⁴⁵ After formation of HNCs, the binding energy of Ag 3d and Bi 4f shifted toward lower binding energies compared to AgBiS₂ QDs (Figure 2b,c). Theoretically, the increase of electron concentration will lead to the decrease of binding energy because of the enhanced electron screening effect. Thus, it is reasonable to conclude that the lower shifts of binding energies of Ag 3d and Bi 4f can be ascribed to Ag and Bi becoming electron-rich. Also, the binding energies of Cs, Pb, and Br are in accordance with those for the pure phase of CsPbBr₃ NCs,⁴⁶ which may be due to the



Figure 4. Photoconductors based on AgBiS₂ QDs, CsPbBr₃ NCs, 150 °C HNCs, and 160 °C HNCs. (a) I-V curves of thin-film photoconductors fabricated via AgBiS₂ QDs (red line), CsPbBr₃ NCs (black line), 150 °C HNCs (blue line), and 160 °C HNCs (green line), under illumination (450 nm light illumination with power of 12.50 mW cm⁻², bias of 1.0 V). (b) I-V curves under different illumination intensities (from 0.01 to 12.5 mW cm⁻²) for a 150 °C HNC photoconductor. The black line in (b) is the same one with the blue line in (a) (the same photodetector device with the same test conditions). (c–e) Photocurrent, responsivity (R) and detectivity (D^*), and I_{light}/I_{dark} ratio, respectively (bias of 1.0 V). (f) On–off switching behavior of 150 °C HNC photoconductor with varied illumination intensities of 12.50 (black line), 0.01 (purple line), 3.15 (red line), 0.13 (magenta line), and 0.63 (blue line) mW cm⁻², respectively (bias of 1.0 V).

combined effects of multiple factors, including changes of chemical states and electron concentration (Figure S13).

For the normalized PL spectra, 150 and 160 °C HNCs are blue-shifted in wavelength with respect to the control CsPbBr₃ NCs (Figure 2d), verifying the direct influence of the formation of the heterointerface (e.g., the surface etching of CsPbBr₃ NCs or Ag-doping on the excited-state properties). A similar blue-shift of PL spectra has also been witnessed in Au-CsPbBr₃ NCs,¹⁰ PbS-CsPbI₃ NCs,⁴⁷ and CsPbBr₃–PbS QDs.¹⁵ Steady-state UV–visible absorption of CsPbBr₃ NCs features a flat baseline within the >540 nm range (black line in Figure 2e). With the formation of HNCs, an additional absorption tail became prominent within the >520 nm range (an absorption band edge from 520 to 1200 nm). We ascribe the absorption tail to the AgBiS₂ domain of the HNCs, consistent with the steady-state UV–visible absorption of the AgBiS₂ QDs (red line in Figure 2e).

We employed ultrafast transient absorption (TA) spectra of CsPbBr₃ NCs and 150 °C HNCs within the range of 0.5 ps to 3.6 ns, to further investigate the transient carrier dynamics. The TA spectra of CsPbBr₃ NCs show typical ground state bleach (GSB) signals over a range of 490–650 nm (Figure 3a) and exciton bleach recovery kinetics in exponential x-axis (Figure 3b). The formation of heterostructure led to a substantial suppression of the CsPbBr₃ NC emission (Figure 3c), which is consistent with the CsPbBr₃–PbSe HNCs with a similar electronic structure.¹⁹ A 400 nm pump laser was employed in this measurement, which can excite ground state electrons in both CsPbBr₃ and AgBiS₂ domains to initially occupy highly dense energy states. Figure 3d illustrates the evolution of the TA signal for 150 °C HNCs. The TA spectra of CsPbBr₃ show GSB signals over a range of 490–530 nm (centered at 512 nm).^{22,48} Additional broadband GSB signals (780-1200 nm) were observed in 150 °C HNCs, corresponding to the indirect band gap in the UV-visible steady-state

absorption spectra. These broadband GSB signals are consistent with the reported GSB signals of AgBiS₂ QDs,⁴⁴ which are derived from the AgBiS₂ domain. We fixed the range of ordinates from -1.3 to 0.3 mOD and from -0.05 to 0.01 mOD, to trace the transient bleach decay of CsPbBr₃ and AgBiS₂ domains, respectively (Figure 3e,f). The GSB signal of the CsPbBr3 domain reached a negative maximum with the time of 0.5 ps, followed by a continuous recovery process due to the excited state electrons returning to the ground state. The GSB signal of the AgBiS₂ domain reached a negative maximum within 0.2 ps, and a rapid recovery appeared from 0.2 to 0.5 ps, followed by a new negative maximum from 0.5 ps to 0.5 ns. The new negative maximum of the AgBiS₂ GSB signal can be attributed to the transfer of the CB electron from CsPbBr₃ to AgBiS₂. The increased electron density in CB of AgBiS₂ brings a decreased absorption of the probe laser, leading to an amplified GSB signal.⁴⁹ Kaur et al. reported that the CsPbBr₃ bleach width is seen to be reduced in the CsPbBr3-PbS composite NCs, compared with CsPbBr₃ NCs.⁵⁰ They explained that bleach width is directly proportional to the number of carriers. A similar reduction can be observed in the 150 °C HNC bleach broadness (Figure 3g), which is a clear hint of carrier concentration dilution in the CsPbBr₃ domain. Beyond that, by comparing the normalized ΔA values of CsPbBr₃ NCs and 150 °C HNCs, the delay of the 150 °C HNC bleach can be found to be slower than that of CsPbBr₃ NCs for the same time. Similar to CsPbBr₃-PbS HNCs,⁵⁰ the bleach kinetics were observed to be more delayed in 150 °C HNCs than CsPbBr₃ NCs (Figure S14 and Table S1), which may be due to the hot charge carrier transfer and carrier delocalization. The kinetics probed at 512 nm for 150 °C HNCs shows a continuous attenuation of the bleach peak, and the broad GSB signal at 1000 nm shows a fluctuating trend of attenuation-rise-attenuation (Figure 3h). The whole carrier transfer process can be broken into four stages (Figure 3i):

ground state electron transition, the CB electron in the $AgBiS_2$ domain falling back to the VB, the continuous carrier (electron and hole) transfer from the CsPbBr₃ domain to $AgBiS_2$ domain, and the received CB electron in the $AgBiS_2$ domain falling back to the VB again (more discussion about analysis of TA spectra in Supplementary Text: Part-3).

The spatial decoupling of photogenerated electrons and holes in the CsPbBr₃ domain favors photoelectrical conversion. As a proof of concept, we fabricated photodetectors by spincoating thin-films on SiO₂/Si substrates with integrated Au interdigitated electrodes (3 μ m wide and 575 μ m long for a Au single electrode). The UV-visible absorption spectra, high profiles, and SEM images of thin-films prepared from different samples are shown in Figure S15-S17 (more discussion in Supplementary Text: Part-4). In order to evaluate the optoelectronic performance of the HNCs compared to that of CsPbBr₃ NCs or AgBiS₂ QDs, we obtained the I-V curves of the four different devices with 450 nm light illumination (Figure 4a). The detected current (voltage of 1.0 V) of the 150 °C HNC photodetector increases by 2, 297, and 1028 times compared with that of 160 °C HNCs, CsPbBr₃ NCs, and AgBiS₂ QDs photodetectors, respectively. The remarkable increase of the detected current of HNCs can be attributed to the strong light absorption of both CsPbBr₃ and AgBiS₂ domains and the effective charge carrier transfer across the heterointerface. Also, the performance of the photodetector is independent of the thickness of thin film when the thickness reaches a certain value (Figure S18).

Figure 4b shows the logarithmic I-V curves of the 150 °C HNC photodetector with different incident light intensities. At the same applied voltage, the detected current increased gradually with an increase in the light intensity from 0.01 to 12.5 mW cm⁻², which can be attributed to a change in the photon intensity from the incident light. The detailed calculative processes of photocurrent $(I_{\rm ph})$, responsivity (R), and specific detectivity (D^*) are shown in Supplementary Text: Part-4. Photocurrent (I_{ph}) was linearly dependent on the incident light intensity when plotted in log scale (Figure 4c). Responsivity (R) and specific detectivity (D^*) represent the performance of a photodetector with light illumination. It is noteworthy that under light intensity of 0.01 mW cm⁻², the photodetector fabricated by 150 °C HNCs reached a maximum value of R (183.8 A W⁻¹) and D^* (5.0 × 10¹⁴ Jones) (Figure 4d). The comparison of these parameters (calculated by using I_{dark}) for some previously reported CsPbBr₃ NCs and HNCs-based devices is shown in Table S2. The light-to-dark current ratio $(I_{\text{light}}/I_{\text{dark}})$ of the 150 °C HNC photodetector with various light intensities exhibits an analogous variation trend with photocurrent (Figure 4e). The maximum value of $I_{\text{light}}/I_{\text{dark}}$ can reach up to 5.8 × 10⁶ with the incident light intensity of 12.50 mW cm⁻² at the bias of 1.0 V. The response/recovery times of the 150 °C HNC photodetector were measured to be 4.1 ms/8.7 ms, respectively (Figure S19). Figure 4f shows the I-t characteristics of the 150 °C HNC photodetector with different incident light illuminations at the bias of 1.0 V. The detected current in the dark and under illumination was controlled by a light shutter. The 150 °C HNC photodetector exhibits excellent stability and reversibility under five different light intensities with four cycles of on/off switching. The schematic diagram of the photodetector and energy band diagram of HNCs are shown in Figure S20.

In conclusion, we for the first time synthesized the colloidal $CsPbBr_3-AgBiS_2$ HNCs, and employed TEM, HRTEM, EDS mappings, XRD and XPS measurements to display these two domains. TA measurement was employed to better understand the transient carrier dynamics, and four stages of the relaxation process were presented. Following the ultrafast charge carrier transfer, HNC-based devices show significantly improved photoconducting behavior (D^* of 5.0 × 10¹⁴ Jones). Compared with the control devices based on CsPbBr₃ NCs and AgBiS₂ QDs, the detected current of the 150 °C HNC photodetector increases by 297 and 1028 times, respectively. The results in this work complementing the progress on HNCs and opens up a new designer space for perovskite NCs toward advanced functionalities in optoelectronics, photocatalysis, and related fields.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.4c06595.

Additional experimental methods; supplementary text; additional TEM images and EDS mappings of HNCs; additional TEM images of corresponding control CsPbBr₃ NC samples; detailed XRD patterns, XPS spectra, and TA spectra of HNCs and corresponding control samples; additional *I*-*t* characteristics of thinfilm photoconductors made from HNCs and corresponding control CsPbBr₃ NCs; summary of device performance of photoconductors made from HNCs and CsPbBr₃ NCs; and comparison with reported photoconductors (PDF)

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Author Contributions

³H.Q. and Y.J. contributed equally to this work. H.Q., Y.J., L.Z., and M.L. conceived the concept, designed the experiments, and wrote the manuscript with input from all authors. H.Q. and Y.J. led the synthesis, characterization, device fabrication, and collection of TA spectra of different samples with help from W.H., F.L., D.J., and X.L., under the supervision of M.L. L.Z. and M.L. supervised the project. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work is supported partially by National Natural Science Foundation of China (grant numbers: 62404080, 62305111, 52303335, 52402255, 52232008, 51972110, 52102245, 52402254, and 22409061), Beijing Natural Science Foundation (2222076 and 2222077), 2022 Strategic Research Key Project of Science and Technology Commission of the Ministry of Education, Huaneng Group Headquarters Science and Technology Project (HNKJ20-H88), State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources (LAPS2024-05), the Fundamental Research Funds for the Central Universities (2024MS034, 2024MS073, 2024MS037, 2023MS042, and 2023MS047), the NCEPU "Double First-Class" Program, and National Key Research and Development Program of China (2024YFA1409900).

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