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High-efficiency visible-light-driven oxidation of primary C–H bonds in toluene over a CsPbBr₃ perovskite supported by hierarchical TiO₂ nanoflakes†

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Photocatalytic oxidation of toluene to valuable fine chemicals is of great significance, yet faces challenges in the development of advanced catalysts with both high activity and selectivity for the activation of inert C(sp³)-H bonds. Halide perovskites with remarkable optoelectronic properties have shown to be prospective photoactive materials, but the bulky structure with a small surface area and severe recombination of photogenerated electron-hole pairs are obstacles to application. Here, we fabricate a hierarchical nanoflower-shaped CsPbBr₃/TiO₂ heterojunction by assembling CsPbBr₃ nanoparticles on 2D TiO₂ nanoflake subunits. The design significantly downsizes the size of CsPbBr₃ from micrometers to nanometers, and forms a type II heterojunction with intimate interfacial contact between CsPbBr₃ and TiO₂ nanoflakes, thereby accelerating the separation and transfer of photogenerated charges. Moreover, the formed hierarchical heterojunction increases light absorption by refraction and scattering, offers a large surface area and enhances the adsorption of toluene molecules. Consequently, the optimized CsPbBr₃/TiO₂ exhibits a high performance (10 200 μmol g⁻¹ h⁻¹) for photocatalytic toluene oxidation with high selectivity (85%) for benzaldehyde generation under visible light. The photoactivity is about 20 times higher than that of blank CsPbBr₃, and is among the best photocatalytic performances reported for selective oxidation of toluene under visible light irradiation.

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Introduction

The direct oxidation of toluene to high-added-value fine chemicals, such as alcohols and aldehydes, is one of the most important conversions in the chemical industry.^{1–4} However, due to the inertness and high bond dissociation energy (89.8 kcal mol⁻¹) of the C(sp³)-H bond,⁵ the activation of toluene generally needs to be performed under harsh reaction conditions (high pressure and temperature) and with the assistance of specific metal complexes or aggressive oxidants, which is expensive, energy intensive and causes negative impacts on the environment.^{6–8} Solar-driven photocatalytic aerobic oxidation using molecular O₂ as an oxidant represents a promising method-

ology to overcome these challenges, but the overall photocatalytic performance reported so far is still unsatisfactory due to the lack of desired photocatalysts with broad optical absorption windows, efficient charge separation, and high product selectivity.^{9–11}

Over the past years, halide perovskite materials have triggered wide attention in photocatalysis because of their outstanding optical and electronic properties.^{12–16} High charge carrier mobility, visible light absorption, and tunable band structures enable them to be potential competitors for photocatalytic oxidation of toluene.^{17,18} Nevertheless, single-component halide perovskites typically evolve into bulky aggregates with a large particle size (several to tens of micrometers), which leads to severe bulk recombination of charge carriers and restricts the photoactivity.^{19,20} To tackle this problem, the construction of a heterojunction is an effective strategy. Hybridization of the halide perovskite with preferred substrates not only can prevent the aggregation of the halide perovskite to mediate the bulk recombination of photoexcited electron-hole pairs, but also can establish an interfacial built-in electric field to further facilitate the spatial charge transfer and separation.²¹

Moreover, the catalytic functions of photocatalysts also strongly depend on the nanostructure.^{22,23} To realize high

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photocatalytic performance, the delicate design of a well-defined nanostructure for heterojunction composites is also critical.^{24–27} For diverse structural configurations, 3D hierarchical flower-like nanostructures constructed using 2D nanoflake subunits have demonstrated intrinsic advantages for photocatalysis. Such hierarchical structures can strengthen the light absorption of photocatalysts by multi-light reflection and scattering within the nanoflake subunits, and prohibit the aggregation of 2D nanoflakes to afford a large surface area with abundant active sites.^{28,29} In addition, the nanoflake subunits will greatly shorten the diffusion path of charges, thereby facilitating the separation and transfer of photogenerated charges to the surface for redox reactions.^{30,31} Thus, the development of advanced 2D subunit-assembled hierarchical structures with a heterogeneous junction would be promising for high-efficiency photocatalytic toluene oxidation.

Here, inspired by the above considerations, we design and fabricate a hierarchical nanoflower-shaped CsPbBr₃/TiO₂ (abbreviated as CPB/TiO₂) heterojunction composed of TiO₂ nanoflake-supported all-inorganic CsPbBr₃ perovskite nanoparticles. Benefiting from the composition and nanostructure engineering, the CPB/TiO₂ heterojunction displays excellent performance for photocatalytic toluene oxidation under the irradiation of visible light. The optimized 20%CPB/TiO₂ heterojunction composite delivers a toluene conversion rate of 10 200 μmol g⁻¹ h⁻¹ and a high selectivity of 85% towards benzaldehyde (benzyl alcohol as the main by-product). This performance outperforms most of the state-of-the-art catalysts in the literature for visible-light-driven oxidation of toluene. This work provides a new idea by constructing a hierarchical heterojunction structure over halide perovskite materials for high-efficiency photocatalytic toluene conversion.

Experimental section

Materials

Cesium bromide (CsBr, 99.999%), lead bromide (PbBr₂, 99.0%) and tetrahydrofuran (THF) were purchased from Macklin (Shanghai, China). *N,N*-Dimethylformamide (DMF), toluene, tetrabutyl titanate (TBOT), ethanol (EtOH), concentrated hydrochloric acid (HCl, 36%), acetic acid and glycerol were obtained from Sinopharm Chemical Reagent Co., Ltd (Shanghai, China). All chemicals and solvents were used without further purification.

Synthesis of mesoporous hierarchical TiO₂ nanoflowers

Typically, 1.5 g of Pluronic F127 was dispersed in a mixed solvent of 2.4 mL of acetic acid, 3.2 mL of concentrated hydrochloric acid (HCl) and 30 mL of tetrahydrofuran (THF). After vigorously stirring for 20 min, 3.4 mL of tetrabutyl titanate (TBOT) and 0.2 mL of H₂O were added subsequently to obtain a clear primrose yellow solution. After that, the solution was dried in an oven at 45 °C for 24 h to form a light-yellow gel. Then, 1.0 g of the gel was added into 25 mL of ethanol (EtOH) and 5 mL of glycerin under vigorous stirring. After 20 min, the

transparent solution was transferred to a 50 mL Teflon-lined autoclave, heated at 150 °C for 15 h, and then cooled naturally to room temperature. The precipitate was washed with ethanol and dried in an oven at 60 °C.³² Finally, the precipitate was calcined in a muffle furnace at 400 °C for 5 h at a heating rate of 1 °C min⁻¹ to obtain the hierarchical TiO₂ nanoflowers. To synthesize the collapsed TiO₂ without the hierarchical nanoflower structure, the precipitate was calcined in the same muffle furnace at 400 °C for 5 h, but at a heating rate of 5 °C min⁻¹.

Synthesis of CsPbBr₃/TiO₂ composites and blank CsPbBr₃

CsPbBr₃/TiO₂ composites were synthesized according to an antisolvent precipitation method at room temperature.³³ Typically, 1 mmol CsBr and 1 mmol PbBr₂ were dissolved in 10 mL of *N,N*-dimethylformamide (DMF) by ultrasonication to form a precursor solution. Meanwhile, 100 mg of TiO₂ was dispersed in 10 mL of DMF and stirred to form a uniform white dispersion. Then a certain amount of the CsPbBr₃ precursor solution was added into the TiO₂ dispersion under ultrasonication. Then, the mixture was added dropwise into 50 mL of toluene and stirred vigorously for 30 min. After that, the solution was centrifuged at 8000 rpm for 3 min. The precipitate was collected and dried in a vacuum oven. A series of *x*% CsPbBr₃/TiO₂ composites were synthesized by changing the volume of the added CsPbBr₃ precursor solution, where *x* is the mass ratio of CsPbBr₃ in the composite (*x* = 10, 20, 30, and 40). Blank CsPbBr₃ was prepared by the same procedure without the addition of TiO₂.

Characterization

Scanning electron microscopy (SEM) images were captured using a Hitachi 8100. Transmission electron microscopy (TEM) and high-resolution transmission electron microscopy (HRTEM) images were recorded using a JEM-2100F EX microscope at an accelerating voltage of 200 kV. The Brunauer–Emmett–Teller (BET) specific surface area was measured using an N₂ adsorption–desorption instrument (BELSORP-mini II). The X-ray diffraction (XRD) patterns of the catalysts were characterized on a Bruker D8 Advance X-ray diffractometer operated at 40 kV and 40 mA with Cu Kα radiation and 2θ ranging from 10° to 80°. The UV-vis diffuse reflectance spectra (DRS) were obtained on a CARY-100 spectrophotometer (Agilent) using 100% BaSO₄ powder as a standard sample. X-ray photoelectron spectroscopy (XPS) spectra were recorded using an X-ray photoelectron spectrometer (Thermo Escalab 250 electron spectrometer) with Al-Kα radiation. Raman spectra were obtained using a laser at a wavelength of 785 nm (Thermo Fisher Scientific, DXR 2xi). Photoluminescence (PL) spectra of solid samples were obtained using an RF-5301PC spectrophotometer (Shimadzu, Japan) with a 435 nm excitation wavelength.

Electron paramagnetic resonance (EPR) measurements were performed at room temperature using a Magnettech ESR5000X spectrometer. In general, 10 mg samples were dispersed in a mixed solution of 2 mL of CH₃CN containing 1 mL

of toluene and 2 μL of 5,5-dimethyl-1-pyrroline-*N*-oxide (DMPO). The suspension was then transferred into a glass capillary. The sealed glass tube was then placed in the microwave cavity of an EPR spectrometer and exposed to a 300 W Xe lamp source (CEL-PF300-T8, Beijing China Education Au-light Co., Ltd) at room temperature.

Photoelectrochemical measurements

The photoelectrochemical analysis was carried out in a conventional three-electrode cell using a Pt plate and an Ag/AgCl electrode as the counter electrode and the reference electrode, respectively. The working electrode was prepared on fluorine-doped tin oxide (FTO) glass that was cleaned by ultrasonication in ethanol for 1 h. Typically, 5 mg of the catalyst was dispersed in 0.5 mL of isopropanol to obtain a slurry. After that, 20 μL of the slurry was dropped onto FTO with a size of 1 cm^2 and dried in air. The electrochemical impedance spectroscopy (EIS) measurement was performed in an electrolyte of tetrabutylammonium hexafluorophosphate (TBAPF₆) in ethyl acetate (EA). The transient photocurrent was tested in the same electrolyte and a 300 W xenon lamp (CEL-PF300-T8, Beijing China Education Au-light Co., Ltd) equipped with a 420 nm cutoff filter ($\lambda \geq 420$ nm) was used as the light source. Mott–Schottky measurement was performed in an electrolyte of 0.1 M TBAPF₆ in CH_2Cl_2 .

Density functional theory (DFT) calculations

DFT calculations were carried out using the Vienna *ab initio* simulation package (VASP) with the projector-augmented-wave (PAW) method.³⁴ The Perdew–Burke–Ernzerhof (PBE) scheme was used for the exchange correlation function, employing the generalized gradient approximation (GGA).³⁵ The electronic wave function was expanded using a plane wave basis with an energy cutoff of 500 eV. The energy convergence criterion was set to 1.0×10^{-5} eV, and the force convergence criterion was set to 0.03 eV \AA^{-1} for each atom. For the CsPbBr₃ (110) and TiO₂ (101) slabs, a $6 \times 3 \times 1$ and $3 \times 9 \times 1$ *k*-point mesh was used, respectively. A 30 \AA vacuum layer along the *z*-direction was used to prevent unintended periodic interactions between adjacent slabs. The CsPbBr₃/TiO₂ heterostructure model consists of two CsPbBr₃ layers and one TiO₂ layer, with a 20 \AA vacuum space along the *z*-direction. To save computing resources, a $1 \times 1 \times 1$ *k*-point mesh was employed for the CsPbBr₃/TiO₂ heterostructure. The van der Waals interactions between TiO₂ and CsPbBr₃ were taken into account using the DFT-D3 correction method.

Photocatalytic activity measurements

All photocatalytic reactions were conducted in a quartz reactor. Typically, 10 mg of the photocatalyst and 1 mL of toluene (9.4 mmol) were dispersed in a reactor containing 2 mL of acetonitrile. The reactor was purged with O₂ for 10 min, and then irradiated with visible light ($\lambda > 420$ nm) using a 300 W xenon lamp (CEL-PF300-T8, Beijing China Education Au-light Co., Ltd). After light irradiation for 2 h, the liquid product was analyzed by gas chromatography (GC-2030, Shimadzu, Japan,

FID detector, nitrogen (N₂) as the carrier gas) after centrifuging the suspension at 10 000 rpm for 3 min.

Results and discussion

Characterization of catalysts

The 3D hierarchical CPB/TiO₂ heterostructure was prepared by a simple anti-solvent precipitation method with the addition of TiO₂ nanoflowers into the precursor solution of CsPbBr₃, as schematically illustrated in Fig. 1a. X-ray diffraction (XRD) was exploited to characterize the crystal structure of blank CsPbBr₃, CPB/TiO₂ composites and TiO₂. As shown in Fig. 1b, the diffraction peaks at 15.1°, 21.5°, 30.7°, 34.4°, and 43.8° can be ascribed to the monoclinic CsPbBr₃ (100), (110), (200), (210) and (220) planes (JCPDS no. 18-0364).^{36–38} In addition, the peaks at 25.3°, 37.7°, 48.0°, 53.8°, 55.0°, and 62.6° can be attributed to the (101), (004), (200), (105), (211), and (204) planes of anatase TiO₂, respectively.³² The XRD patterns of CPB/TiO₂ composites indicate both characteristic peaks of CsPbBr₃ and TiO₂, and the peak intensity of CsPbBr₃ increases as the CsPbBr₃ content increases (Fig. S1†).

Raman spectra were used to further confirm the composition of the synthesized catalysts. As shown in Fig. 1c, the peaks at 151 cm^{-1} (E_g), 403 cm^{-1} (E_g), 523 cm^{-1} (A_{1g} + B_{1g}), and 646 cm^{-1} (E_g) belong to the anatase TiO₂ vibration modes. A new peak of 74 cm^{-1} assigned to the vibrational mode of the [PbBr₆]⁴⁻ octahedron of CsPbBr₃ is observed in the CPB/TiO₂ composite.^{39–41} The characteristic peak of CsPbBr₃ is also enhanced with the increment of the loading amount of CsPbBr₃ (Fig. S2†). This coincides with the XRD analysis, validating the successful preparation of the CPB/TiO₂ composites. Notably, after the growth of CsPbBr₃ on the TiO₂ nanosheets, the Raman peaks of TiO₂ shift to a lower wavenumber compared to that of blank TiO₂. The shift indicates an increase in the bond length and a decrease in the bond energy of the Ti–O bond, which can be attributed to the strong electrostatic interaction between CsPbBr₃ and TiO₂.^{42–45} Fig. 1d shows the UV-vis diffuse reflectance spectroscopy (DRS) analysis of the samples, which is employed to assess the optical absorption properties. It can be seen that the light absorption edge of blank TiO₂ is around 390 nm, denoting its UV light response nature. After integrating with CsPbBr₃, the light absorption of CPB/TiO₂ is extended to approximately 540 nm. Meanwhile, the absorption edge of TiO₂ at 390 nm can also be detected. This should be ascribed to the hybridization of the high weight content of CsPbBr₃ with the TiO₂ support. As such, both absorption features are present in the composite. The greatly extended light absorption enables the visible light excitation of the CPB/TiO₂ composites, which is beneficial for promoting solar energy utilization. With the increase of the CsPbBr₃ content, the visible light absorption of CPB/TiO₂ is also gradually enhanced (Fig. S3†). Moreover, in comparison with blank CsPbBr₃, it is notable that the visible light absorption edge of the hybrid CPB/TiO₂ composite is slightly blue shifted (*ca.* 14 nm). This can be attributed to the quantum size

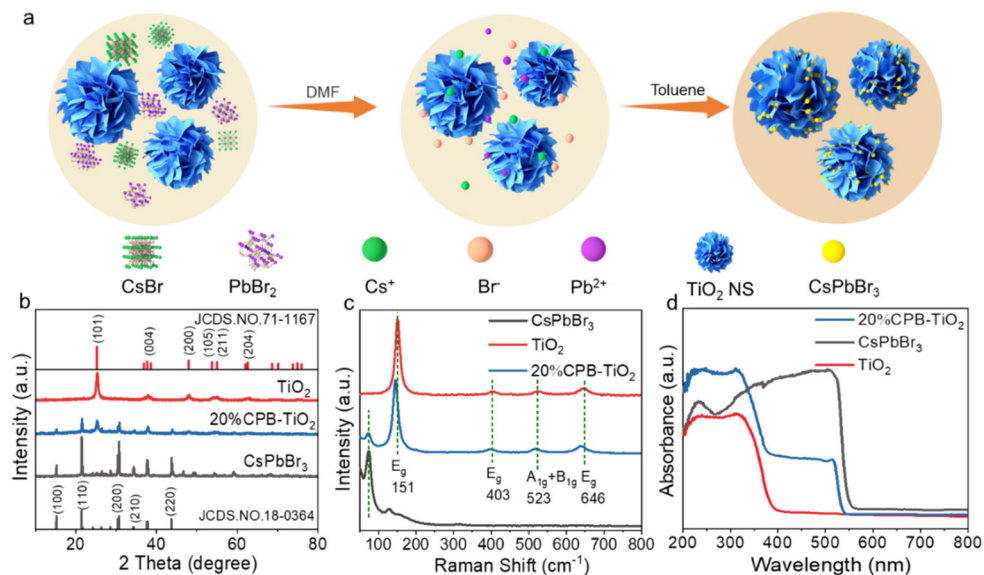


Fig. 1 (a) Schematic diagram of the synthesis of 3D nanoflower-shaped CPB/TiO₂ heterostructure. (b) XRD patterns, (c) Raman spectra, and (d) UV-vis DRS spectra of CsPbBr₃, CPB/TiO₂ and TiO₂.

effect resulting from the smaller size of CsPbBr₃ in the composite. The inference has been demonstrated by the following scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analyses.

As shown in Fig. 2, Fig. S4 and S5,[†] SEM is firstly utilized to characterize the morphology and microstructure of the CPB/TiO₂, blank TiO₂ and CsPbBr₃ samples. The blank TiO₂ presents a nanoflower shape, which is assembled by vertical nano-

flakes (Fig. S4[†]). The surface of the nanoflake subunits is clean and smooth. For blank CsPbBr₃, it shows a large particle morphology and the particle sizes range from 0.9 to 2.0 μm (Fig. S5[†]). After the construction of the CPB/TiO₂ heterojunction, the TiO₂ nanoflower-shaped structure is maintained (Fig. 2), while the surface of the nanoflake subunits becomes rough due to the *in situ* growth of CsPbBr₃. From Fig. 2b–i, it can be clearly seen that for all the CPB/TiO₂ samples, the sizes

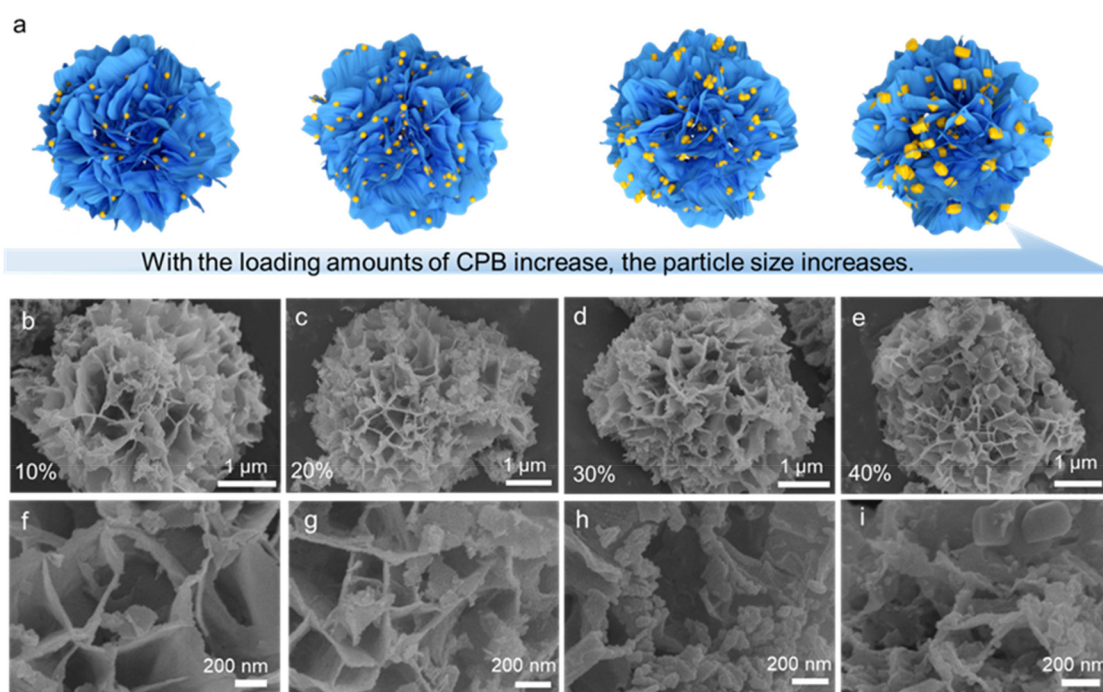


Fig. 2 (a) Schematic and (b–i) SEM images showing the morphology evolution of x% CPB/TiO₂ (where x = 10, 20, 30, and 40) composites.

of the CsPbBr₃ particles in the composites are much smaller than that of blank CsPbBr₃, indicating that the formation of a heterojunction is beneficial for preventing the aggregation and reducing the size of the CsPbBr₃ halide perovskite. This can be ascribed to the fact that the presence of TiO₂ nanoflowers with nanoflake subunits can act as heterogeneous nucleus sites to facilitate the nucleation and growth of CsPbBr₃, which generates more seeds and leads to the smaller size of the CsPbBr₃ particles.²⁰ The significantly decreased particle size could greatly promote the exposure of surface active sites and inhibit the charge recombination of CsPbBr₃ under light irradiation. Moreover, it is notable that with the increase of the CsPbBr₃ contents from 10% to 40% in the composites, the particle sizes of CsPbBr₃ are increased, as schematically illustrated in Fig. 2a. This can be attributed to the further growth of CsPbBr₃ at high concentrations.

To further obtain the microscopic structural information of the samples, transmission electron microscopy (TEM) analysis is carried out. Taking 20%CPB/TiO₂ as an example, the TEM image of the sample (Fig. 3a and b) shows a nanoflake structure of TiO₂. The surface is rough and densely covered by small CsPbBr₃ nanoparticles. Since the sample for TEM analysis is prepared by strong ultrasonication, the well-defined CsPbBr₃ nanoparticles on the 2D nanoflake surface indicate intimate interfacial contact between the two components. Meanwhile, the intensive coverage of CsPbBr₃ forms a large contact interface with TiO₂ nanoflakes, which is conducive to the migration of charge carriers across the CPB/TiO₂ heterojunction.⁴⁶ Moreover, nanopores can be observed on the CPB/TiO₂, which results from the mesoporous structure of the TiO₂ nanoflakes, as demonstrated by the N₂ adsorption-desorption analysis (Fig. S6†). The high-resolution TEM (HRTEM) image (Fig. 3c) shows distinct lattice fringes of 0.35 nm and 0.41 nm, corresponding to the (101) planes and (110) planes of anatase

TiO₂ and monoclinic CsPbBr₃, respectively. Furthermore, Fig. 3d shows the corresponding energy dispersive X-ray spectroscopy (EDS) elemental mapping analysis of 20%CPB/TiO₂. Cs, Pb, Br, Ti and O elements are uniformly distributed on the nanoflake structure, indicating that CsPbBr₃ and TiO₂ are well combined. The results further verify the formation of CPB/TiO₂ hybrid composite with intimate interfacial contact. Moreover, in comparison with blank TiO₂, the 20%CPB/TiO₂ composite displays a smaller specific surface area (Table S1†), which can be attributed to the fact that the growth of CsPbBr₃ nanoparticles on the surface of TiO₂ may aggregate in the TiO₂ pores. Correspondingly, the total pore volume of 20%CPB/TiO₂ is also slightly lower than that of blank TiO₂. The result matches with the SEM measurement.

To study the surface chemical states of the samples, X-ray photoelectron spectroscopy (XPS) has been performed. As shown in Fig. 4a, the presence of Cs, Pb, Br, O and Ti elements can be detected from the XPS survey spectrum of CPB/TiO₂. The high-resolution spectrum of Ti 2p shows two peaks of Ti 2p_{3/2} and Ti 2p_{1/2} at 458.5 eV and 464.2 eV (Fig. 4b), which indicates that Ti element mainly exists as Ti⁴⁺ ions. For the O 1s pattern (Fig. 4c), it can be divided into two peaks, which are attributed to the lattice O (Ti–O) and hydroxyl O (–OH). Fig. S7† shows the fine-scanned Cs 3d XPS spectrum, and the two peaks with binding energies at 724.2 eV and 738.1 eV are assigned to Cs 3d_{5/2} and Cs 3d_{3/2}, indicating that the chemical state of the Cs in the composite is +1. The Pb 4f spectrum in Fig. 4d shows characteristic peaks at 138.0 eV and 142.9 eV, corresponding to Pb 4f_{7/2} and Pb 4f_{5/2} orbitals of Pb²⁺ ion. Moreover, the Br 3d is decomposed into two peaks at 67.9 eV and 68.9 eV, corresponding to the binding energies of Br 3d_{5/2} and 3d_{3/2}, attributed to the presence of Br[–] (Fig. 4e). It is worth noting that for the CPB/TiO₂ composite, the Ti 2p and O

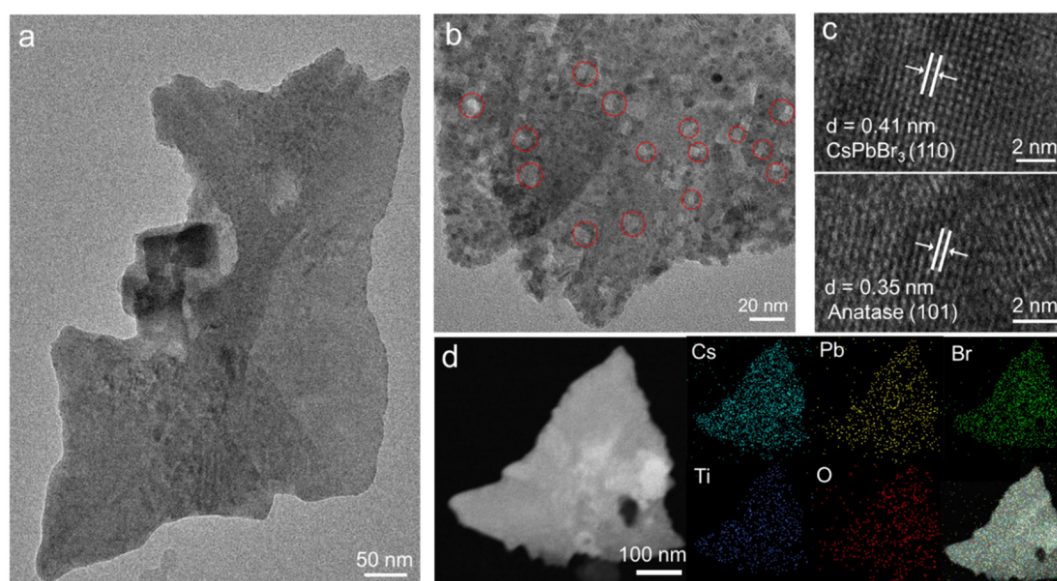


Fig. 3 (a and b) TEM images, (c) HRTEM image, and (d) corresponding EDS elemental mapping images of 20%CPB/TiO₂.

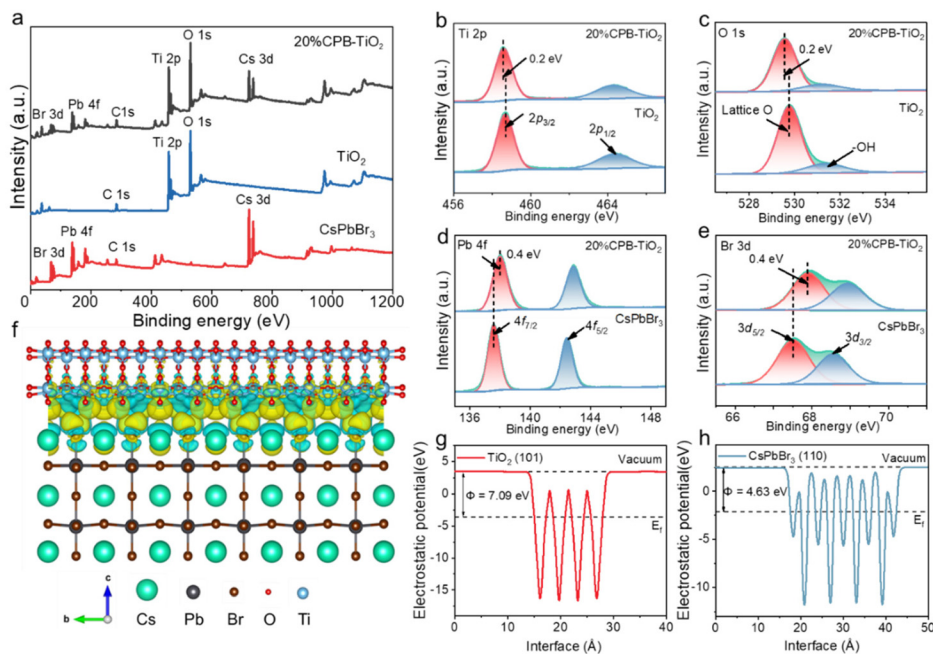


Fig. 4 XPS spectra of CsPbBr₃, TiO₂ and 20%CPB/TiO₂: (a) survey, (b) Ti 2p, (c) O 1s, (d) Pb 4f and (e) Br 3d. (f) Charge density differences in the CPB/TiO₂ composite. (g and h) The work functions of blank TiO₂ and CsPbBr₃.

1s peaks show a negative shift of 0.2 eV in comparison with blank TiO₂ (Fig. 4b and c). In contrast, the binding energies of Cs 4d, Pb 4f, and Br 3d in the CPB/TiO₂ show a positive shift (Fig. 4d and e and S7[†]), which are higher than those of blank CsPbBr₃ by 0.4 eV. The results verify the strongly interacted interface with electron transfer from the CsPbBr₃ to the TiO₂ nanosheets in the heterostructure, which is in accordance with the Raman analysis. To further clarify the interaction and electron transfer at the interface, density functional theory (DFT) calculations have been carried out. Fig. 4g and h shows the work functions of the TiO₂ (101) and CsPbBr₃ (110) slabs, which are 7.09 eV and 4.63 eV, respectively, corresponding to the Fermi levels (E_f) of -3.61 eV and -2.51 eV (vs. the vacuum level). Due to the lower E_f value of TiO₂ than that of blank CsPbBr₃, the electrons would be migrated from CsPbBr₃ to TiO₂ at the heterojunction interface until their E_f are aligned. A similar result is obtained from the calculated planar-averaged charge density difference of CPB/TiO₂. As shown in Fig. 4f, the light cyan and yellow regions indicate the charge depletion and accumulation area, respectively. The calculation results reveal that the cyan region is mainly on the CsPbBr₃ side, while the yellow region is on the TiO₂ side, further validating the transfer of electrons from CsPbBr₃ to TiO₂. This is consistent with the XPS analysis results.

Photocatalytic performances

Collectively, the above characterization faithfully verifies the successful fabrication of CPB/TiO₂ hybrid composites with intimate interfacial contact and strong chemical interaction. The presence of TiO₂ nanoflower with 2D nanoflake subunits greatly inhibits the agglomeration of the halide perovskites,

while CsPbBr₃ extends the light absorption range of TiO₂. In view of the desired structural and optical properties, the photocatalytic oxidation of toluene over the hybrid CPB/TiO₂ composites has been tested. A 300 W xenon lamp equipped with a 420 nm cutoff filter is utilized as a visible light source. It is well known that the solvent/reactant ratio has great influence on the oxidation of toluene,^{2,47} and thus, the reaction condition of different acetonitrile/toluene ratio is firstly optimized using 20%CPB/TiO₂ as an example. As shown in Fig. 5a, as the ratio of toluene increases from 0.3 to 1 mL, the photoactivity of the 20%CPB/TiO₂ composite gradually increases. The catalyst shows the highest toluene conversion rate of $10\,200\ \mu\text{mol g}^{-1}\ \text{h}^{-1}$ when the volume ratio of acetonitrile solvent and toluene reactant is 2 : 1. The enhanced photoactivity can be attributed to the fact that the increased toluene concentration enhances the reaction possibility between the photogenerated charge carriers and the toluene molecules. However, further increase of toluene to 1.5 mL and 2 mL decreases the conversion rate. This might be ascribed to the excess adsorption of the toluene reactant on the catalyst surface, which would slow down the desorption of the BA and BAD products and suppress the oxidation activity.⁴⁸ Based on the result, the following photoactivity tests of all the other samples are carried out under the optimized condition with a acetonitrile/toluene ratio of 2 : 1.

Fig. 5b shows the visible-light-driven photocatalytic performances of the blank CsPbBr₃ and CPB/TiO₂ composites with different ratios of CPB for the selective oxidation of toluene. The blank CsPbBr₃ exhibits a low activity with generation rates of $390\ \mu\text{mol g}^{-1}\ \text{h}^{-1}$ for BAD and $130\ \mu\text{mol g}^{-1}\ \text{h}^{-1}$ for BA. The unsatisfactory photocatalytic performance should

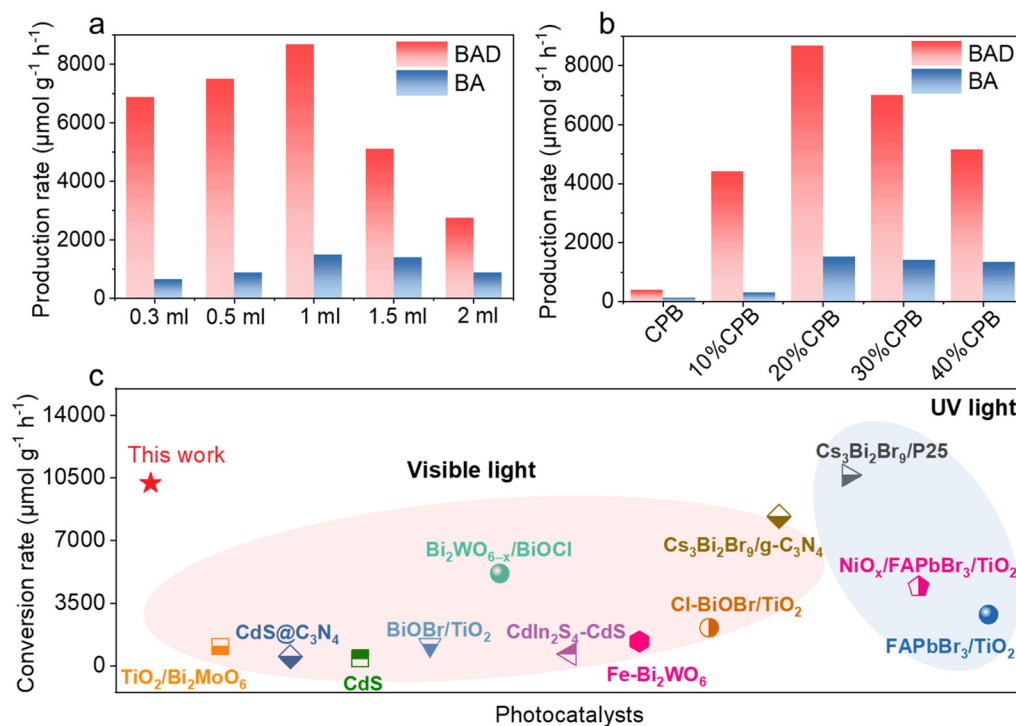


Fig. 5 (a) Photocatalytic oxidation of toluene with different toluene amounts in acetonitrile solvent over 20%CPB/TiO₂. The total volume is 3 ml. (b) Photocatalytic oxidation of toluene over blank TiO₂, CPB/TiO₂ composite and blank CsPbBr₃. (c) Performance comparison with reported photocatalysts for UV and visible-light-driven selective oxidation of toluene.








be due to the severe charge recombination caused by the large particle size of CsPbBr₃. For blank TiO₂, it presents no activity. This is reasonable since the TiO₂ has no visible light absorption and cannot be excited by visible light. In contrast, after the hybridization of CsPbBr₃ with TiO₂, the photocatalytic performances of all the hierarchical CPB/TiO₂ heterojunctions are significantly improved. The best photocatalytic toluene oxidation activity is achieved over the 20%CPB/TiO₂ composite, which shows a toluene conversion rate of 10 200 $\mu\text{mol g}^{-1} \text{h}^{-1}$ (with a BAD production rate of 8670 $\mu\text{mol g}^{-1} \text{h}^{-1}$ and a BA generation rate of 1530 $\mu\text{mol g}^{-1} \text{h}^{-1}$). The photoactivity is about 20 times higher than that of blank CsPbBr₃, which is also among the top photocatalytic performances reported so far for UV and visible-light-driven selective oxidation of toluene (Fig. 5c and Table S2[†]). The apparent quantum efficiency (AQE) of the 20%CsPbBr₃/TiO₂ composite reaches 2.9% at $\lambda = 420 \text{ nm}$ for the transformation of toluene into BA and BAD (Fig. S14[†]). The gas chromatography-mass spectrometry (GC-MS) analysis of the reaction solution after light irradiation reveals four peaks, which are ascribed to the acetonitrile solvent, toluene reactant, BAD and BA products (Fig. S8[†]). No other product or intermediate is detected, validating the high selectivity of the reaction. With the increase of CsPbBr₃ loading to higher contents (30% and 40%), it results in a performance degradation. This may be ascribed to the fact that: (1) an excess of halide perovskite tends to aggregate into large particles, which will lead to longer migration distances of charge carriers and increase charge recombination; (2) the

coverage of excessive and oversized CsPbBr₃ on the TiO₂ surface will lead to the reduction of the exposed surface area, inhibiting the adsorption of toluene molecules.

Furthermore, the broad applicability of the CPB/TiO₂ photocatalyst is investigated for the photocatalytic selective oxidation of C(sp³)-H of toluene derivatives with different substituents. As shown in Table 1, these aromatics are efficiently converted into the corresponding aldehydes and alcohols. The selectivity for the aldehyde product is higher than 70%. Notably, the substrate with electron-withdrawing substituents (-F, -Cl, and -Br) displays lower photocatalytic activity. This can be attributed to the fact that the electron-withdrawing groups on the benzene ring inhibit the abstraction of hydrogen from the methyl group.^{49,50} In addition, *p*-xylene shows a higher toluene conversion rate (12 746 $\mu\text{mol g}^{-1} \text{h}^{-1}$) than its isomers of *o*-xylene (9900 $\mu\text{mol g}^{-1} \text{h}^{-1}$) and *m*-xylene (10 930 $\mu\text{mol g}^{-1} \text{h}^{-1}$), which can be attributed to the steric hindrance of the methyl groups hindering the reactant adsorption and activation on the catalyst surface.^{51,52}

Moreover, the cycle test of the 20%CsPbBr₃/TiO₂ has been carried out. After repeating the photoactivity test for 4 cycles (Fig. S16[†]), the catalyst still maintains a high activity with negligible decrease in the conversion rate of toluene. In addition, the used 20%CsPbBr₃/TiO₂ has been further characterized by XRD and XPS (Fig. S17 and S18[†]). No obvious change in the crystal structure and surface chemical state is observed for the composite before and after the reaction. These results indicate the high stability of the CsPbBr₃/TiO₂ composite.

Table 1 Photocatalytic oxidation of C(sp³)-H in substituted toluene over 20%CPB/TiO₂^a

Entry	Substrates	Conversion rate ($\mu\text{mol g}^{-1} \text{h}^{-1}$)	Selectivity (%)	
			A	B
1		10 200	85	15
2		5950	83	17
3		9040	88	12
4		9770	87	13
5		9900	76	24
6		10 930	72	28
7		12 746	71	29

^a Reaction conditions: catalyst (10 mg 20%CPB/TiO₂), substrate (1 mL), MeCN (2 mL), 1 atm of O₂, 2 h irradiation with visible light ($\lambda > 420 \text{ nm}$).

Photoelectric properties

In order to better understand the reasons for the improved photocatalytic performance, the band structures of the CsPbBr₃ and the TiO₂ are investigated using Mott-Schottky (M-S) measurements and the DRS analysis. As shown in Fig. 6a and b, the positive slopes indicate that CsPbBr₃ and TiO₂ are typical n-type semiconductors.⁵³ The flat band potentials (E_{FB}) are calculated to be -0.86 V and -0.34 V (vs. NHE) for CsPbBr₃ and TiO₂, respectively. Usually, the conduction band potential (E_{CB}) for an n-type semiconductor is more negative of about 0.1 eV than that of E_{FB} .⁵⁴ Thus, the E_{CB} values of CsPbBr₃ and TiO₂ are determined to be -0.96 V and -0.44 V (vs. NHE), respectively. In addition, the corresponding bandgaps of TiO₂ and CsPbBr₃ are estimated by Tauc plots transformed from the DRS spectra (Fig. S9†), which are 3.20 eV and 2.28 eV, respectively. Based on these, the valence band positions (E_{VB}) of CsPbBr₃ and TiO₂ are calculated to be 1.32 V and 2.76 V. As a result, a type-II heterojunction is formed between CsPbBr₃ and TiO₂ because of the staggered band structures.

To study the influence of the heterojunction structure on the transfer behavior of photogenerated charge carriers, transient photocurrent and electrochemical impedance spectra (EIS) tests are performed. As shown in Fig. 6c, under visible light irradiation, both CsPbBr₃ and CPB/TiO₂ show rapid and stable photocurrent responses, while TiO₂ does not. This can be

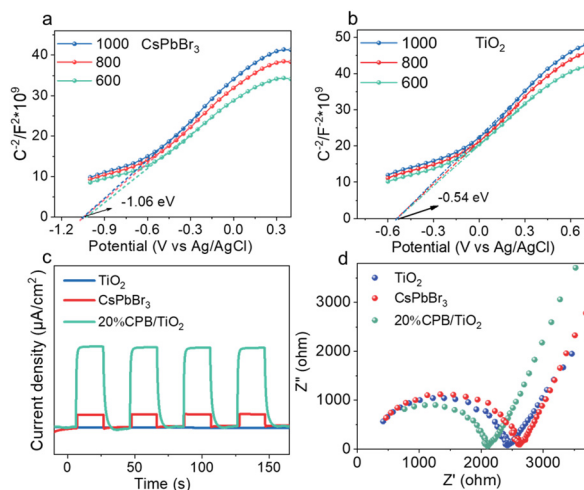


Fig. 6 (a and b) M-S plots of CsPbBr₃ and TiO₂. (c) Transient photocurrent responses, and (d) EIS Nyquist plots of blank TiO₂, CsPbBr₃ and the CPB/TiO₂ composite.

attributed to the inability of TiO₂ to be excited by visible light (Fig. 1d). The photocurrent intensity of blank CsPbBr₃ is markedly lower than that of 20% CPB/TiO₂. This should be due to the agglomerated large particle size of the blank CsPbBr₃, which leads to a severe recombination of photogenerated charge carriers.⁵⁴ Moreover, Fig. 6d shows the Nyquist plots of the samples, which is employed to investigate the interfacial charge transfer efficiency.⁵⁵ In general, the smaller diameter of the semicircular arc in the Nyquist plots reflects the lower electron transfer resistance. It can be found that the 20%CPB/TiO₂ sample has the minimum arc radius, which means the best electronic conductivity and charge separation ability.^{56,57} Furthermore, the steady-state photoluminescence (PL) spectra are also used to examine the charge separation efficiency. As shown in Fig. S19,† the 20%CsPbBr₃/TiO₂ composite shows a much lower PL intensity than that of CsPbBr₃, revealing that the charge recombination is significantly suppressed in the composite. In addition, the TiO₂ shows no obvious PL signal. This is in accordance with the photocurrent analysis that the TiO₂ is unable to be excited to generate charge carriers by visible light. These photoelectrochemical findings highlight that the construction of the type-II heterojunction between CsPbBr₃ and TiO₂ could effectively accelerate charge transfer, thus contributing to improving the photocatalytic performance.

Furthermore, for heterogeneous photocatalytic reactions, the effective adsorption of the reactant on the catalyst surface is another requisite for the ignition of the redox reaction.^{23,58–60} The BET surface area and porous structure analyses of the TiO₂, CsPbBr₃ and 20%CPB/TiO₂ samples have shown that the introduction of TiO₂ nanoflower significantly improves the specific surface area and pore volume of 20% CPB/TiO₂ in comparison with that of blank TiO₂ (Fig. S6 and Table S1†). Generally, a larger specific surface area and a porous structure enable better adsorption capacity, and

exposure of more active sites of catalysts. To further reveal the contribution of the heterostructure for the reactant adsorption, Fourier transform infrared (FTIR) spectroscopy is used to identify the adsorbed toluene species on the CsPbBr₃, TiO₂ and 20%CPB/TiO₂ surface. As shown in Fig. 7a, for all three samples after adsorption equilibrium, the typical absorption peaks of toluene are observed, including the C–H stretching vibration of the aromatic ring at 3083 and 3038 cm⁻¹, the skeleton vibration of the aromatic ring at 1606 and 1495 cm⁻¹, and the C–H symmetric and asymmetric stretching of the methylene group at 2934 and 2875 cm⁻¹.^{61,62} Notably, the signal of toluene molecules of 20%CPB/TiO₂ is obviously higher than that of blank CsPbBr₃, yet is lower than that of blank TiO₂. The result indicates that the introduction of TiO₂ can promote the toluene adsorption capacity of CPB/TiO₂, which is conducive to the catalytic conversion.

Finally, to investigate the influence of the hierarchical flower-like nanostructure constructed using 2D nanoflake sub-units on the photocatalytic performance, a collapsed 20%CPB/TiO₂ catalyst (marked as 20%CPB/TiO₂-C) without such structure has been fabricated for comparison. As shown in Fig. 7b, the photoactivity test reveals that the 20%CPB/TiO₂-C has a BAD generation rate of 6000 μmol g⁻¹ h⁻¹ and a BA production rate of 1250 μmol g⁻¹ h⁻¹, which is notably lower than the CPB/TiO₂ catalyst. Fig. S10† shows the morphology analysis of the 20%CPB/TiO₂-C catalyst, which reveals a bulky grain structure with a rough surface. CsPbBr₃ nanoparticles are dispersed on the surface of the massive TiO₂. The size of the CsPbBr₃ particles in the composite is also much smaller than that of blank CsPbBr₃, which once again proves that TiO₂ plays a critical role in inhibiting the growth of CsPbBr₃. Nevertheless, compared with 20%CPB/TiO₂, the size of the CsPbBr₃ particles is much larger in the 20%CPB/TiO₂-C catalyst. The result indicates that the TiO₂ nanoflakes are more beneficial for preventing the agglomeration of the CsPbBr₃ particles.

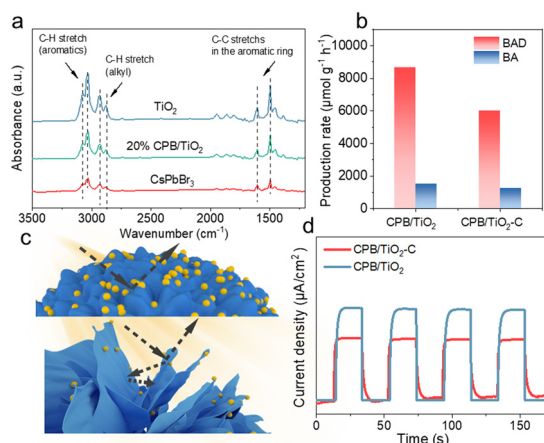


Fig. 7 (a) FTIR spectra of 20%CPB/TiO₂, TiO₂ and CsPbBr₃ after adsorption of saturated toluene. (b) Photoactivity comparison between CPB/TiO₂ and CPB/TiO₂-C. (c) Schematic diagram of light absorption over CPB/TiO₂ and CPB/TiO₂-C. (d) Transient photocurrent responses of CPB/TiO₂ and CPB/TiO₂-C.

In addition, UV-vis DRS is performed to study the optical absorption property of the 20%CPB/TiO₂-C catalyst. The sample shows a similar absorption edge as that of 20%CPB/TiO₂, but the light absorption intensity in the range of 200–550 nm is lower (Fig. S11†). The result indicates that the 3D hierarchical CPB/TiO₂ structure is more efficient for solar energy collection, which can be attributed to the multiple light reflection and refraction caused by the vertical nanoflakes, as schematically illustrated in Fig. 7c. Meanwhile, the transient photocurrent response test shows that the 20%CPB/TiO₂ catalyst exhibits a higher photocurrent density than that of CPB/TiO₂-C under visible light irradiation, indicating more efficient charge transfer (Fig. 7d). This can be related to the fact that TiO₂ nanoflakes facilitate the formation of smaller CsPbBr₃ particle, which could shorten the charge transfer distance to the surface and promote the interfacial charge separation. Hence, to sum up, the construction of the unique hierarchical CPB/TiO₂ structure greatly enhances the photocatalytic performance due to the existence of TiO₂ nanoflakes, which (1) greatly prohibits the aggregation of CsPbBr₃, forming much smaller perovskite particles that shorten the charge transfer distance; (2) increases light absorption by multiple reflection and scattering between the nanoflakes structure that benefits the solar energy harvesting and conversion; (3) enhances the adsorption of toluene molecules and promotes the surface reaction rates.

Photocatalytic mechanism

To elucidate the photocatalytic mechanism of toluene oxidation over the CPB/TiO₂ photocatalyst, a series of control experiments have been conducted in the absence of O₂ or with the addition of specific radical scavengers. As shown in Fig. 8a, toluene oxidation is almost completely suppressed when O₂ is replaced by Ar, indicating that O₂ is indispensable. When isopropanol (IPA) is added into the reaction system as a scavenger of hydroxyl radicals (·OH), it has almost no effect on toluene conversion, suggesting that ·OH is rarely involved in the reaction. In contrast, whether adding ammonium oxalate (AO) to eliminate holes (h⁺) or butylated hydroxytoluene (BHT) to capture carbon-centered radicals, the reaction rate significantly reduces. Besides, the toluene conversion is also significantly decreased when BQ is added as a superoxide free radical (·O₂⁻) scavenger. The above results clearly indicate that ·O₂⁻, h⁺, and carbon-centered radicals play key roles in the photocatalytic selective oxidation of toluene.

Subsequently, to further identify the existence of ·O₂⁻, electron paramagnetic resonance (EPR) spectroscopy was employed using 5,5-dimethyl-pyrroline-N-oxide (DMPO) as a trapping agent. As shown in Fig. S12† and Fig. 8b, no DMPO·O₂⁻ signal is detected under dark conditions. After visible light irradiation, distinct signals of DMPO·O₂⁻ are observed for both CsPbBr₃ and CPB/TiO₂, while no signals are detected from TiO₂. The CPB/TiO₂ catalyst exhibits a higher ability to generate more ·O₂⁻ radicals than that of pure CsPbBr₃, which is important to promote the oxidation of toluene. Moreover, no DMPO·OH signal is observed under the

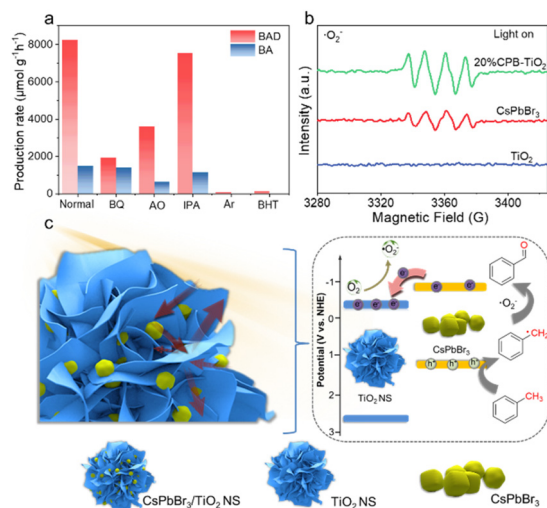


Fig. 8 (a) Photocatalytic toluene oxidation in the absence or presence of various radical scavengers. (b) EPR spectra of DMPO- O_2^- . (c) Schematic illustration of the proposed mechanism of photocatalytic oxidation of toluene over the CPB/TiO₂ composite.

same conditions, demonstrating that $\cdot\text{OH}$ is absent in the reaction process (Fig. S13 and S15[†]).

Based on the above analyses, a possible photocatalytic reaction mechanism over the hierarchical CPB/TiO₂ heterojunction is proposed. As schematically illustrated in Fig. 8c, upon photoexcitation, electrons and holes are generated in the conduction band (CB) and the valence band (VB) of CsPbBr₃. Due to the staggered energy bands, the photogenerated electrons in the CB of CsPbBr₃ can efficiently migrate towards the CB of TiO₂ and left holes on the VB of CsPbBr₃, which prolongs the lifetime of the photogenerated charge carriers. After that, molecular O₂ can be activated by electrons on the CB of TiO₂. Meanwhile, photogenerated holes oxidize the toluene to produce benzyl radicals ($\cdot\text{CH}_2\text{-R}$) on the VB of CsPbBr₃. Then, the $\cdot\text{O}_2^-$ radical reacts with the benzyl radicals to produce benzaldehyde.

Conclusions

In summary, we have designed and synthesized a hierarchical CPB/TiO₂ heterojunction as an advanced photocatalyst for efficient visible-light-driven toluene oxidation by assembling CsPbBr₃ nanoparticles onto nanoflower-shaped TiO₂ with 2D nanoflake subunits. The formed CPB/TiO₂ composite integrates the structural and electronical merits of the nanoflower-shaped TiO₂ and halide perovskite CsPbBr₃, which not only enhances solar light utilization, but also enhances the adsorption of the toluene reactant, and boosts the separation and transportation of photogenerated carriers. A high toluene oxidation rate of 10 200 $\mu\text{mol g}^{-1} \text{h}^{-1}$ is achieved over the optimal CPB/TiO₂ composite, which is about 20-fold higher than that of blank CsPbBr₃. The study demonstrates the significance of rational design of well-defined hierarchical heterojunction cat-

alysts over metal halide perovskites for efficient photocatalytic redox reactions.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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