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Recent progress in metal halide perovskite photocatalysts for hydrogen evolution

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Photocatalytic hydrogen production, which directly converts solar energy into green chemical fuel, has received widespread attention. However, despite significant efforts, the efficiency of conventional photocatalytic materials remains below industrial requirements, owing to the intrinsic limitations such as insufficient light absorption and poor carrier transport capability. Metal halide perovskite (MHP) materials feature superior optoelectronic properties and structural flexibility, rendering them highly attractive candidates for photocatalysis. This review provides a concise introduction to the structural characteristics of MHPs and summarizes their recent progress in the field of photocatalytic hydrogen evolution, including single-component MHPs and MHP-based composites. The review also discusses the current challenges and prospects of MHP photocatalysts, which hold promise for advancing photocatalytic solar-to-hydrogen technology.

1. Introduction

Solar energy is a clean and renewable energy source that is abundant, almost infinite, and widely distributed on earth. However, only 1% of the solar energy received by earth has been effectively used,^{1,2} highlighting the importance of finding a suitable solar energy carrier to use this valuable resource more efficiently.^{3–5} Hydrogen (H₂) is a clean, non-toxic, colorless, and environmentally friendly fuel without carbon dioxide emissions. Additionally, H₂ offers a broad range of energy applications, including H₂ fuel cells,^{6–8} combustible fuels,^{9–11}

and synthetic chemical materials.^{12–14} Thus, H₂ serves as an ideal carrier for solar energy. Among the various solar-to-H₂ conversion methods (e.g. photoelectrochemical H₂ evolution, photothermochemical H₂ evolution, and photocatalytic H₂ evolution), photocatalytic H₂ evolution technology, which converts solar energy to H₂ resembling natural photosynthesis, has garnered significant research interests.^{15–18}

Photocatalytic H₂ evolution reaction (HER) involves three main steps: (1) absorption of light by a photocatalyst to generate excitons; (2) separation and migration of carriers from the bulk to the surface of the photocatalyst; and (3) reduction and oxidation reactions on the photocatalyst surface. For achieving high-efficiency photocatalytic H₂ evolution, photocatalysts need to meet several requirements. First, appropriate energy levels are thermodynamically necessary for suitable photocatalysts.

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As exemplified by photocatalytic water splitting, the conduction band minimum (CBM) of photocatalysts should locate at a more negative potential than the redox potential of H^+/H_2 (0 V at pH = 0 with respect to the normal hydrogen electrode (NHE)), the valence band maximum (VBM) of photocatalysts should locate at a more positive potential than the oxide potential of O_2/H_2O (1.23 V versus NHE), and a minimum bandgap of 1.23 eV is required. In addition, the bandgap of photocatalysts should be narrow enough to make full use of sunlight while satisfying the sufficient overpotential, together with sufficient carrier separation and transport ability. Since the original research of Fujishima and Honda in 1972, a rich variety of semiconductors have been exploited in the field of photocatalytic H_2 evolution, such as TiO_2 ,^{19–21} CdS ,^{22–24} $SrTiO_3$,^{25–27} and $g-C_3N_4$.^{28–30} However, state-of-the-art solar-to-hydrogen (STH) efficiencies of most reported photocatalysts are still around 1%, far below the commercialization requirements, owing to the intrinsic limitations such as insufficient light absorption, poor carrier transport capability, and prevailing electron–hole recombination. In this context, it is highly urgent to develop

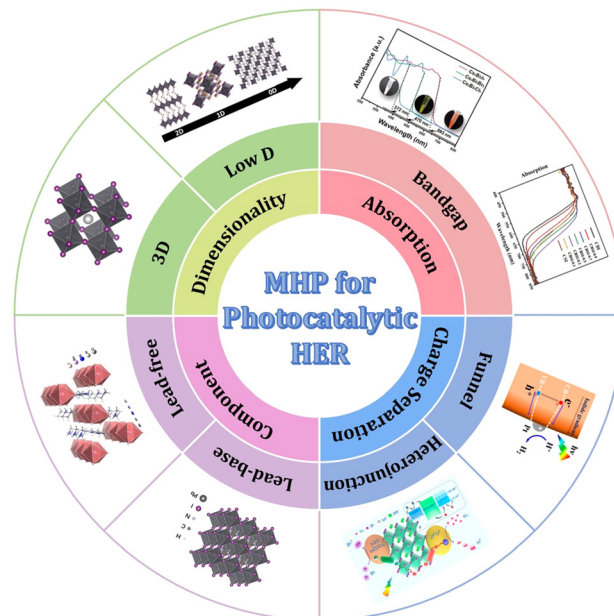


Fig. 1 Schematic overview of metal halide perovskite for photocatalytic hydrogen evolution.



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a new class of photocatalysts with suitable optical and electronic properties for efficient photocatalytic H_2 evolution.

In the past few years, metal halide perovskites (MHPs) have achieved noteworthy breakthroughs in the field of optoelectronics,^{31–33} including solar cells,^{34–37} light emitting diodes,^{38–40} and photodetectors.^{41–43} Particularly, the light conversion efficiency (PCE) of MHP-based solar cells reached a record of 25.73%,⁴⁴ suggesting the highly efficient light absorption and charge transport abilities of MHP materials. Emphatically, MHP materials have plentiful superiorities for photocatalysts, such as high light absorption coefficient,^{45,46} long carrier diffusion lengths, low binding energy,^{47,48} tunable bandgaps,^{49,50} and low-cost fabrication, rendering MHPs as viable candidates for photocatalytic H_2 evolution.

To date, despite several reviews on MHPs in photocatalysis,^{51–53} comprehensive assessments focusing on

elucidating the crucial relationship between the structure of MHPs (including the intrinsic structure of MHPs and the composites based on MHPs) and their performance in photocatalytic hydrogen evolution have been scarce. In this review, a thorough overview of recent advancements in the field of photocatalytic H₂ evolution is provided, including component engineering, energy band adjustment (e.g., extra halogen element doping), and composite structure (e.g., MHPs/conductor, MHPs/semiconductor). A specific emphasis is placed on elucidating the correlation between the structure of MHP-based photocatalysts and their performance in hydrogen evolution (Fig. 1). Additionally, the review highlights the current challenges and provides valuable perspectives for the further development of halide perovskites in photocatalytic H₂ evolution. This comprehensive review serves as a valuable reference for the design and development of highly efficient and stable MHP-based photocatalysts for H₂ evolution.

2. Structure and properties of metal halide perovskites

MHPs have a general formula ABX₃, where A is a univalent organic or inorganic cation, such as methylamine cation (MA⁺), formamidinium cation (FA⁺), and Cs⁺; B site is a divalent metal ion, such as Pb²⁺ and Sn²⁺; and X is a halogen ion, such as Cl⁻, Br⁻, and I⁻.^{54,55} As shown in Fig. 2a, the B site and X site form a [BX₆]⁴⁻ octahedron, with B at the center and X at the vertices of the octahedron. Then, [BX₆]⁴⁻ octahedra are connected in three-dimensional (3D) space by sharing vertices to form a 3D network structure. The formability and structural stability of these perovskite-type metal halide materials can be evaluated by tolerance factor *t*, which is calculated as follows:

$$t = \frac{R_A + R_X}{\sqrt{2}(R_B + R_X)}$$

where *R*_A, *R*_B, and *R*_X are the effective ionic radii of ion A, ion B, and ion X in perovskite respectively. In general, to form a stable perovskite structure at room temperature, the *t* values need to be 0.81–1.11. An ideal cubic perovskite will be formed when *t* is 0.9 to 1.0, while the orthorhombic or tetragonal (Fig. 2b and c) may be formed when *t* is larger or smaller.⁵⁶

The introduction of large-sized organic cations at A site can break down the 3D framework, giving rise to low-dimensional perovskites including two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) perovskites (Fig. 3).⁵⁷ 2D

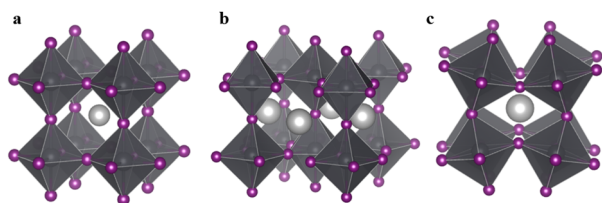


Fig. 2 The different crystal structures of MHPs: (a) cubic structure, (b) tetragonal structure, and (c) orthorhombic structure.

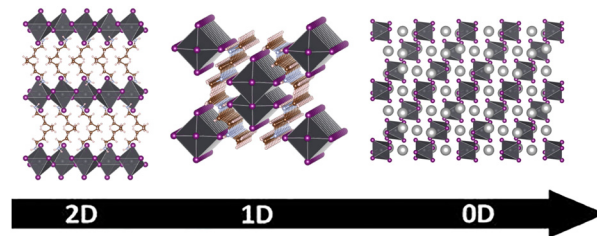


Fig. 3 The crystal structures of 2D, 1D, and 0D perovskite.

perovskites consist of alternating arrangements of inorganic [BX₆]⁴⁻ slabs and the interlayer organic molecules. Notably, the formation of 2D perovskites is not affected by the Goldschmidt tolerance factor, allowing for the utilization of an extensive library of organic cations for their preparation. Based on their crystal structure, 2D perovskites can be divided into Ruddlesden–Popper (RP) phase, Dion–Jacobson (DJ) phase, and the alternating cations in the interlayer space (ACI) phase. The structural formula of RP phase 2D perovskite is A¹₂A_{*n*-1}B_{*n*}X_{3*n*+1}, where A¹ is a long-chain univalent organic cation such as butylamine cation (BA⁺) or phenethylamine cation (PEA⁺), and A is a short-chain organic cation such as MA⁺ or FA⁺. *n* represents the number of inorganic skeleton layers wrapped by long-chain organic cations. When *n* = 1, it represents a single-layer perovskite at the molecular scale, and when *n* ≥ 2, it is a multilayer quasi-2D perovskite structure. The structural formula of the DJ phase 2D perovskite is A²A_{*n*-1}B_{*n*}X_{3*n*+1}, where A² represents a long-chain divalent organic cation, such as ethylenediamine cation (EDA²⁺) or 1,3-propanediamine cation (PDA²⁺). The structural formula of the ACI phase 2D perovskite is A³A_{*n*}B_{*n*}X_{3*n*+1}, where A³ is limited to some specific univalent organic cations, such as guanidine cation (GA⁺) and methylphenethylammonium cation (MPA⁺).^{58,59}

Further increase in the size of A-site organic cations will lead to a reduction in the structural dimension of MHPs to 1D and 0D. The structure of 1D perovskites consists of [BX₆]⁴⁻ octahedra chains with shells of organic cations, such as [DME-DA]PbBr₄ (DMEDA = *N,N'*-dimethylethylenediamine),⁶⁰ and [TDMP]PbBr₄ (TDMP = *trans*-2,5-dimethylpiperazine).⁶¹ 0D perovskites are bulk assemblies of individual [BX₆]⁴⁻ octahedra at the molecular level, where the [BX₆]⁴⁻ octahedra are separated by organic molecules, such as (C₉NH₂₀)₂SnBr₄,⁶² (C₄N₂H₁₄Br)₄SnBr₆.⁶³

On the one hand, the electronic dimension of MHPs decreases as the structural dimension decreases from 3D to 0D.⁶⁴ Thus, the bandgaps and quantum confinement effect of MHPs increase with decreasing structural dimension, leading to narrower absorption ranges and larger excitation binding energies for low-dimensional MHPs.^{31,65} On the other hand, in contrast to 3D MHPs, where the A-site cation is limited to a few cations (including MA⁺, FA⁺, and Cs⁺), low-dimensional MHPs are less limited by the Goldschmidt tolerance factor and compatible with an abundance of functional organic cations such as chiral cations,^{66,67} π-conjugated cations,^{68,69} and flexible asymmetric cations.^{70,71} This facilitates the separation and transportation of photogenerated carriers by reducing the

quantum confinement effect and forming a polarization-induced electric field. Furthermore, owing to the hydrophobicity of bulky organic cations, low-dimensional MHPs exhibit much better stability than 3D MHPs, which has been confirmed in a lot of previously reported works.^{72–74}

3. Single-component MHP photocatalysts

Driven by their outstanding performance in optoelectronic devices, MHPs have captured significant attention in the field of photocatalysis. However, their susceptibility to moisture poses challenges for their application in photocatalytic water-splitting. Recently, Park *et al.* have found that MHPs can be stabilized in saturated HI solutions, leading to a surge of interest in photocatalytic HI splitting for H₂ production (Fig. 4).^{75,76} In comparison to water splitting, which involves four electrons, photocatalytic HI splitting utilizes only two electrons,⁷⁷ resulting in an extremely low overpotential.^{78,79} Additionally, this reaction presents a feasible alternative to the thermodynamic unfavourable HI thermal decomposition and holds promise for facilitating the industrial iodine-sulphur cycle for H₂ generation.⁸⁰ Consequently, there is considerable potential for designing efficient and stable MHPs for photocatalytic HER. In this section, we discuss the progress of single-component MHPs, classified into Pb-based and lead-free MHPs, for photocatalytic H₂ production (Table 1).

3.1 Pb-based perovskites for photocatalytic hydrogen evolution

In 2016, Park *et al.* successfully demonstrated the first photocatalytic HER of MHP by stabilizing MAPbI₃ in its saturated HI solution using the dynamic equilibrium between dissolution

and precipitation (as shown in Fig. 5a and b). Under visible light excitation, the photogenerated electrons in MAPbI₃ reduced H⁺ to H₂ and the photogenerated holes oxidized I[−] to I₃[−]. The oxidized I₃[−] ions were subsequently reduced back to I[−] by H₃PO₂, achieving sustainable photocatalytic H₂ production. With Pt as co-catalyst, the HER rate and STH efficiency of MAPbI₃ (200 mg) were measured to be 11.4 μmol h^{−1} and 0.81%, respectively. This result provided a new solution for the photocatalytic application of MHPs.

Following this approach, halide perovskites with different structures have been explored for photocatalytic HER. For example, Wang *et al.* synthesized three 2D RP perovskites with different lengths of phenylalkylammonium ions (C₆H₅(CH₂)_nNH₃⁺; n = 1, 2, and 3).⁸¹ In 2D MHP-based solar cells, the 2D MHP layer is consistently oriented parallel to the charge extraction layer, necessitating the passage of carriers through the poorly conductive organic layer for utilization, ultimately resulting in decreased overall charge transport capacity. (Fig. 5d). However, in 2D MHP-based powder photocatalytic systems, carriers traveling along the more conductive inorganic layer can be effectively utilized (Fig. 5e), thus rendering 2D MHPs as promising candidates for photocatalytic HER. Moreover, the excellent moisture resistance of 2D RP MHPs allows the photocatalytic measurement to be carried out in aqueous salt solutions, reducing reliance on strongly acidic HI-saturated solutions. This improvement significantly reduced the acidity of the solution, making the experimental conditions milder, and improved the reproducibility of the measurement due to the lower solubility of 2D perovskite in the aqueous salt solution. Further analysis demonstrated that the length of organic cations could significantly affect the dissolution behaviour, morphology, and photoelectric properties, such as bandgap and band edge position of 2D MHP crystals. Among the investigated 2D MHPs, (C₆H₅CH₂NH₃)₂PbI₄ with the shortest length of organic cations showed the best photocatalytic

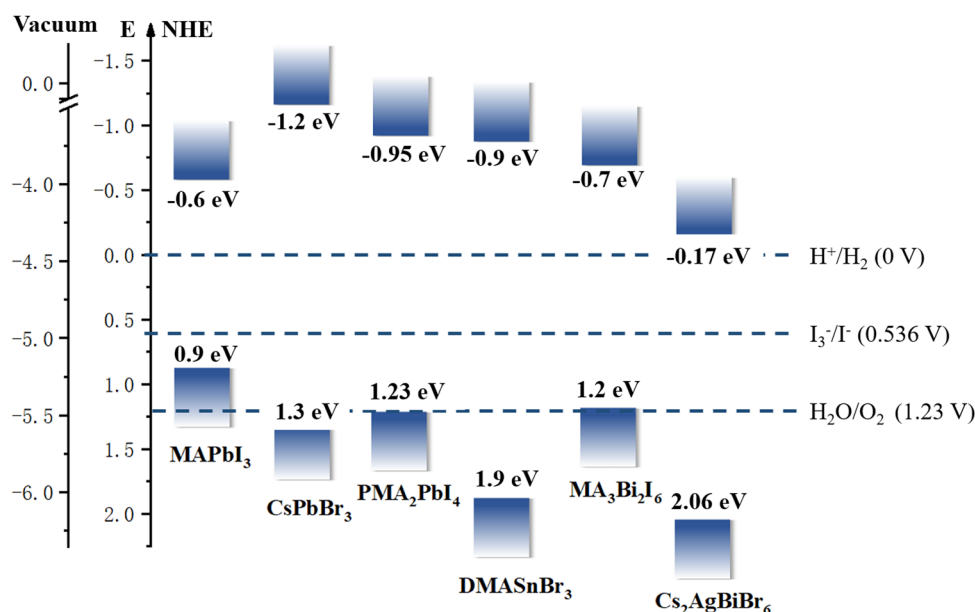


Fig. 4 The schematic diagram of HI splitting with different MHP photocatalysts.^{81,83,84}

Table 1 Summary of works on photocatalytic application of MHPs. R = H_2 evolution reaction rate, S = STH efficiency, A = AQE

MHP catalysts	Test conditions	Cocatalysts	MHP usage (mg)	Performance	Year ^{Ref.}
MAPbI ₃	Xe lamp ($\lambda \geq 475$ nm) 100 mW cm ⁻²	Pt	200	$R = 11.4 \mu\text{mol h}^{-1}$	2016 ⁷⁵
MAPbBr _{3-x} I _x	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻²	Pt	250	$S = 0.81\%$ $R = 651.2 \mu\text{mol h}^{-1}$	2018 ⁸⁵
DMA ₃ BiI ₆	LED ($\lambda = 465$ nm, 9 mW) HI solution	Pt	500	$S = 0.81\%$ $R = 47 \mu\text{mol h}^{-1}$	2018 ⁸⁶
DMASnI ₃	Xe lamp (300 W) DI water	Pt	200	$A = 82.8\%$ at 465 nm $R = 0.64 \mu\text{mol h}^{-1}$	2018 ⁸⁷
MAPb(I _{0.9} Br _{0.1}) ₃	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻²	Pt	20	$R = 66.69 \mu\text{mol h}^{-1}$	2019 ⁸⁸
CsPbBr _{3-x} I _x	The mixed HI/HBr solution Xe lamp ($\lambda \geq 420$ nm) 120 mW cm ⁻²	Pt	200	$S = 1.42\%$ $R = 44.8 \mu\text{mol h}^{-1}$	2019 ⁸⁹
MAPbI ₃	Xe lamp 120 mW cm ⁻² HI solution Ultrasonication (70 W)	Pt	50	$A = 2.15\%$ at 450 nm $R = 11.2 \mu\text{mol h}^{-1}$	2019 ⁹⁰
2-AMPSBi ₅ (Sb-precursor is SbI ₃)	ABET 103 solar simulator (150 W, $\lambda = 250$ -1900 nm) 100 mW cm ⁻²		10	$R = 1.86 \mu\text{mol h}^{-1}$	2019 ⁹¹
MA ₃ Bi ₂ I ₉	Methanol solution (10% vol) Xe lamp (300 W, $\lambda \geq 400$ nm) HI solution	Pt	40	$R = 6.77 \mu\text{mol h}^{-1}$ $S = 0.48\%$	2019 ⁹²
Cs ₃ Bi _{0.6} Sb _{1.4} I ₉	Simulated sunlight (AM 1.5 G) 100 mW cm ⁻² HI solution	Pt	100	$R = 92.6 \mu\text{mol h}^{-1}$	2020 ⁹³
MAPbI ₃ with MA ⁺ film	Xe lamp (300 W) HI solution		50	$R = 15.65 \mu\text{mol h}^{-1}$	2021 ⁹⁴
(C ₆ H ₅ CH ₂ NH ₃) ₂ PbI ₄	Xe lamp (300 W, $\lambda \geq 420$ nm) HI solution	Pt	150	$R = 333 \mu\text{mol h}^{-1}$ $S = 1.57\%$	2021 ⁸¹
Cs ₂ Pt _{0.09} Sn _{0.95} Cl ₆	Xe lamp (300 W) TEOA solution (10% vol)	Pt		$R = 16.11 \mu\text{mol h}^{-1}$	2021 ⁹⁵
DMA ₃ BiI ₆	LED lamp (100 W) 76.4 mW cm ⁻² HI solution	Pt	50	$R = 5.7 \mu\text{mol h}^{-1}$	2021 ⁹⁶
Defect-rich Cs ₂ AgBiBr ₆	Xe lamp (300 W, $\lambda \geq 420$ nm) 332.5 mW cm ⁻² HBr solution		500	$A = 0.83\%$ at 535 nm $R = 0.406 \mu\text{mol h}^{-1}$	2021 ⁹⁷
Cs ₂ SnI ₆	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻² HI solution	PtSA	10	$R = 4.30 \mu\text{mol h}^{-1}$	2021 ⁹⁸
FAPbBr _{3-x} I _x	Xe lamp with an AM1.5G filter (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻² The mixed HI/HBr solution	PtSA	100	$R = 682.6 \mu\text{mol h}^{-1}$ $S = 4.50\%$ $A = 33.4\%$ at 530 nm	2022 ⁹⁹
OA _{0.15} MA _{0.85} PbI ₃	PL-MW2000 light source in the full visible range HI solution	Pt	5	$R = 2.68 \mu\text{mol h}^{-1}$ $A = 1.67\%$ at 420 nm	2022 ⁸²
MA ₃ Bi ₂ Cl _{9-x} I _x	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻² Saturated HCl (or HCl/HI) solution	Pt	500	$R = 341 \pm 61.7 \mu\text{mol h}^{-1}$	2022 ¹⁰⁰
Cs ₃ Bi ₂ I ₉ PNPs	Xe lamp (300 W, $\lambda = 350$ -780 nm, 790 mW cm ⁻²) Ethanol solution		50	$A = 1.25\%$ at 435 nm $R = 10.79 \mu\text{mol h}^{-1}$	2022 ¹⁰¹

performance with an HER rate of $333 \mu\text{mol h}^{-1}$ (150 mg) and an STH efficiency of 1.57% when using Pt as cocatalyst (Fig. 5f).

In addition, Li *et al.* combined the 3D perovskite MAPbI₃ with the 2D octadecylammonium lead iodide perovskite (OA₂PbI₄) to create multidimensional perovskites, denoted as OA_xMA_{1-x}PbI₃.⁸² These materials exhibited superior charge transfer abilities compared to traditional 3D perovskites and better photocatalytic performance than 2D perovskites. Consequently, OA_xMA_{1-x}PbI₃ samples showed an optimal photocatalytic HER rate of $2.68 \mu\text{mol h}^{-1}$ (5 mg), outperforming bare

MAPbI₃ ($1.38 \mu\text{mol h}^{-1}$, 5 mg). This excellent performance was ascribed to their superior absorption properties throughout the visible region compared to other OA_xMA_{1-x}PbI₃ samples.

Notably, the structural flexibility of MHPs imparts them great potential to tune their energy levels by adjusting halide composition. Huang *et al.* fabricated a mixed halide perovskite MAPbBr_{3-x}I_x (I-doped MAPbBr₃) with I gradient distribution in a mixed HI/HBr solution, *via* a light-assisted halide exchange method. In this material, the concentration of I⁻ increases gradually from the interior to the surface, forming a suitable

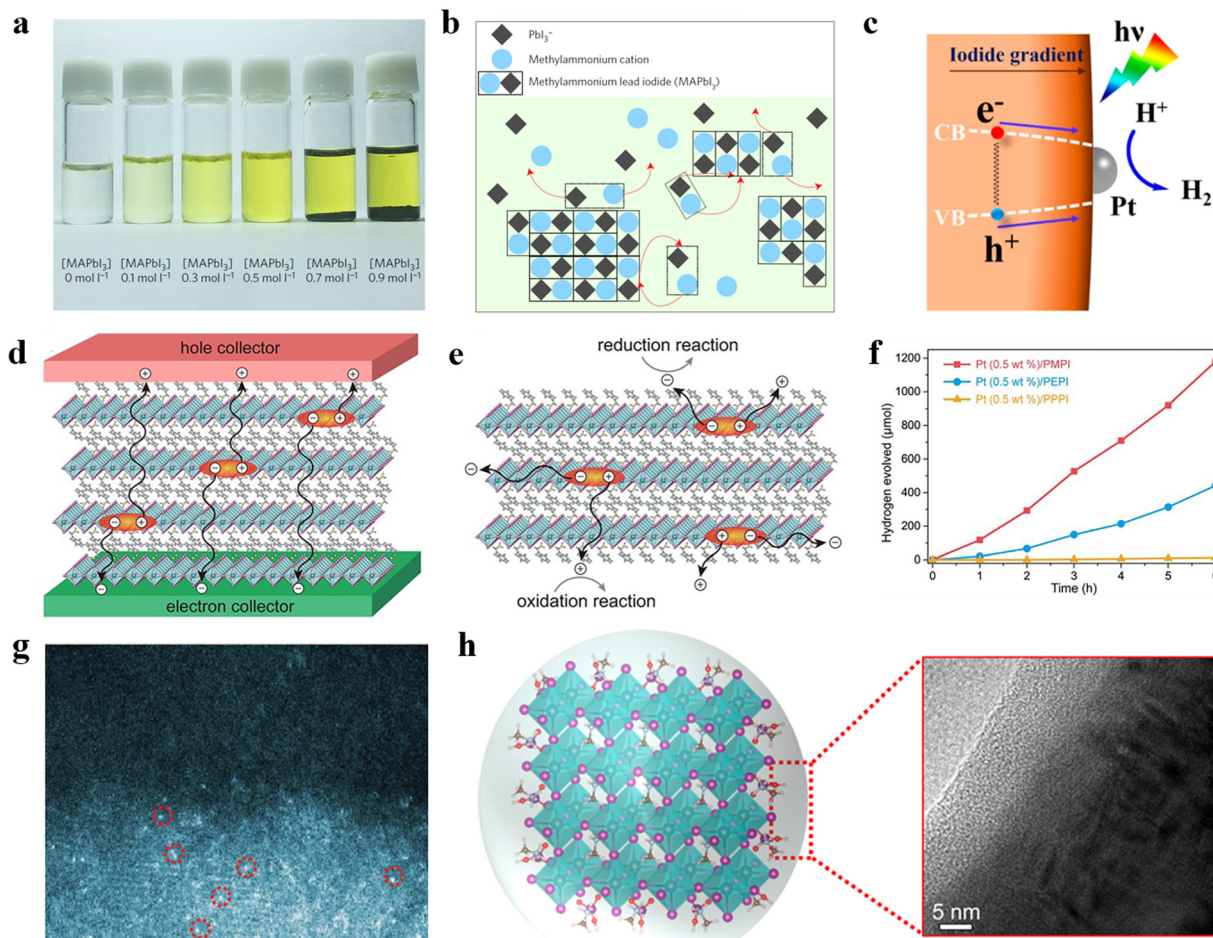


Fig. 5 (a) Photographs of MAPbI₃ in different concentrations of HI solution. (b) Diagram of equilibrium dissolution of MAPbI₃ powder in saturated HI solution.⁷⁵ Copyright 2016 Springer Nature. (c) The funnel bandgap of MAPbBr_{3-x}I_x. Copyright 2018 American Chemical Society. (d) Schematic diagram of the migration of carriers for 2D perovskite in (d) solar cell and (e) photocatalyst. (f) The photocatalytic HER rates of (C₆H₅CH₂NH₃)₂PbI₄ (PMPI), (C₆H₅(CH₂)₂NH₃)₂PbI₄ (PEPI), and (C₆H₅(CH₂)₃NH₃)₂PbI₄ (PPPI).⁸¹ Copyright 2021 Wiley-VCH GmbH. (g) The scanning transmission electron microscope-high angle annular dark field (STEM-HAADF) images of PtSA/FAPbBr_{3-x}I_x. Copyright 2022 Wiley-VCH GmbH. (h) Schematic diagram of the growth of organic passivation membrane on the surface of MAPbI₃.⁹⁴ Copyright 2021 American Chemical Society.

bandgap funnel structure (Fig. 5c). As a result, MAPbBr_{3-x}I_x exhibited an HER rate of 652.1 μmol h⁻¹ (250 mg) and an STH efficiency of 1.05% with the use of Pt as co-catalyst, owing to the bandgap funnel facilitated transfer of photogenerated carriers. Furthermore, Zhao *et al.* tuned the energy levels of MAPbI₃ by one-pot crystallization.⁸⁸ It should be noticed that there was no bandgap funnel in obtained MAPb(I_{1-x}Br_x)₃ (Br-doped MAPbI₃) by this method. The synthesized mixed halide perovskite showed a championing HER rate of 66.96 μmol h⁻¹ (20 mg) and an outstanding STH efficiency of 1.42% without the use of co-catalysts when $x = 0.1$. This material exhibited great stability without significant decrease in photocatalytic activity over 252 h (63 runs, 4 h per run).

Similarly, Guan *et al.* synthesized an all-inorganic perovskite CsPbBr_{3-x}I_x with a funnel bandgap for photocatalytic HER.⁸⁹ The CsPbBr_{3-x}I_x/Pt system showed an optimized HER rate of 224 μmol h⁻¹. Moreover, the CsPbBr_{3-x}I_x/Pt system also displayed an apparent quantum efficiency (AQE) of 2.15% at 450 nm without obvious decrease in 50 h continuous HER.

Such all-inorganic MHPs exhibit better stability compared with organic-inorganic hybrid MHPs, according to the previously reported works in MHPs-based solar cells.^{102,103}

Halide perovskites with FA⁺ ion as the A cation exhibit significantly longer carrier lifetimes and diffusion lengths compared to those based on MA⁺ ion,¹⁰⁴ making them promising candidates for photocatalytic HER. Wu *et al.* investigated the photocatalytic HER performance of Pt single atoms (PtSA) loaded FAPbBr_{3-x}I_x in mixed HBr/HI solution, whose crystal structure and morphology are depicted in Fig. 5g.⁹⁹ The PtSAs, which were uniformly distributed on the surface of FAPbBr_{3-x}I_x by coordinating with Br/I ions, decreased the free energy of H* adsorption for Pt/FAPbBr_{3-x}I_x to almost 0 (around 0.04 eV), leading to an enhanced photocatalytic HER rate of 682.6 μmol h⁻¹ (100 mg) and an impressive STH efficiency of 4.50%.

In addition, Wang *et al.* demonstrated that ultrasonication could improve the photocatalytic HER performance of MAPbI₃, resulting in a 7 times higher photocatalytic HER rate under ultrasonic conditions (23.30 μmol h⁻¹, ultrasonic power = 70 W)

than under visible-light conditions alone ($3.42 \mu\text{mol h}^{-1}$).⁹⁰ This enhancement in the HER rate can be attributed to the establishment of a built-in polarized electric field triggered by dipole moments under ultrasonication, which can efficiently separate photogenerated carriers and thus enhance catalytic efficiency.

Though great progress has been made, the water-stability of MHPs remains a critical issue that needs to be addressed. To improve their moisture stability, Liu *et al.* created an organic membrane that effectively passivates MAPbI₃, using a light- and solution-based treatment (Fig. 5h).⁹⁴ The HIO₃ molecule on the surface of MAPbI₃ formed a hydrogen bond with another HIO₃ molecule on the neighbouring MAPbI₃ crystal, enhancing the crystallinity of MAPbI₃. Moreover, MA⁺ was anchored to the surface of the HIO₃ layer by electrostatic interaction with IO₃⁻, further enhancing the stability of MAPbI₃. In consequence, the photocatalytic HER rate was 2.24-fold enhancement than the bare MAPbI₃ without a passivating layer.

3.2 Lead-free perovskites for photocatalytic hydrogen evolution

Despite the impressive achievements of Pb-based perovskites in photocatalytic H₂ production, the toxicity of Pb limits their

further application. To address this issue, lead-free perovskites have been explored, involving the replacement of Pb²⁺ with Sn²⁺, Bi³⁺, Sb³⁺, or the substitution of two Pb²⁺ with one univalent metal cation (*e.g.* K⁺, Ag⁺, and Cu⁺) and one trivalent metal cation (*e.g.* Sb³⁺, Bi³⁺).^{105–107} In this section, the recent advances in lead-free perovskites for photocatalytic HER are discussed.

3.2.1 Sn-based metal halide perovskites. Sn, a non-toxic element possessing a similar electron configuration to Pb, is regarded as a promising substitute for Pb. Ju *et al.* reported the fabrication of a Sn-based halide perovskite, DMASnI₃ (DMA = dimethylammonium cation, CH₃NH₂CH₃⁺) (Fig. 6a), which displayed excellent water stability with no decomposition observed after 16 h of immersion in deionized (DI) water (Fig. 6b).⁸⁷ They observed that DMASnI₃ crystals exhibited invertible bandgap narrowing behaviour and long carrier lifetimes, indicating enormous potential for optoelectronic applications. However, the HER rate of DMASnI₃ crystals was measured to be only $0.64 \mu\text{mol h}^{-1}$ (Fig. 6c), which could be ascribed to the 1D structure-induced broad bandgap, large effective masses of electrons/holes, and Sn-vacancies induced deep defect states.

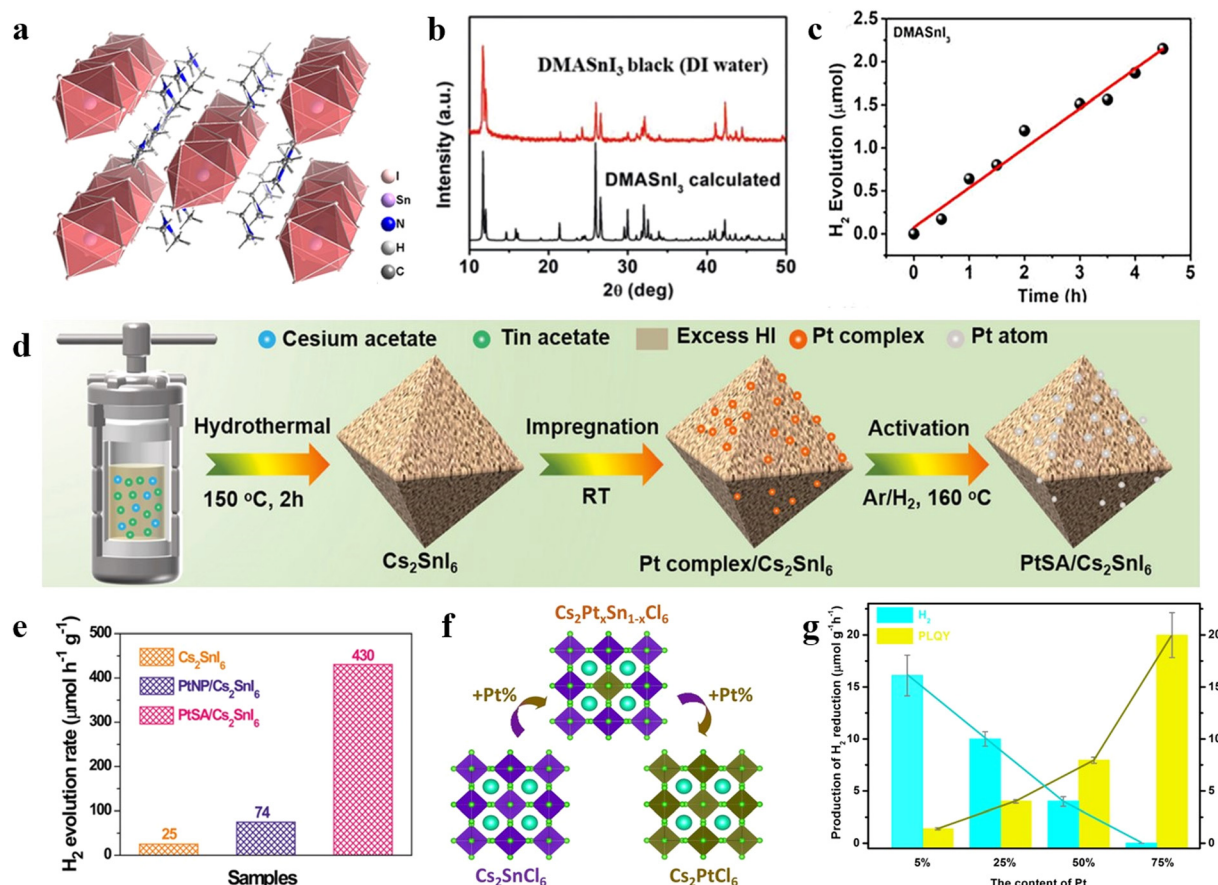


Fig. 6 (a) The crystal structure of DMASnI₃. (b) The XRD pattern of black DMASnI₃ after treatment of DI water. (c) The photocatalytic HER rate of DMASnI₃ in DI water.⁸⁷ Copyright 2021 Wiley-VCH GmbH. (d) The schematic diagram of PtSA/Cs₂SnI₆ preparation process. (e) The photocatalytic HER rates of Cs₂SnI₆, PtNP/Cs₂SnI₆, and PtSA/Cs₂SnI₆.⁹⁸ Copyright 2021 Springer Nature. (f) The crystal structure of Cs₂Pt_xSn_{1-x}Cl₆ with different Pt doping concentrations. (g) The photocatalytic HER rates and average photoluminescence quantum yields of Cs₂Pt_xSn_{1-x}Cl₆ (0 < x < 1).⁹⁵ Copyright 2021 Wiley-VCH GmbH.

Furthermore, Zhuo *et al.* synthesized Cs_2SnI_6 perovskite and loaded PtSA on its surface using an impregnation-heat activation method (Fig. 6d).⁹⁸ The unique coordination structure and electronic properties of Pt-I₃ sites led to a strong metal-support interaction effect and promoted the photogenerated electron transfer from Cs_2SnI_6 to the PtSA, reducing the Gibbs free energy and accelerating the H₂ generation kinetics. The 0.12 wt% PtSA/ Cs_2SnI_6 demonstrated the highest activity for photocatalytic H₂ production, with a rate of 4.30 $\mu\text{mol h}^{-1}$ (10 mg), which was 17.2- and 5.8-fold enhancement than that of pure Cs_2SnI_6 and optimized 3.88 wt% Pt nanoparticle/ Cs_2SnI_6 , respectively (Fig. 6e).

Yin *et al.* employed a hydrothermal method to partially replace Sn⁴⁺ in Cs_2SnI_6 with Pt⁴⁺ to obtain a range of highly stable $\text{Cs}_2\text{Pt}_x\text{Sn}_{1-x}\text{Cl}_6$ perovskites, where Cs⁺, Cl⁻, Sn⁴⁺, and Pt⁴⁺ ions were uniformly distributed (Fig. 6f).⁹⁵ Among them, $\text{Cs}_2\text{Pt}_{0.05}\text{Sn}_{0.95}\text{Cl}_6$ demonstrated remarkable phase stability in water for 25 days and exhibited an excellent photocatalytic HER rate (16.11 $\mu\text{mol h}^{-1}$). Interestingly, the photocatalytic function

of $\text{Cs}_2\text{Pt}_x\text{Sn}_{1-x}\text{Cl}_6$ could be fine-tuned by controlling the amount of Pt⁴⁺ (Fig. 6g). As the amount of Pt⁴⁺ increased, the photocatalytic HER performance of $\text{Cs}_2\text{Pt}_x\text{Sn}_{1-x}\text{Cl}_6$ decreased.

3.2.2 Bi- and Sb-based metal halide perovskites. Bi³⁺ with lone-pair 6s² exhibits a similar outer electronic configuration as Pb²⁺. Owing to their shallow carrier traps and excellent transport properties, Bi-based MHPs have emerged as promising candidates for lead-free halide perovskite photocatalysts. In this context, Zhao *et al.* synthesized a crystalline photocatalyst DMA_3BiI_6 via a solvothermal method (Fig. 7a).⁸⁶ Photocatalytic measurements were carried out in its well-dispersed HI-H₃PO₂ system containing separated Pt ions and $[\text{BiI}_6]^{3-}$ ions. When irradiated at 465 nm, the Pt/ DMA_3BiI_6 photocatalytic system exhibited a superior AQE of ~82.8% for photocatalytic H₂ production, achieving an impressive photocatalytic HER rate of 47 $\mu\text{mol h}^{-1}$ (500 mg) and showing stable activity without obvious decrease over 100 h. This high activity could be attributed to the efficient separation of carriers at the interface between $[\text{BiI}_6]^{3-}$ and Pt ions.¹⁰⁸ In a subsequent study, they

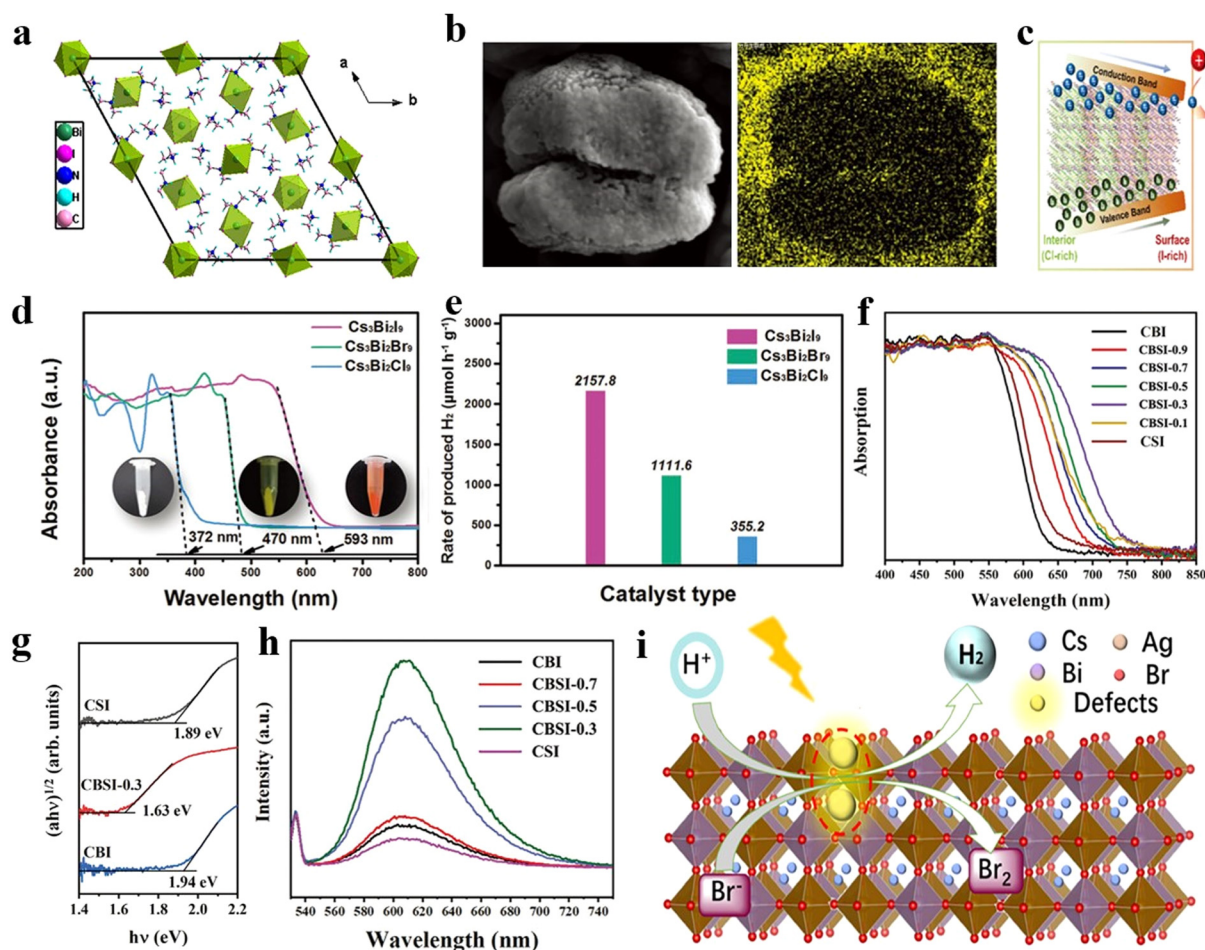


Fig. 7 (a) The crystal structure of DMA_3BiI_6 .⁸⁶ Copyright 2018 Elsevier. (b) The SEM image (left) and EDS mapping (right) for I of $\text{MA}_3\text{Bi}_2\text{Cl}_{9-x}\text{I}_x$. (c) The funnel bandgap of $\text{MA}_3\text{Bi}_2\text{Cl}_{9-x}\text{I}_x$.¹⁰⁰ Copyright 2022 Wiley-VCH GmbH. (d) ultraviolet-visible diffuse reflection spectra (UV-vis DRS) of $\text{Cs}_3\text{Bi}_2\text{X}_9$ (X = Cl, Br, I) (the inset are physical photographs of them). (e) The photocatalytic HER rates of $\text{Cs}_3\text{Bi}_2\text{X}_9$ (X = Cl, Br, I).¹⁰¹ Copyright 2022 Wiley-VCH GmbH. (f) The UV-vis DRS of $\text{Cs}_3\text{Bi}_2\text{Sb}_{2-x}\text{I}_9$ with different x. (g) Optical absorptions of $\text{Cs}_3\text{Bi}_2\text{I}_9$, $\text{Cs}_3\text{Sb}_2\text{I}_9$, and $\text{Cs}_3\text{Bi}_{0.6}\text{Sb}_{1.4}\text{I}_9$. (h) The steady-state photoluminescence spectra of $\text{Cs}_3\text{Bi}_2\text{I}_9$, $\text{Cs}_3\text{Sb}_2\text{I}_9$, and $\text{Cs}_3\text{Bi}_{0.6}\text{Sb}_{1.4}\text{I}_9$.⁹³ Copyright 2020 Wiley-VCH GmbH. (i) The schematic diagram of photocatalytic HER on defect-rich $\text{Cs}_2\text{AgBiBr}_6$.⁹⁷ Copyright 2021 American Chemical Society.

found that DMA_3BiI_6 could be stabilized in the aqueous DMAI solution for at least two weeks without additional acids or coatings, through a dissolution–recrystallization process of DMA_3BiI_6 surface molecules.⁹⁶ However, the photocatalytic performance of DMA_3BiI_6 in the DMAI solution was unsatisfactory, showing an HER rate of $4.55 \mu\text{mol h}^{-1}$ (50 mg) and an AQE of 0.83% at 535 nm with Pt as the co-catalyst.

Furthermore, Guo *et al.* synthesized a Bi-based perovskite $\text{MA}_3\text{Bi}_2\text{I}_9$ using a facile hydrothermal method, which displayed a photocatalytic HER rate of $6.77 \mu\text{mol h}^{-1}$ (40 mg) and an STH efficiency of 0.48%.⁹² Additionally, it displayed no obvious decrease in HER rate after a 70 h test. In the later study, Tang *et al.* developed a mixed halide perovskite $\text{MA}_3\text{Bi}_2\text{Cl}_{9-x}\text{I}_x$ in which the iodine element exhibited a gradient distribution (Fig. 7b). The $\text{MA}_3\text{Bi}_2\text{Cl}_{9-x}\text{I}_x$ possessed a funnel bandgap (Fig. 7c), which could efficiently promote the migration of photogenerated carriers from the bulk to the surface to participate in the photocatalytic redox reaction.¹⁰⁰ Consequently, the HER rate of $\text{MA}_3\text{Bi}_2\text{Cl}_{9-x}\text{I}_x$ (500 mg) was significantly improved to $341 \pm 61.7 \mu\text{mol h}^{-1}$ with Pt as the co-catalyst.

Ji *et al.* fabricated a number of $\text{Cs}_3\text{Bi}_2\text{X}_9$ perovskites, where X represents Cl, Br, or I.¹⁰¹ They observed that the absorption range of $\text{Cs}_3\text{Bi}_2\text{X}_9$ increases with the atomic number of halogens (Fig. 7d). Additionally, the Bi–Bi distance in the octahedral units gradually decreases from $\text{Cs}_3\text{Bi}_2\text{Cl}_9$ to $\text{Cs}_3\text{Bi}_2\text{I}_9$, alleviating the strong confinement effect of electron–hole pairs and accelerating the separation and transfer of photogenerated charges. Consequently, $\text{Cs}_3\text{Bi}_2\text{I}_9$ with the higher light absorption exhibited the most outstanding photocatalytic activity, with an HER rate of $107.89 \mu\text{mol h}^{-1}$ (50 mg) in ethanol solution (Fig. 7e).

In contrast, under I-rich and Bi-poor conditions, Bi^{3+} vacancies readily appear in Bi-based perovskites with the formation energy of 1.34 eV.⁹³ These vacancies form deep energy levels within the band gap, impeding the separation of photogenerated carriers and serving as sites for recombination. To confront this challenge, Chen *et al.* introduced Sb into $\text{Cs}_3\text{Bi}_2\text{I}_9$ and obtained $\text{Cs}_3\text{Bi}_{2-x}\text{Sb}_{2-2x}\text{I}_9$.⁹³ The theoretical calculation confirmed that the addition of Sb resulted in a lower participation of Bi^{3+} in the conduction band, which weakened the impact of Bi vacancies on the band structure. This effect was reflected in the narrower band gap and fewer intermediate band of $\text{Cs}_3\text{Bi}_{2-x}\text{Sb}_{2-2x}\text{I}_9$ than pure $\text{Cs}_3\text{Bi}_2\text{I}_9$ and $\text{Cs}_3\text{Sb}_2\text{I}_9$ (Fig. 7f–h), which significantly improved its performance of H_2 evolution reaction, with an optimal HER rate of $92.6 \mu\text{mol h}^{-1}$ (100 mg) among all reported lead-free perovskites.

Additionally, He *et al.* prepared a defect-rich $\text{Cs}_2\text{AgBiBr}_6$ by inducing surface defects by visible light, which exhibited better photocatalytic efficiency than $\text{Cs}_2\text{AgBiBr}_6$.⁹⁷ The defect-rich $\text{Cs}_2\text{AgBiBr}_6$ exhibited an HER rate of $0.406 \mu\text{mol h}^{-1}$ (500 mg), surpassing that of pure $\text{Cs}_2\text{AgBiBr}_6$ ($0.04 \mu\text{mol h}^{-1}$, 500 mg), and exhibited no performance degradation after an 80 h photocatalytic HER.

Similarly, the Sb element, which is adjacent to Pb, also contains ns^2 lone pair electrons and exhibits stable positive trivalent state, making it a promising alternative to Pb.¹⁰⁹ Rokesh *et al.* synthesized a new organic–inorganic hybrid

perovskite, named 2-(aminomethyl pyridine) SbI_5 (2-AMPSbI₅), *via* sol–gel method.⁹¹ The 2-AMPSbI₅, using Sb-iodide precursors, displayed a promising HER rate ($1.86 \mu\text{mol h}^{-1}$, 10 mg) in ethanol solution.

4. MHP-based composite photocatalysts

4.1 Band structure of composite photocatalysts

To enhance the separation of photogenerated carriers, composite photocatalysts with heterogeneous structures have been investigated. These composite photocatalysts often consist of a combination of photocatalysts with other materials, including conductors, semiconductors, and insulators. Among the various composites, heterojunctions formed between semiconductors have received significant attention, primarily categorized into I-type, II-type, Z-type, and S-type heterojunctions.

The band arrangement of two semiconductors in a I-type heterojunction is straddling. When exposed to light, photogenerated carriers are transferred from the wide-bandgap semiconductor to the semiconductor with lower conduction and higher valence bands to participate in the photocatalytic reaction (Fig. 8a).¹¹⁰ In contrast, the band arrangement of two semiconductors in a II-type heterojunction is staggered. Under illumination, electrons transfer to the lower conduction band, while holes transfer to the higher valence band, both actively participating in the photocatalytic reaction (Fig. 8b).¹¹¹ Although the II-type heterojunction enhances charge carrier separation, it comes at the expense of the oxidation–reduction capacity of the two semiconductors. Z-type heterojunctions, named for their photogenerated carrier transfer process resembling the letter “Z”, share a similar structure with II-type heterojunctions.¹¹² However, oxidation and reduction reactions occur in semiconductors with higher conduction band and lower valence band, respectively. The remaining electrons and holes are recombined indirectly or interactively (Fig. 8c). The S-type heterojunction originates from the band bending that

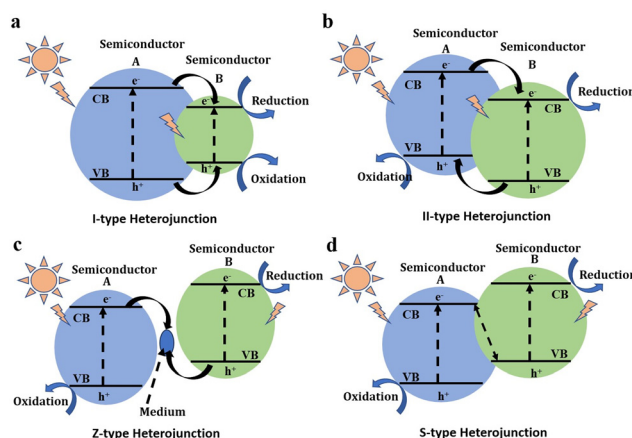


Fig. 8 Schematic diagrams of semiconductor heterojunctions. (a) I-type heterojunction. (b) II-type heterojunction. (c) Z-type heterojunction. (d) S-type heterojunction.

Table 2 Summary of works on photocatalytic application of MHP-based composite catalysts. R = H_2 evolution reaction rate, S = STH efficiency, A = AQE

Composite catalysts	Test conditions	Total catalyst usage (mg)	Performance	Year ^{Ref.}
Pt(0.75 wt%)/TiO ₂ /MAPbI ₃	Xe lamp (300 W, $\lambda \geq 420$ nm) 200 mW cm ⁻² HI solution	15	$R = 79.4 \mu\text{mol h}^{-1}$ $S = 0.86\%$ $A = 70\%$ at 420 nm	2018 ¹¹³
CsPbBr ₃ /Ru@TiO ₂	Continuous wave (CW) laser (445 nm, 50 mW) Trifluoroacetic acid/triethylamine	3.2	$R = 30.72 \mu\text{mol h}^{-1}$ $A = 0.4 \pm 0.1\%$ at 445 nm	2018 ¹¹⁴
5% rGO/MAPbI ₃	Xe lamp (300 W, $\lambda \geq 420$ nm) 120 mW cm ⁻² HI solution	100	$R = 93.9 \mu\text{mol h}^{-1}$ $A = 1.5\%$ at 450 nm	2018 ¹¹⁵
1.2% BP/MAPbI ₃	Xe lamp (300 mW cm ⁻² , $\lambda \geq 420$ nm) 25.3 mW cm ⁻² HI solution	30	$R = 112.26 \mu\text{mol h}^{-1}$ $S = 0.93\%$ $A = 1.5\%$ at 450 nm	2019 ¹¹⁶
15% Ni ₃ C/MAPbI ₃	Xe lamp (300 mW cm ⁻² , $\lambda \geq 420$ nm) 100 mW cm ⁻² HI solution	50	$R = 118.1 \mu\text{mol h}^{-1}$ $S = 0.91\%$ $A = 16.6\%$ at 420 nm	2019 ¹¹⁷
MAPbBr ₃ @Pt/Ta ₂ O ₅ /PEDOT:PSS	Xe lamp (300 W, $\lambda \geq 420$ nm) 150 mW cm ⁻² HBr solution	157.5	$R = 105 \mu\text{mol h}^{-1}$ $A = 16.4\%$ at 420 nm	2019 ¹¹⁸
2.5% rGO/Cs ₂ AgBiBr ₆	Xe lamp (300 W, $\lambda \geq 420$ nm) HBr solution	200	$R = 9.78 \mu\text{mol h}^{-1}$ $A = 0.16\%$ at 450 nm	2020 ¹¹⁹
g-C ₃ N ₄ /Cs ₃ Bi ₂ I ₉ (10 : 0.1 wt%)	Xe lamp (450 W) equipped with a water-filter and a WG320-filter Methanol solution (10% vol)	6	$R = 5.52 \mu\text{mol h}^{-1}$	2020 ¹²⁰
Pt(1.25 wt%)/TiO ₂ /EtbtBi ₂ I ₁₀ /rGO	Xe lamp (300 W) HF solution	61	$R = 16.76 \mu\text{mol h}^{-1}$	2020 ¹²¹
CPD(1 wt%)/MAPbI ₃ /Pt(2 wt%)	Xe lamp (300 W, $\lambda \geq 420$ nm, 300 mW cm ⁻²) 100 mW cm ⁻² HI solution	103	$R = 1184.2 \mu\text{mol h}^{-1}$ $S = 2.15\%$ $A = 53.6\%$ at 420 nm	2020 ¹²²
MoS ₂ NSs/MAPbI ₃	White-light LED lamps (10 W × 9, 380 nm ≤ λ ≤ 780 nm, 105 450 mW cm ⁻²) HI solution	105	$R = 206.1 \mu\text{mol h}^{-1}$	2020 ¹²³
MA ₃ Bi ₂ I ₉ /DMA ₃ BiI ₆	Xe lamp (300 W, $\lambda \geq 420$ nm) HI solution	200	$R = 39.64 \mu\text{mol h}^{-1}$	2020 ¹²⁴
MAPbI ₃ /CoP	Xe lamp (150 W, $\lambda \geq 420$ nm) HF solution	ca. 3.12	$R = 6.5 \mu\text{mol h}^{-1}$	2020 ¹²⁵
MAPbI ₃ -MC/ML-MoS ₂	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻² HI solution	100	$R = 1360 \mu\text{mol h}^{-1}$ $S = 1.09\%$	2020 ¹²⁶
MoS ₂ (20 wt%)/MA _{0.6} FA _{0.4} PbI ₃	Xe lamp ($\lambda \geq 420$ nm, 300 mW cm ⁻²) 35 mW cm ⁻² HI solution	50	$R = 66.4 \mu\text{mol h}^{-1}$ $S = 0.87\%$ $A = 14.5\%$ at 550 nm	2020 ¹²⁷
DMASnBr ₃ (33 wt%)/g-C ₃ N ₄ @Pt(3 wt%)	Xe lamp (1500 W, 300–800 nm, 500 W m ⁻²) equipped with UV outdoor filter TEOA solution (10% vol)	21	$R = 36.33 \mu\text{mol h}^{-1}$	2021 ¹²⁸
NiCoB/MAPbI ₃	Xe lamp (300 W, $\lambda \geq 420$ nm) HI solution	65	$R = 170.7 \mu\text{mol h}^{-1}$ $A = 1.96\%$ at 450 nm	2021 ¹²⁹
Cs ₃ Bi ₂ Br ₉ /g-C ₃ N ₄	Xe lamp (1500 W, 300–800 nm, 500 W m ⁻²) equipped with UV outdoor filter TEOA solution (10% vol)	21	$R = 22.05 \mu\text{mol h}^{-1}$	2021 ¹³⁰
MAPbI ₃ /MoS ₂ nanoflowers	Xe lamp (280 W, $\lambda \geq 420$ nm, 410 mW cm ⁻²) 100 mW cm ⁻² HI solution	50	$R = 1469.45 \mu\text{mol h}^{-1}$ $S = 7.35\%$ $A = 22.1\%$ at 500 nm	2021 ¹³¹
Cs ₂ AgBiBr ₆ /N-C	Xe lamp (300 W, $\lambda \geq 420$ nm) 100 mW cm ⁻² HBr solution	10	$R = 3.8 \mu\text{mol h}^{-1}$ $A = 0.59\%$ at 420 nm	2021 ¹³²
MAPbI ₃ /PANI NWs	White-light LED lamps (10 W, 380 nm ≤ λ ≤ 780 nm) HI solution	107	$R = 38.8 \mu\text{mol h}^{-1}$ $A = 0.3\%$ at 420 nm	2021 ¹³³
Cs ₂ AgBiBr ₆ /MoS ₂ (20 wt%)	Xe lamp (300 W, $\lambda \geq 420$ nm, 300 mW cm ⁻²) 41 mW cm ⁻² HBr solution	50	$R = 4.375 \mu\text{mol h}^{-1}$ $A = 0.2\%$ at 450 nm	2022 ¹³⁴
CsPbBr ₃ (30 wt%)/ZIF-8	Xe lamp (300 W) Na ₂ SO ₃ DI water solution	300	$R = 2.36 \mu\text{mol h}^{-1}$	2022 ¹³⁵
g-C ₃ N ₄ /Cs ₂ AgBiBr ₆ (1 : 10 wt%)	Xe lamp (300 W, $\lambda \geq 420$ nm) HBr solution	50	$R = 3 \mu\text{mol h}^{-1}$	2022 ¹³⁶
NiCoP(12.5% wt%)/Cs ₂ AgBiBr ₆	Xe lamp (300 W, $\lambda \geq 420$ nm) HBr solution	100	$R = 37.32 \mu\text{mol h}^{-1}$	2022 ¹³⁷
CsPbBr ₃ /GO-Pt	Xe lamp (300 W, $\lambda \geq 400$ nm) Aromatic alcohol	10	$R = 10.6 \mu\text{mol h}^{-1}$	2022 ¹³⁸

occurs at the interface of two semiconductors, which resembles the shape of the letter “S”, and its internal charge transfer is akin to the Z-type heterojunction (Fig. 8d).¹³⁹ Both S-type and Z-type heterostructures effectively promote charge transfer without compromising the respective oxidation and reduction capabilities of the two semiconductors, garnering considerable research interest in recent years.^{140–143} Meanwhile, the redox reaction is separated in space, and it is therefore expected to achieve an efficient overall water splitting through the appropriate medium and test system.⁷⁷

In order to improve the hydrogen production performance of MHP-based photocatalysts, various composite structures have been constructed, such as black phosphorus/MAPbI₃ I heterojunction,¹¹⁶ MAPbI₃/MoS₂ II heterojunction,¹³¹ *etc.* (Table 2). In the following section, we mainly introduce the applications of MHP/conductor or MHP/semiconductor composites in the photocatalytic HER.

4.2 Metal halide perovskite/0D nanoparticles composites

4.2.1 Metal oxide nanoparticles. TiO₂ is often used as an electron transport layer in perovskite solar cells due to its good energy level alignment with MHP materials,^{144,145} making MHPs/TiO₂ composite systems highly promising for photocatalytic HER. Pavliuk *et al.* first prepared a Pt@TiO₂/CsPbBr₃ composite photocatalyst in which CsPbBr₃ and Pt@TiO₂ acted as solar-light harvesters and photocatalysts (Fig. 9a), respectively. Triethylamine and trifluoroacetic acid were employed as a sacrificial agent and an electron donor, respectively, to stabilize CsPbBr₃. As a result, the Pt@TiO₂/CsPbBr₃ system demonstrated an HER rate of approximately 30.72 μmol h⁻¹ (3.2 mg) and an STH efficiency of about 0.4%. Similarly, Wang *et al.* established a TiO₂ electron-transporting

channel between Pt and MAPbI₃.¹¹³ This combination resulted in a significant elevation in the photocatalytic HER rate of 79.4 μmol h⁻¹ (15 mg), an approximately 89-fold increase compared to the HER rate of Pt/MAPbI₃. Additionally, the AQE of HER was about 70% at 420 nm, and the STH efficiency was approximately 0.86%. Furthermore, Ta₂O₅ nanoparticles were loaded with Pt and then combined with MAPbI₃ as Ta₂O₅/MAPbI₃/Pt composite photocatalyst, which exhibited an HER rate of 39.9 μmol h⁻¹ (15 mg).¹¹³

In a subsequent study, Wang *et al.* prepared a MAPbBr₃@Pt/Ta₂O₅/PEDOT:PSS composite photocatalyst by simultaneously introducing a photogenerated electron extractor (Ta₂O₅) and a photogenerated hole extractor (PEDOT:PSS) (Fig. 9b).¹¹⁸ By combining MAPbBr₃ with Pt/Ta₂O₅ and PEDOT:PSS, electron and hole transport channels were established, which greatly improved the charge transport efficiency and realized efficient catalytic reactions. Consequently, the HER rate of the MAPbBr₃@Pt/Ta₂O₅/PEDOT:PSS composite photocatalyst (105 μmol h⁻¹, 157.5 mg) was 52-fold higher than that of pristine MAPbBr₃, emphasizing the outstanding advantages of establishing a dual charge transport highway for improving the photocatalytic performance of MHP materials.

4.2.2 Transition metal carbide nanoparticles. Ni₃C, as an earth-abundant and fascinating iron group transition metal carbide, has demonstrated exceptional photocatalytic activity for H₂ production in acidic conditions.^{146–148} Through a simple surface charge-promoted self-assembly technique, Zhao *et al.* synthesized a MAPbI₃/Ni₃C composite photocatalyst.¹¹⁷ Scanning electron microscope (SEM) images showed that Ni₃C was loaded on the surface of MAPbI₃ (Fig. 9c). The photocatalytic process of this composite is shown in the Fig. 9d. The HER rate of 15% Ni₃C/MAPbI₃ reached 118.1 μmol h⁻¹ (50 mg),

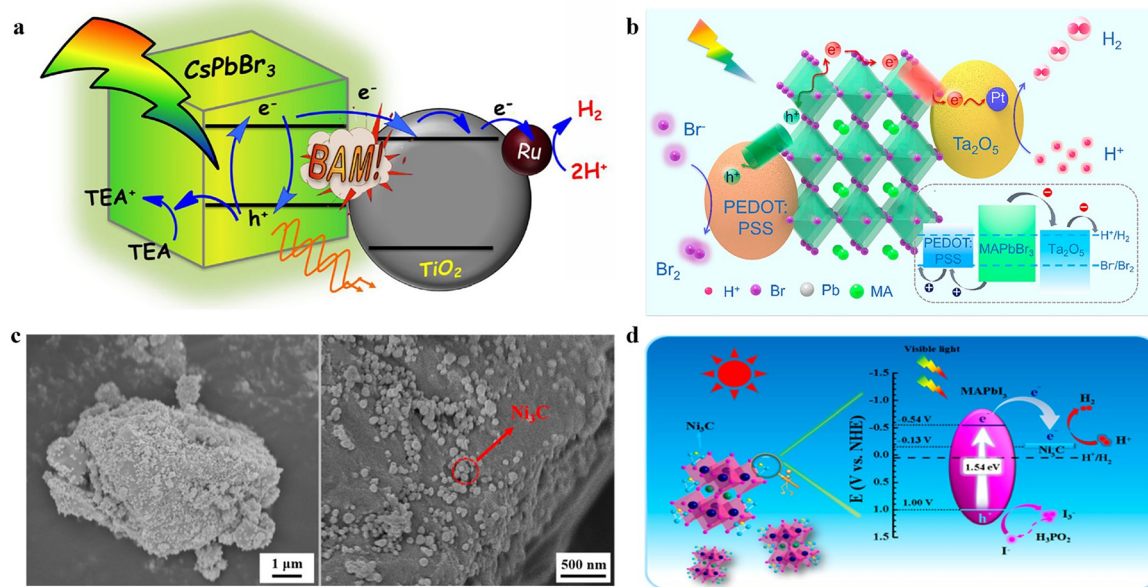


Fig. 9 (a) The schematic diagram of photocatalytic HER on Pt@TiO₂/CsPbBr₃ in TEOA solution.¹¹⁴ Copyright 2018 Elsevier. (b) The schematic diagram of photocatalytic HER on Pt@Ta₂O₅/MAPbBr₃/PEDOT:PSS in HBr solution.¹¹⁸ Copyright 2019 American Chemical Society. (c) SEM images of Ni₃C/MAPbI₃. (d) The mechanism of photocatalytic HER of Ni₃C/MAPbI₃.¹¹⁷ Copyright 2019 American Chemical Society.

which was about 55-fold enhancement than that of MAPbI₃ (2.15 μmol h⁻¹, 50 mg) and far higher than that of Pt/MAPbI₃ (26.7 μmol h⁻¹, 50 mg). Notably, the photocatalytic HER rate of Ni₃C/MAPbI₃ showed no obvious decrease after a designed photoreaction process involving 10 cycles, one-month storage, and an additional 10 cycles, highlighting the superb stability of this composite photocatalyst. The excellent photocatalytic HER activity and stability of Ni₃C/MAPbI₃ were believed to originate from the improved carrier separation and transfer ability, the increased number of reaction sites on the surface of MAPbI₃, and the intrinsic stability of the composite photocatalyst.

4.2.3 Transition metal phosphide nanoparticles. Transition metal phosphides are hopeful substitutes for noble metal cocatalysts to enhance the outstanding carriers' separation and migration capacity and enable low-cost production.^{149–151} Using a simple *in situ* photosynthesis method, Cai *et al.* first synthesized a MAPbI₃/cobalt phosphide (CoP) composite structure.¹²⁵ CoP nanoparticles could be used as cocatalysts as they can not only effectively extract photoinduced electrons from MAPbI₃ and enhance the separation of carriers but also promote interfacial photocatalytic reactions. Based on these advantages, the MAPbI₃/CoP composite photocatalyst exhibited an excellent HER rate of *ca.* 2.45 μmol h⁻¹ (*ca.* 3.12 mg) in HI solution within 3 h, which was about 8-fold enhancement than that of bare MAPbI₃. Moreover, when the photocatalytic reaction time increased to 27 h, its HER rate reached *ca.* 6.5 μmol h⁻¹ (*ca.* 3.12 mg), which could be attributed to the ameliorative crystallinity of MAPbI₃ and the increased reaction active sites of CoP co-catalyst during the incessant photocatalytic reaction. Furthermore, Huang *et al.* developed a NiCoP/Cs₂AgBiBr₆ composite photocatalyst *via* the electrostatic coupling method.¹³⁷ With visible-light irradiation, NiCoP acted as an electron extractor to improve the charge separation efficiency of Cs₂AgBiBr₆, thereby boosting the photocatalytic H₂ production ability. Specifically, the composite photocatalyst displayed a maximum HER rate of 37.32 μmol h⁻¹ (100 mg) at a loading amount of 12.5% NiCoP, with approximately 88-fold enhancement over that of pristine Cs₂AgBiBr₆. In addition, transition metal phosphides are economical and environmentally friendly, favouring their further development.

4.2.4 Carbon-based nanomaterials. Being part of the carbon-based nanomaterial family, carbonized polymer dots (CPDs) exhibit exceptional potential in enhancing the photocatalytic HER activity of MHP owing to their high photochemical stability, outstanding photophysical, and chemical properties.^{152,153} Zhao *et al.* developed a hybrid photocatalytic system by combining Pt/MAPbI₃ with CPDs synthesized from citric acid (CA) and *p*-aminosalicylic acid (PASA), in which the CPDs acted as efficient photogenerated hole extractors. Benefiting from the well-matched energy levels, the optimized Pt/MAPbI₃/CA-PASA CPD hybrid photocatalytic system exhibited an outstanding HER rate of 1184.2 μmol h⁻¹ (103 mg), an STH efficiency of 2.15%, and an AQE of 53.6% at 420 nm.

4.3 Metal halide perovskite/2D vdW material composites

In recent years, 2D van der Waals (vdW) materials have demonstrated promising potential in the field of photocatalysis. The

advantages of using 2D vdW materials can be summarized as follows: (1) the 2D nature of these materials leads to unique electronic properties that can enhance electron transport and improve charge transfer capacity; (2) the atomic-scale thickness can effectively shorten the carrier diffusion distance and improve carrier utilization; (3) the inherently large specific surface area is beneficial for the adsorption and activation of reactive molecules. Thus, combining MHPs with 2D vdW materials provides great potential for photocatalytic HER.

4.3.1 Graphene derivatives. Graphene derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), which hold good electron transfer properties and acid stability,^{154–156} have been utilized in MHP-based composites to improve the HER performance of MHP. For instance, Wu *et al.* synthesized a MAPbI₃/rGO composite using a photoreduction method.¹¹⁵ SEM images showed that rGO was loaded on the surface of MAPbI₃. During photocatalytic HER, photoinduced electrons in MAPbI₃ were transferred to rGO *via* the Pb–O–C bond to participate in the reduction of H⁺ at the rGO position, and photogenerated holes oxidized I⁻ to I₃⁻ (Fig. 10a). Consequently, the MAPbI₃/rGO composite displayed an enhanced HER rate of 93.9 μmol h⁻¹ (100 mg), which was 67-fold enhancement than that of bare MAPbI₃. In another study, Chen *et al.* first demonstrated the selective oxidation of aromatic alcohol to the aromatic aldehyde using CsPbBr₃/GO-Pt composite, accompanied by HER.¹³⁸ GO with abundant functional groups induced the nucleation process of CsPbBr₃, leading to the smaller size perovskite nanocrystals. Additionally, GO-Pt acted as photogenerated electron extractors, inhibiting the recombination of electron–hole pairs. Consequently, the optimized CsPbBr₃/GO-Pt exhibited an HER rate of 10.6 μmol h⁻¹ (10 mg) with high selectivity (>99%) for benzyl aldehyde generation (10.5 μmol h⁻¹, 10 mg) under visible light, which was about 5-fold enhancement than that of the CsPbBr₃-Pt sample.

Liu *et al.* reported a 0D lead-free perovskite (Etb_t)₄Bi₂I₁₀ (Etb_t = 3-ethylbenzo[*d*]thiazol-3-ium) and constructed a (Etb_t)₄Bi₂I₁₀-based composite photocatalyst by introducing Pt/TiO₂ and rGO as an electron extractor and a hole extractor, respectively.¹²¹ Unlike conventional protonated cations, Etb_t does not contain conventional hydrogen-bond donors, which helps prevent hydrogen-bonding interactions from eroding hybrid perovskites. Consequently, (Etb_t)₄Bi₂I₁₀ showed outstanding stability in DI water, acid solution, and ultraviolet light, achieving a potential HER rate of 0.736 μmol h⁻¹ (130 mg) with 0.5 wt% Pt nanoparticles loading. After incorporating Pt/TiO₂ and rGO to achieve a dual-charge transport-modulated composite photocatalyst, the photocatalytic system showed a significantly improved HER rate of 16.76 μmol h⁻¹ (61 mg). In a later study, Wang *et al.* combined Cs₂AgBiBr₆ with rGO by a photo-reduction process and applied it for HER in a saturated HBr aqueous solution.¹¹⁹ The Cs₂AgBiBr₆/rGO with optimal rGO loading displayed improved photocatalytic performance compared to that of pure Cs₂AgBiBr₆, which could be attributed to the promoted separation and migration of carriers by rGO. The HER rate reached 9.78 μmol h⁻¹ (200 mg) under

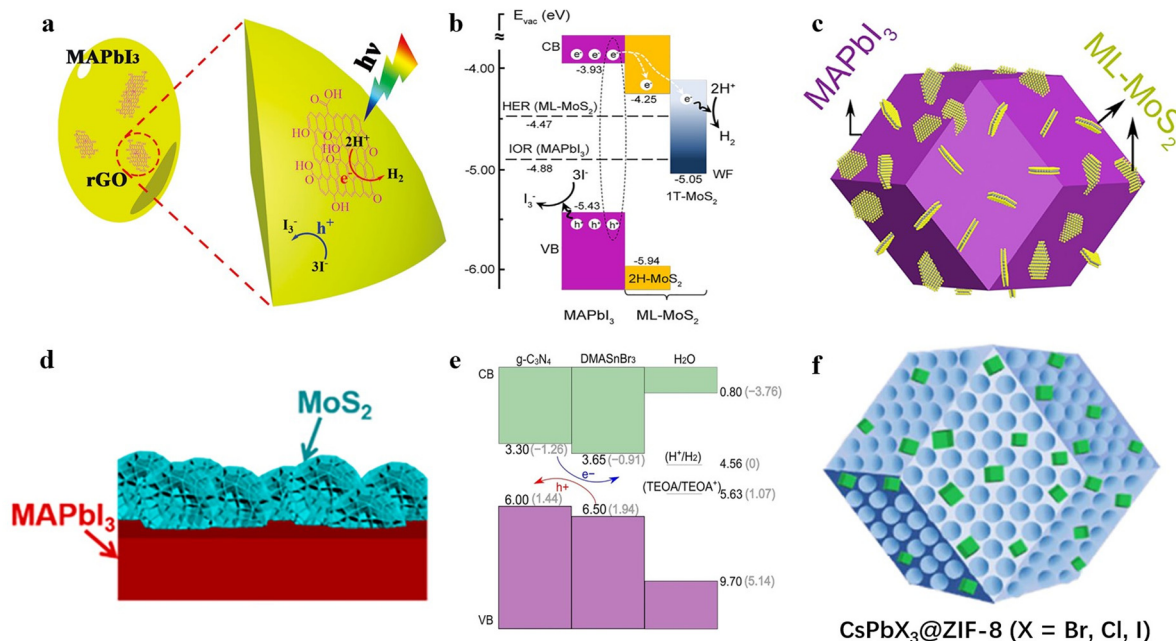


Fig. 10 (a) The schematic diagram of photocatalytic HER on MAPbI₃/rGO.¹¹⁵ Copyright 2018 Wiley-VCH GmbH. (b) The schematic diagram of photocatalytic HER on ML-MoS₂/MAPbI₃-MCs. (c) The schematic illustration of structure of ML-MoS₂/MAPbI₃-MCs.¹²⁶ Copyright 2020 Elsevier. (d) The schematic illustration of structure of MoS₂ nanoflowers/MAPbI₃ microcrystals.¹³¹ Copyright 2021 American Chemical Society. (e) The schematic mechanism of photocatalytic HER on g-C₃N₄@DMASnBr₃/Pt in triethanolamine solution.¹²⁸ Copyright 2018 Wiley-VCH GmbH. (f) The schematic illustration of structure of CsPbX₃@ZIF-8 (X = Br, Cl, I).¹³⁵ Copyright 2022 American Chemical Society.

visible light irradiation, without significant decrease for 120 h continuous photocatalytic HER.

4.3.2 Molybdenum disulphide. MoS₂ is a layered material that contains unsaturated sulphur, providing plentiful active sites for H₂ at the edges.^{157–160} Owing to its specific structure and properties, MoS₂ has been combined with various semiconductors to improve their catalytic performance in HER.^{161,162} Wang *et al.* demonstrated the *in situ* coupling of MAPbI₃ with MoS₂ nanosheets (MoS₂ NSs), resulting in a hybrid photocatalyst with high efficiency for visible-light-driven photocatalytic HER.¹²³ The composite exhibited excellent HER performance with an HER rate of 206.1 μmol h⁻¹ (105 mg), which was a 121-fold enhancement compared to that of bare MAPbI₃. In addition, Zhang *et al.* fabricated a series of MA_{1-x}FA_xPbI₃ by partially replacing MA⁺ with FA⁺, which was then coupled with MoS₂ cocatalyst for photocatalytic HER. The optimized MoS₂/MA_{0.6}FA_{0.4}PbI₃ composite (*i.e.*, 20 wt% MoS₂/MA_{0.6}FA_{0.4}PbI₃) exhibited a superior 66.4 μmol h⁻¹ (50 mg) visible HER rate, which was approximately 88-fold enhancement compared to that of pristine MAPbI₃ (1.2 μmol h⁻¹, 50 mg). The outstanding photocatalytic HER performances of MoS₂/MA_{0.6}FA_{0.4}PbI₃ could be attributed to the prolonged lifetime of photoinduced carriers inside MA_{0.6}FA_{0.4}PbI₃ due to the partial replacement of MA⁺ with FA⁺, and the enhanced carrier transfer and separation capabilities by MoS₂ decoration.

Subsequently, Zhao *et al.* developed a novel II-type heterojunction composite photocatalyst (Fig. 10b), consisting of monolayer MoS₂ nanosheets (ML-MoS₂) and MAPbI₃ microcrystals (MAPbI₃-MCs) (Fig. 10c), which could effectively inhibit

carriers recombination for high-efficiency photocatalytic HER.¹²⁶ This discovery developed new possibilities for enhancing the HER performance of perovskite-based photocatalysts, achieving a remarkable STH efficiency of 1.09% and an HER rate of 1360 μmol h⁻¹ (100 mg) under visible light. Furthermore, when other MHP microcrystals such as δ-FAPbI₃-MCs, MASnI₃-MCs, and MA₃Bi₂I₉-MCs were combined with ML-MoS₂ nanosheets, their HER rates increased by 8.4, 14.4, and 26 times, respectively, compared to their respective bare perovskite microcrystals. This indicates a hopeful approach for promoting the photocatalytic HER performance of halide perovskites. To further increase the active area of MoS₂, Guan *et al.* fabricated a MoS₂ nanoflowers/MAPbI₃ microcrystals heterostructure (Fig. 10d),¹³¹ The MoS₂ edges offered large amounts of unsaturated S₂²⁻ that could be considered as active sites for HER.^{163,164} Specifically, MAPbI₃/MoS₂ (3 : 7) exhibited a drastic enhancement in the HER rate, reaching up to 1469.45 μmol h⁻¹ (50 mg) and a champion STH efficiency of 7.35%. Based on available research, this is one of the highest STHs in photocatalytic HER. Furthermore, Zhang *et al.* fabricated an I-type heterostructured MoS₂/Cs₂AgBiBr₆ for efficient and enduring photocatalytic HER *via* loading MoS₂ on Cs₂AgBiBr₆ using a dissolution–recrystallization method.¹³⁴ The optimized MoS₂/Cs₂AgBiBr₆ composite achieved an HER rate of 4.375 μmol h⁻¹ (50 mg) in aqueous HBr solution, approximately 20-fold enhancement compared to that of bare Cs₂AgBiBr₆ (0.215 μmol h⁻¹, 50 mg), and presented an intermittent 500 h photocatalytic HER stability without obvious decrease. The enhanced activity of MoS₂/Cs₂AgBiBr₆ could be attributed to the kinetics-

facilitated heterostructure consisting of stable $\text{Cs}_2\text{AgBiBr}_6$ and MoS_2 .

4.3.3 Graphitic carbon nitride. $g\text{-C}_3\text{N}_4$ is a promising photocatalyst due to its high surface area, excellent interfacial charge separation and transport capability, and easy preparation, which is expected to integrate with MHPs with high light absorption ability.^{165–168} Bresolin *et al.* first fabricated a $\text{Cs}_3\text{Bi}_2\text{I}_9/g\text{-C}_3\text{N}_4$ composite photocatalyst *via* anchoring $\text{Cs}_3\text{Bi}_2\text{I}_9$ perovskite on $g\text{-C}_3\text{N}_4$ nanosheets.¹²⁰ This composite was tested in a methanol solution (10 vol% in water) with an HER rate of $5.52 \mu\text{mol h}^{-1}$ (6 mg), which was approximately 46% higher than that of bare $g\text{-C}_3\text{N}_4$. The improved photocatalytic performance was attributed to the enhanced light absorption and electrochemical properties of the newly designed composite. Romani *et al.* synthesized water-insoluble $\text{DMASnBr}_3/g\text{-C}_3\text{N}_4$ heterostructures for photocatalytic HER in a 10 vol% triethanolamine (TEOA) solution (Fig. 10e).¹²⁸ The HER rate of the optimized $g\text{-C}_3\text{N}_4/\text{DMASnBr}_3/\text{Pt}$ heterostructure ($36.33 \mu\text{mol h}^{-1}$, 21 mg) was more than 288-fold higher than that of $\text{Pt}/\text{DMASnBr}_3$ and 100-fold better than that of bare $g\text{-C}_3\text{N}_4$. This excellent photocatalytic HER performance could be attributed to the good band alignment of $g\text{-C}_3\text{N}_4/\text{DMASnBr}_3$, which effectively enhance the separation of photogenerated carriers. The researchers also developed a heterostructured photocatalyst by combining $\text{Cs}_3\text{Bi}_2\text{Br}_9$ with $g\text{-C}_3\text{N}_4$.¹³⁰ Photocatalytic HER was performed in a 10 vol% aqueous TEOA with Pt as the cocatalyst. The optimal photocatalytic HER rate was achieved when the loading of $\text{Cs}_3\text{Bi}_2\text{Br}_9$ was 2.5%, reaching approximately $22.05 \mu\text{mol h}^{-1}$ (21 mg), which was about an order of magnitude better than that of bare $g\text{-C}_3\text{N}_4$ ($1.701 \mu\text{mol h}^{-1}$, 21 mg). However, when the $\text{Cs}_3\text{Bi}_2\text{Br}_9$ loading amount exceeded 5%, the HER capacity of the composite photocatalyst decreased, probably due to the self-trapping of the photogenerated electrons.

Additionally, Song *et al.* synthesized mesoporous $g\text{-C}_3\text{N}_4$ and then loaded it onto the surface of $\text{Cs}_2\text{AgBiBr}_6$.¹³⁶ High-resolution transmission electron microscope (HRTEM) images clearly showed the secure contact between $\text{Cs}_2\text{AgBiBr}_6$ and $g\text{-C}_3\text{N}_4$. Spectroscopy analysis indicated the establishment of a II-type heterojunction structure between $\text{Cs}_2\text{AgBiBr}_6$ and $g\text{-C}_3\text{N}_4$. The optimized $g\text{-C}_3\text{N}_4/\text{Cs}_2\text{AgBiBr}_6\text{-10}$ (with a mass ratio of $g\text{-C}_3\text{N}_4$ and $\text{Cs}_2\text{AgBiBr}_6$ being 1 : 10) exhibited an excellent photocatalytic HER rate of $3 \mu\text{mol h}^{-1}$ (50 mg) without using any noble metal cocatalyst, achieving a 2.5-fold enhancement compared to that of the original $\text{Cs}_2\text{AgBiBr}_6$. Moreover, its photocatalytic HER efficiency showed no obvious decrease after storage for 40 days in air condition, indicating excellent stability and photocatalytic recyclability. Jiang *et al.* utilized a nitrogen-doped carbon (N-C) material based on $g\text{-C}_3\text{N}_4$ and coupled it with $\text{Cs}_2\text{AgBiBr}_6$ *via* a facile hydrothermal method.^{132,169} The photocatalytic HER performance test found that N-C itself had no photocatalytic HER ability. After combining with $\text{Cs}_2\text{AgBiBr}_6$, the composite material exhibited good photocatalytic HER activity. Particularly, when tested a hydrothermal temperature of 140°C , $\text{Cs}_2\text{AgBiBr}_6/\text{N-C-140}$ exhibited the best HER rate of $3.8 \mu\text{mol h}^{-1}$ (10 mg), about 19 times that

of the bare $\text{Cs}_2\text{AgBiBr}_6$. This improvement was ascribed to the large surface area of N-C and the presence of nitrogen atoms in N-C, which enhanced electron conductivity and promoted interfacial charge separation between $\text{Cs}_2\text{AgBiBr}_6$ and N-C.

4.3.4 Black phosphorous. Black phosphorus (BP) with high charge carrier mobility and abundant active sites has also been introduced to improve light absorption and photoinduced carriers separation of MHPs.^{170,171} For example, Li *et al.* reported a BP/MAPbI_3 heterostructure.¹¹⁶ Under solar-light irradiation, the photogenerated electrons could transfer from perovskite MAPbI_3 to BP to participate in the HER. Interestingly, the HER rate of the BP/MAPbI_3 heterostructure ($112.26 \mu\text{mol h}^{-1}$, 30 mg) was more than 100-fold enhancement compared to that of bare MAPbI_3 . This outstanding photocatalytic HER activity could be ascribed to the construction of a type I heterojunction, which could broaden light harvesting and enhance the separation and migration of carriers at the interface of BP/MAPbI_3 .

4.3.5 Lamellar transition metal borides. Jiang *et al.* developed a $\text{NiCoB}/\text{MAPbI}_3$ composite photocatalyst by combining amorphous NiCoB with a nanoscale lamellar structure, and MAPbI_3 using electrostatic self-assembly.¹²⁹ The photogenerated electrons from MAPbI_3 were able to transfer to NiCoB and participate in the reduction of H^+ , thereby promoting the separation of photoinduced carriers. At a NiCoB loading of 30%, the photocatalytic HER rate of MAPbI_3 reached a maximum of $170.7 \mu\text{mol h}^{-1}$ (65 mg) under visible light irradiation. Additionally, the composite showed good stability in a 24-hour cycling photocatalytic HER.

4.4 Metal halide perovskite/1D semiconductor composites

Conductive 1D polyaniline nanowires (PANI NWs) with high electrical conductivity and excellent chemical stability have been coupled with MHP to create high-performance composite photocatalysts. For example, Li *et al.* fabricated a high-performance 3D/1D heterostructured composite photocatalyst by combining conductive 1D polyaniline nanowires (PANI NWs) with MAPbI_3 using an *in situ* doping-induced assembly method.¹³³ SEM images obtained by Li *et al.* showed that PANI NWs were firmly embedded on the surface of MAPbI_3 . The $\text{MAPbI}_3/\text{PANI}$ NWs composite photocatalyst showed a remarkable 29-fold increase in the photocatalytic HER rate ($38.8 \mu\text{mol h}^{-1}$, 107 mg) compared to that of pristine MAPbI_3 microcrystals. Additionally, this composite photocatalyst demonstrated good stability during 30 h of irradiation, with each cycle lasting 6 h.

4.5 Metal halide perovskite/other material composites

In addition to the aforementioned materials, other semiconductors have also been used to couple with MHPs to create efficient photocatalytic systems. One such material is metal-organic frameworks (MOFs), which possess a large specific surface area, adjustable morphology, and diverse structure.^{172,173} By coupling MOFs with MHPs, the photocatalytic HER performance of MHPs can be enhanced. For instance, Feng *et al.* fabricated a $\text{CsPbBr}_3/\text{zeolitic imidazolate framework}$

(ZIF-8) composite using the mechanical milling method. This fabrication method was expected to enable large-scale synthesis of ZIF-8 composites (Fig. 10f).¹³⁵ SEM images showed that ZIF-8 was loaded on the surface of CsPbBr₃. The HER rate of this composite was measured to be ~11 times higher (2.36 μmol·h⁻¹, 300 mg, 2.5 h) than that of ZIF-8 alone (0.205 μmol·h⁻¹, 300 mg, 2.5 h), benefiting from the ZIF-8 promoted photogenerated carrier separation. Moreover, ZIF-8 was discerned to enhance the stability of CsPbBr₃ in aqueous solution, with only ~8% decrease in H₂ productivity after 4 weeks.

In addition to the above-mentioned strategies, the formation of MHP-MHPs heterojunctions has also been demonstrated as an effective approach to obtaining high-performance photocatalytic systems. For example, Tang *et al.* developed a lead-free Bi-based hybrid perovskite heterojunction, MA₃Bi₂I₉/DMA₃BiI₆, through an *in situ* growth method.¹²⁴ The VB and CB positions of MA₃Bi₂I₉ and DMA₃BiI₆ showed a well-matched II-type heterostructure, which facilitates the formation of an interfacial carriers transfer pathway at the interface of MA₃Bi₂I₉ and DMA₃BiI₆. This resulted in an HER rate of 39.64 μmol h⁻¹ (200 mg) without the addition of Pt co-catalysts.

5. Summary and prospects

MHPs have garnered significant interest in the field of photocatalytic H₂ evolution due to their outstanding photoelectric properties and tunable crystal structure. This review comprehensively discusses the structure and photocatalytic HER performance of different kinds of MHPs, including both lead-based perovskites and lead-free perovskites. Additionally, we summarize the developed strategies used to improve the photocatalytic performance of MHPs, including energy band structure adjustment (*e.g.*, extra halogen element doping), and composite structures (*e.g.*, MHPs/conductor, MHPs/semiconductor). However, despite their potential, the current photocatalytic performance of MHPs remains unsatisfactory for practical application, due to energy loss during charge generation, separation, and transfer, as well as concerns about the instability and toxicity of MHPs. In light of current MHP research, we propose several possible methods to further enhance the photocatalytic performance of MHP-based photocatalysts.

(1) Designing MHPs with optimal intrinsic crystalline structures at the molecular level. Photocatalysts play a crucial role in photocatalytic reactions, encompassing light absorption, photogenerated carriers generation, separation, transport, and surface redox reactions. To achieve efficient H₂ evolution, photocatalysts require appropriate electronic structures, wide light absorption range, large absorption coefficients, and excellent carrier transport performance.¹⁷⁴ The strong structural diversity and designability of MHPs make them highly advantageous for the design of photocatalysts. Emphatically, incorporating bulky organic cations at the A site can improve the intrinsic moisture resistance of MHPs, owing to the hydrophobic nature of the organic cations. However, introducing bulky

organic cations may cause the breakdown of the 3D perovskite framework, leading to the formation of low-dimensional perovskites such as 2D, 1D, and 0D perovskites. These low-dimensional perovskites, especially 1D and 0D perovskites, usually exhibit stronger quantum confinement effects and wider bandgaps compared to their 3D analogues, which may impair their optoelectronic properties.⁶⁵ Thus, striking a balance between optoelectronic performance and stability in MHPs design is of utmost importance. For instance, quasi-2D MHPs with a general formula of A₂A_{n-1}'Pb_nI_{3n+1}, (where A' is a bulky organic cation and A is MA or FA) have demonstrated higher environmental stability compared with MAPbI₃, due to the protection of the hydrophobic organic spacers. In particular, solar cells based on quasi-2D MHPs have recently achieved a remarkable power conversion efficiency (PCE) of 22.26%, indicating the preserved excellent semiconducting properties of these materials.¹⁷⁵ Further theoretical calculations and molecular engineering hold promise in promoting the development of MHPs for efficient and stable photocatalytic HER.

(2) Constructing band-matched heterostructured MHP composites. Although some strategies have achieved improved carrier separation efficiency, they often come at the expense of redox ability, ultimately leading to unsatisfactory photocatalytic HER performance. Additionally, the existence of photo-induced electron-hole pairs in the pristine photocatalyst may hinder the efficient interfacial transfer of electron-hole pairs in other catalysts. To overcome these limitations and further improve the photocatalytic HER performance of MHPs, novel forms of heterostructures, such as Z- and S-scheme heterojunctions, are expected.^{139,176} By selectively consuming or recombining a certain portion of photogenerated electrons and holes, electrons and holes with stronger redox ability can be retained, thus enhancing the photocatalytic activity of these heterojunctions. Moreover, it is important to consider the condition under which most MHPs-based photocatalytic HERs are realized, often using a HI solution. Thus, selecting a suitable acid-resistant photocatalyst for oxygen evolution based on the I⁻/I₃⁻ redox pair is expected to improve the efficiency of the photocatalytic HER process and enable overall water splitting.

(3) Developing encapsulation layers. Encapsulation is a crucial step in improving the stability of photocatalytic plate devices, as the water-instability of MHPs presents a significant challenge in the context of photocatalytic H₂ production. An ideal encapsulation material should possess excellent stability, good electrical conductivity, and light transmission. There are generally two types of encapsulations: full coverage and edge encapsulation. Full coverage encapsulation involves preparing the encapsulation layer on top of the module, while edge encapsulation involves placing a sealant around the module.¹⁷⁷⁻¹⁷⁹ Edge encapsulation offers advantages such as reduced impact on the contact layer, lowered light transmission requirements, and minimized potential side reactions between the encapsulating materials and the MHPs. However, the encapsulation effect may be slightly reduced compared to full coverage encapsulation. To further increase the barrier effect, desiccant can be introduced into the edge encapsulation process. Fully covered encapsulation

provides better protection, but it has a greater impact on the MHP layer and has higher light transmission requirements, as it directly contacts the MHP functional layer. An alternative approach involves multilayer encapsulation, which combines the benefits of both full coverage and edge encapsulation methods to improve the water stability of MHPs while maintaining their photocatalytic activity.¹⁸⁰ However, it is important to note that this method may be challenging to fabricate and could incur higher expense.

(4) Developing lead-free MHP photocatalysts. Among the candidates, Sn-based perovskites have shown promise due to the similarity of Sn²⁺ to Pb²⁺ in terms of electron configuration and ionic radius. However, the rapid oxidation of Sn²⁺ to Sn⁴⁺ remains a challenge. Various stabilization methods have been explored, such as adding reducing agents (e.g. H₃PO₂),¹⁸¹ but their stability remains inferior to Pb-based perovskites. A deeper understanding of Sn²⁺ bonding interactions in Sn-based perovskites could offer insights into addressing this issue. Similarly, Ge-based perovskites also face the challenge of Ge²⁺ oxidation. Bi-, Sb-based perovskites and double perovskites have demonstrated good stability under various conditions. However, their photocatalytic performance is generally limited by poor optoelectronic properties arising from their low electronic dimensional.¹⁸² Therefore, a promising direction for MHP-based photocatalytic H₂ evolution is the rational design of Bi-, Sb-based perovskites and double perovskites with high electronic dimensional using theoretical calculations and molecular engineering.

Conflicts of interest

There are no conflicts to declare.

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