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Modulation of the photocatalytic activity of MAPbI₃ crystals via Nb₂CT_x MXenes for high-efficiency photocatalytic hydrogen production

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This study addresses rapid charge recombination and instability in MAPbI₃ photocatalysts for hydrogen production by constructing a Nb₂CT_x MXenes-modulated composite. Leveraging Nb₂CT_x metallic conductivity for efficient electron extraction and proton reduction sites, the composite enables robust photocatalytic HI splitting in strong acid. *In situ* coupling achieved intimate heterointerface contact with Z-scheme characteristics, yielding a remarkable hydrogen evolution rate of 12 046.77 μmol h⁻¹ g⁻¹—a 344-fold enhancement over pristine MAPbI₃—while retaining ~85% activity after 5 cycles. UPS and theoretical calculations confirm a strong built-in electric field at the heterointerface accelerates carrier separation. Critically, the Z-scheme simultaneously suppresses recombination and preserves strong redox capabilities. This interface engineering synergistically enhances efficiency and stability, resolving the charge separation-redox capability trade-off in conventional type II heterojunctions.

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1. Introduction

Hydrogen energy has been widely recognized as the most promising next-generation clean energy carrier because its mass-specific energy density is approximately three times greater than that of gasoline and zero-pollution combustion byproducts.¹ As a crucial pathway for solar-to-chemical energy conversion, photocatalytic water splitting technology for hydrogen production relies fundamentally on the development of highly efficient and stable photocatalytic systems.^{2–8} Compared with conventional electrolytic water splitting, hydroiodic acid (HI) photolysis has significant advantages: an approximately 40% reduction in the reaction activation energy, a theoretical hydrogen production efficiency of 28%, and recyclable reactants under mild reaction conditions.^{9–14} High-performance photocatalysts must possess appropriate electronic structures capable of controlling the fate of photogenerated carriers to effectively suppress charge recombination.^{15–17} While traditional wide-bandgap semiconductors such as TiO₂ ($E_g = 3.2$ eV) exhibit

good chemical stability, their limited photoresponse range (<387 nm, UV region) and insufficient carrier diffusion length severely constrain solar utilization efficiency and charge separation^{18–20} capabilities. In recent years, organic-inorganic hybrid perovskite materials (ABX₃-type) have attracted intensive research interest because of their unique photophysical properties. For example, methylammonium lead iodide (MAPbI₃) possesses an optimal bandgap structure of 1.50 eV, enabling full-spectrum visible light absorption (absorption coefficient > 10⁴ cm⁻¹) and extended carrier lifetimes.^{21–26} Pioneering work by Park *et al.*¹³ first extended MAPbI₃ applications to HI photolysis systems, establishing a new research direction in perovskite photocatalysis. However, MAPbI₃ still faces two critical challenges in photocatalytic processes: rapid recombination of photogenerated carriers at the nanoscale, leading to reduced hydrogen evolution reaction (HER) rates, and structural instability-induced catalyst deactivation in HI solutions.¹¹ These bottlenecks fundamentally originate from the intricate interplay between intrinsic electronic structure modulation and surface/interface stability optimization, urgently requiring breakthroughs through innovative material design and mechanistic understanding.

To address the aforementioned challenges, the construction of heterojunction interfaces has been recognized as a pivotal strategy for overcoming the performance bottleneck in perovskite photocatalysis by modulating carrier dynamics. By loading cocatalysts on MAPbI₃ surfaces to form type II or Schottky

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heterojunctions,²⁷ directional charge transport channels can be effectively established, thereby suppressing the recombination of photogenerated electron-hole pairs. Typical fabrication approaches involve depositing electron transport materials (*e.g.*, reduced graphene oxide (rGO),²⁸ few-layer black phosphorus (BP),¹⁴ Ni₃C,¹⁰ MoS₂,^{29,30} or transition metal compounds) as nanoparticles onto MAPbI₃ perovskite surfaces. Noble metals such as Au, Pt, and Ag have also been widely employed as cocatalysts in heterojunction photocatalysts. For example, in the Pt-TiO₂/MAPbI₃ system, Pt nanoparticles function as electron traps that significantly enhance the carrier separation efficiency, achieving a hydrogen evolution rate of 1.99 mmol g⁻¹ h⁻¹ with a corresponding solar-to-hydrogen (STH) conversion efficiency of 0.86%.¹¹ This performance enhancement originates from heterojunction-induced band bending, which drives the migration of photogenerated electrons from MAPbI₃ to cocatalysts, thereby optimizing the kinetics of H⁺ reduction and substantially improving the photocatalytic hydrogen evolution reaction (HER) activity. Nevertheless, despite their effectiveness, noble metal cocatalysts (*e.g.*, Pt and Au) face critical limitations in large-scale applications because of their low natural abundance and prohibitively high costs.³¹

In recent years, two-dimensional transition metal carbides/nitrides (MXenes) have emerged as novel candidates for developing non-noble metal cocatalysts because of their unique electronic configurations and surface characteristics.^{32–38} MXenes (with the general formula M_{n+1}-X_nT_x) exhibit metal-like electrical conductivity (>10⁴ S m⁻¹), tunable surface functional groups (-O, -F, and -OH),³⁹ and abundant exposed metallic sites. Compared with conventional carbon-based materials, their terminal metal sites demonstrate enhanced redox activity.^{40,41} Theoretical calculations revealed that heterointerfaces in MXenes-based composites can establish efficient charge transfer pathways, significantly improving the photogenerated charge carrier separation efficiency.⁴² The key mechanism lies in the Schottky barrier formed at the MXenes/semiconductor interface, which directionally drives photogenerated electron migration to the MXenes layer.^{43,44} Synchrotron radiation-based photoelectron spectroscopy studies confirm that charge accumulation induces a negative shift in the Fermi level of MXenes, with this band structure realignment substantially optimizing the thermodynamic driving force for photocatalytic hydrogen evolution reactions.⁴⁵ Notably, the hydrogen adsorption Gibbs free energy (ΔG_{H^*}) of MXenes can be regulated through surface termination groups to approach the ideal value ($\Delta G_{H^*} \approx 0$) for optimal HER performance, as exemplified by hydrogenated W₂C, oxidized Mo₂C,⁴⁶ O-terminated Ti₃C₂ (ref. 40) and other systems.⁴⁷ Among various MXenes materials, Nb₂C MXenes have distinctive advantages: their work function (~4.3 eV) is highly compatible with that of common semiconductors (*e.g.*, TiO₂ and g-C₃N₄). The two-dimensional layered structure not only suppresses nanoparticle aggregation and enhances mechanical stability but also facilitates accelerated interfacial

charge transfer through intrinsic carrier mobility at heterojunction interfaces, effectively reducing electron-hole recombination rates.^{48–51}

Through interface engineering strategies, multiple efficient photocatalytic systems have been successfully constructed using Nb₂CT_x MXenes composites. Tayyab *et al.*⁵² developed an In₂S₃/Nb₂O₅/Nb₂C ternary composite *via in situ* chemical anchoring, where Nb₂C suppresses charge recombination while accelerating electron transfer from Nb₂O₅ and In₂S₃ photocatalysts, achieving a hydrogen evolution rate of 68.8 $\mu\text{mol g}^{-1} \text{h}^{-1}$. In another study,⁵³ Tayyab *et al.* established an electrostatic self-assembly system of CdS nanowires on Nb₂C cocatalysts, wherein protons capture photoexcited electrons accumulated on Nb₂C for efficient H₂ generation. Su *et al.*⁵⁴ reported a Nb₂O₅/C/Nb₂C composite whose fourfold enhancement in photocatalytic water splitting over that of pure Nb₂O₅ originates from intimate Nb₂O₅-Nb₂C interfacial contact and efficient carrier separation. Moreover, Xu's team⁵⁵ employed a hydrothermal oxidation strategy to simultaneously reduce Ru³⁺ to metallic nanoparticles and transform Nb₂CT_x into Nb₂O₅ nanowires. The resulting Ru/Nb₂O₅/Nb₂C catalyst exhibited exceptional H₂ production (10.11 mmol g⁻¹ h⁻¹) under 313 nm illumination with 41.25% apparent quantum efficiency.

Despite these advances, the synergistic mechanisms between Nb₂CT_x-based materials and organic-inorganic hybrid perovskites (*e.g.*, MAPbI₃) remain underexplored. While the high electrical conductivity of Nb₂CT_x facilitates photogenerated electron extraction from MAPbI₃, and its metallic sites may lower the energy barrier for HI decomposition, systematic studies on Nb₂CT_x/MAPbI₃ composites for photocatalytic HI splitting are notably absent. Crucially, the synergistic optimization of interfacial stability and charge transfer kinetics in strongly acidic media represents an uncharted frontier. Addressing this knowledge gap is essential for designing perovskite-based photocatalysts with simultaneously high activity and durability.

Conventional type II heterojunctions often sacrifice redox capability for improved charge separation. To overcome this trade-off and enhance stability, we rationally selected Nb₂CT_x MXenes for interfacial modification of MAPbI₃, driven by compelling theoretical foundations: 1) metallic conductivity and interfacial engineering: Nb₂CT_x exceptional metallic conductivity provides an ultra-efficient pathway for rapid electron extraction and transport from MAPbI₃, minimizing recombination losses. Furthermore, it offers active proton reduction sites. The proposed *in situ* coupling ensures an intimate heterointerface, critical for efficient charge transfer and predicted to generate a strong built-in electric field (BIEF). This BIEF acts as an additional driving force, accelerating spatial carrier separation. 2) Z-Scheme mechanism: theoretical band alignment predicts the formation of a direct Z-scheme heterojunction at the MAPbI₃/Nb₂CT_x interface. In this mechanism, photogenerated electrons from MAPbI₃ recombine with holes in Nb₂CT_x (facilitated by its metallic states). This suppresses bulk



recombination within MAPbI₃ while preserving its highly oxidative holes and leaving highly reductive electrons on Nb₂CT_x for efficient proton reduction, thus maintaining strong inherent redox power. Therefore, the MAPbI₃/Nb₂CT_x composite is theoretically designed for synergistic enhancement: the Z-scheme preserves redox capability and suppresses recombination, while Nb₂CT_x conductivity and interfacial engineering ensure efficient charge extraction/utilization and stability, resolving the fundamental limitations of type II systems.

This study successfully constructed a Z-scheme heterojunction MAPbI₃/Nb₂CT_x MXenes composite photocatalytic system *via* an *in situ* coupling strategy, aiming to address the critical challenges of high carrier recombination rates and insufficient redox capability in MAPbI₃ perovskite materials. Structural characterization confirmed that small-sized Nb₂CT_x MXenes nanosheets are uniformly anchored on the MAPbI₃ surface through chemical bonding interactions, forming a heterointerface with directional charge transfer channels. Density functional theory (DFT) calculations revealed that the composite system exhibited an increased density of electronic states near the Fermi level, significantly improving the activity of the electrons participating in surface reduction reactions and thereby facilitating photocatalytic hydrogen evolution. Band structure analysis demonstrated that photogenerated electrons preferentially accumulate in the conduction band of Nb₂CT_x MXenes with higher reduction potentials, whereas photogenerated holes accumulate in the valence band of MAPbI₃ with superior oxidation potential. This directional charge transfer pathway not only suppresses electron-hole recombination but also preserves the high reduction capability of Nb₂CT_x MXenes and the strong oxidation capacity of the MAPbI₃ perovskite. Furthermore, the high electrical conductivity and abundant active sites on the Nb₂CT_x MXenes provide reaction sites for H₂ evolution and accelerate interfacial charge transfer, while the strong built-in electric field enhances the carrier separation efficiency. The synergistic effects endow the composite catalyst with exceptional photocatalytic hydrogen evolution performance (12 046.77 μmol h⁻¹ g⁻¹), retaining approximately 85% of its initial catalytic activity during consecutive cycling tests. This work establishes a novel paradigm for developing efficient and stable MAPbI₃ perovskite-based composite photocatalytic systems through interface engineering and heterojunction structure design.

2. Experimental

2.1 Materials

The raw materials, including lead oxide (PbO, 99%), methylammonium iodide (MAI, CH₃NH₃I, 99%), hydroiodic acid (HI, 47 wt% in H₂O), hydrofluoric acid (HF, 48 wt% in H₂O), MAX phase compound (Nb₂AlC, 400 mesh), and hypophosphorous acid (H₃PO₂, 50 wt% in H₂O), were obtained from Sigma-Aldrich and Jilin Yiyi Technology Co., Ltd. and

were used as received without further purification. Ethanol was purchased from Shaanxi China Pharmaceutical Group Co., Ltd. All the chemicals were of analytical grade and were used without additional refinement or purification. Deionized water was utilized throughout the experimental procedures.

2.2 Materials synthesis

2.2.1 Synthesis of Nb₂CT_x MXenes nanosheets. Two-dimensional layered Nb₂CT_x MXenes nanosheets were synthesized through selective etching of the Al layers from Nb₂AlC in hydrofluoric acid (HF) followed by delamination. Typically, 2 g of Nb₂AlC powder was gradually added to 60 mL of 40% HF solution under continuous magnetic stirring at 50 °C for 90 hours to achieve complete Al layer removal. The etched suspension was then subjected to centrifugation at 4000 rpm for 5 minutes to separate unexfoliated MXenes particles, with the supernatant collected for subsequent processing. The obtained colloidal suspension underwent repeated washing cycles with deionized water followed by centrifugation until neutralization (pH ≈ 7). The resulting sediment was thoroughly degassed with argon gas for 1 hour and subsequently exfoliated through ultrasonication at 400 W for 2 hours. The final purification involved centrifugation-assisted collection of the black precipitate, followed by ethanol washing and vacuum oven drying at 80 °C for 24 hours. This optimized procedure yielded high-quality, oxygen-terminated two-dimensional Nb₂CT_x MXenes nanosheets with well-defined layered structures.

2.2.2 Synthesis of MAPbI₃/Nb₂CT_x MXenes composite photocatalytic materials by an *in situ* coupling method. Initially, 2 mL of hydroiodic acid (HI), 0.5 mL of H₃PO₂, and 0.92 g (4.12 mmol) of PbO were heated at 150 °C with magnetic stirring until complete dissolution of the yellow lead oxide powder was observed, resulting in the formation of a precursor solution. Following complete dissolution, preprepared Nb₂CT_x MXenes nanosheets with different mass ratios were introduced into the mixture under continuous stirring and heating for 15 minutes. Subsequently, 0.32 g (2 mmol) of MAI was added and dissolved through stirring and heating for an additional 20 minutes. Upon completion of these procedures, the reaction system was rapidly cooled to -2 °C in a Petri dish-assisted water bath. During this process in the HI solution, Nb₂CT_x MXenes nanosheets were anchored *in situ* onto the crystallized MAPbI₃ surfaces, forming the MAPbI₃/Nb₂CT_x MXenes composite photocatalytic system. Finally, the obtained MAPbI₃/Nb₂CT_x MXenes composites were sequentially washed with ethanol and diethyl ether through three cycles of centrifugation (5000 rpm, 5 min), followed by vacuum drying at 50 °C for 24 h.

2.3 Characterizations

2.3.1 Characterization of Nb₂CT_x MXenes materials. Powder X-ray diffraction (XRD) measurements were performed on a Bruker D8 Advance diffractometer using Cu Kα radiation (λ = 0.15406 nm) with a 2θ range of 5–90° at a



scanning rate of $10^\circ \text{ min}^{-1}$. The chemical states were investigated *via* X-ray photoelectron spectroscopy (XPS) recorded on a Thermo Scientific K-Alpha surface analysis system equipped with an Al K α X-ray source. Morphological analysis of the etched material was conducted by scanning electron microscopy (SEM) images obtained *via* a GeminiSEM 300 microscope and transmission electron microscopy (TEM) images acquired *via* a JEOL JEM-F200 microscope.

2.3.2 Characterization of the MAPbI₃/Nb₂CT_x MXenes composite photocatalytic material. The phase structure of the composite photocatalyst was analyzed *via* powder X-ray diffraction (XRD) on a Bruker D8 Advance diffractometer with Cu K α radiation ($\lambda = 0.15406 \text{ nm}$), covering a 2θ range of $5\text{--}90^\circ$ at a scanning rate of $10^\circ \text{ min}^{-1}$. Morphological features were examined *via* SEM images from a TESCAN MIRA4 microscope and TEM images from a JEOL JEM-F200 microscope. The elemental composition was characterized *via* energy-dispersive spectroscopy (EDS) on an OXFORD XPLORE 30 microscope. The heterojunction interface between the Nb₂CT_x MXenes and MAPbI₃ was observed through high-resolution transmission electron microscopy (HRTEM) images obtained *via* a JEOL JEM-F200 microscope. Chemical states were further studied by XPS on a Thermo Scientific K-Alpha system. UV-vis absorption spectra were recorded at room temperature using a Shimadzu UV-3600i Plus spectrophotometer with BaSO₄ as the reference background, spanning a wavelength range of 200–800 nm. Ultraviolet photoelectron spectroscopy (UPS) measurements of different crystals were performed using a Thermo Fisher Nexsa system.

2.4 Photocatalytic H₂ evolution

Unless otherwise specified, all photocatalytic hydrogen evolution experiments were conducted *via* a photochemical reactor (Model MC-SPH 2O-A, Merry Change) coupled with an online gas chromatograph (GC 9790 II, FULI INSTRUMENTS) for real-time detection. The reactor system comprises an outer housing and a separate external water-cooled circulation system. The housing contains an 80 mL Pyrex glass reaction chamber, while the external cooling system is equipped with a quartz window. The experimental parameters were standardized as follows: illumination area of 28.26 cm², light intensity of 100 mW cm^{−2} provided by a light source positioned 12 cm above the reaction solution surface, operating current of 10 mA, and irradiation duration of 5 h. Hydrogen production was quantified through GC analysis *via* a pre-established standard calibration curve. The typical experimental procedure consisted of four steps: 1) 200 mg of vacuum-dried MAPbI₃/Nb₂CT_x MXenes composite was mixed with 20 mL of saturated HI/H₃PO₂ aqueous solution in the reaction chamber; 2) the reaction system was cooled to 6 °C and evacuated under vacuum for 10 min; 3) the absence of residual H₂ was confirmed by an online GC prior to illumination; and 4) the photocatalytic HI splitting reaction

was initiated upon light irradiation, while H₂ generation was continuously monitored through GC analysis.

2.5 Calculation method

The computational simulations in this study were conducted *via* density functional theory (DFT) implemented in the Vienna *Ab initio* Simulation Package (VASP),⁵⁶ which uses projector augmented wave (PAW) pseudopotentials.⁵⁷ Electron exchange–correlation interactions were described through the Perdew–Burke–Ernzerhof (PBE)⁵⁶ generalized gradient approximation enhanced with semiempirical dispersion correction (DFT-D).⁵⁸ Spin-polarized calculations were carried out with a plane-wave energy cutoff of 520 eV to ensure basis set completeness. To enhance the structural parameters and refine the unit cell dimensions, a Gamma-centered⁵⁹ $9 \times 9 \times 1$ *k*-point mesh was employed during numerical integration across the Brillouin zone. The electronic self-consistent field iteration process maintained a rigorous convergence criterion of 10–5 eV per atom for total energy differences. All optimized configurations satisfied atomic force thresholds below 0.02 eV Å^{−1} while maintaining residual stress components within computational tolerance limits.

3. Results and discussion

3.1 Characterization of the structures and morphology of the Nb₂CT_x MXenes

The Nb₂CT_x MXenes nanosheets were synthesized by etching the Nb₂AlC MAX phase precursor with HF, as illustrated in Fig. 1(a). As evidenced by the XRD patterns of the materials before and after etching (Fig. 1(b)), the (002) diffraction peak of the Nb₂CT_x MXenes shifted to a lower angle after HF treatment, indicating an expansion of the interlayer spacing due to the removal of Al atoms and the synergistic effects of surface functional groups (–OH, –F, and –O) and intercalated water molecules, which led to structural loosening of the originally closely packed Nb₂AlC layers.⁶⁰ Concurrently, the exposed Nb₂CT_x MXenes surface underwent functionalization with these moieties. XPS analysis confirmed the successful synthesis of the Nb₂CT_x MXenes (Fig. 1(c)). The total XPS spectrum is shown in Fig. S1. The near-complete disappearance of the Al 2p signal at ~74 eV verified the effective removal of the Al layer. In the Nb 3d spectrum, the intensity of the original Nb–C bond (206.9 eV, 3d_{5/2}) decreased significantly, whereas new peaks emerged at 206.9 eV and 210.0 eV, corresponding to Nb–F and Nb–O bonds, respectively, indicating surface fluorination/oxidation. The O 1s spectrum revealed contributions from Nb–O (530.0 eV) and C=O (533.1 eV). These results collectively verify the successful synthesis of Nb₂CT_x MXenes with abundant surface –O and –F functionalities. The SEM and TEM images of the precursor MAX phase and MXenes phase before and after HF acid etching are shown in Fig. S2(a and b). The SEM image combined with the corresponding EDS map presented in Fig. 1(d) reveals that the Nb₂CT_x MXenes material has been uniformly etched into a characteristic accordion-like morphology. Furthermore, the TEM image in Fig. 1(e) further



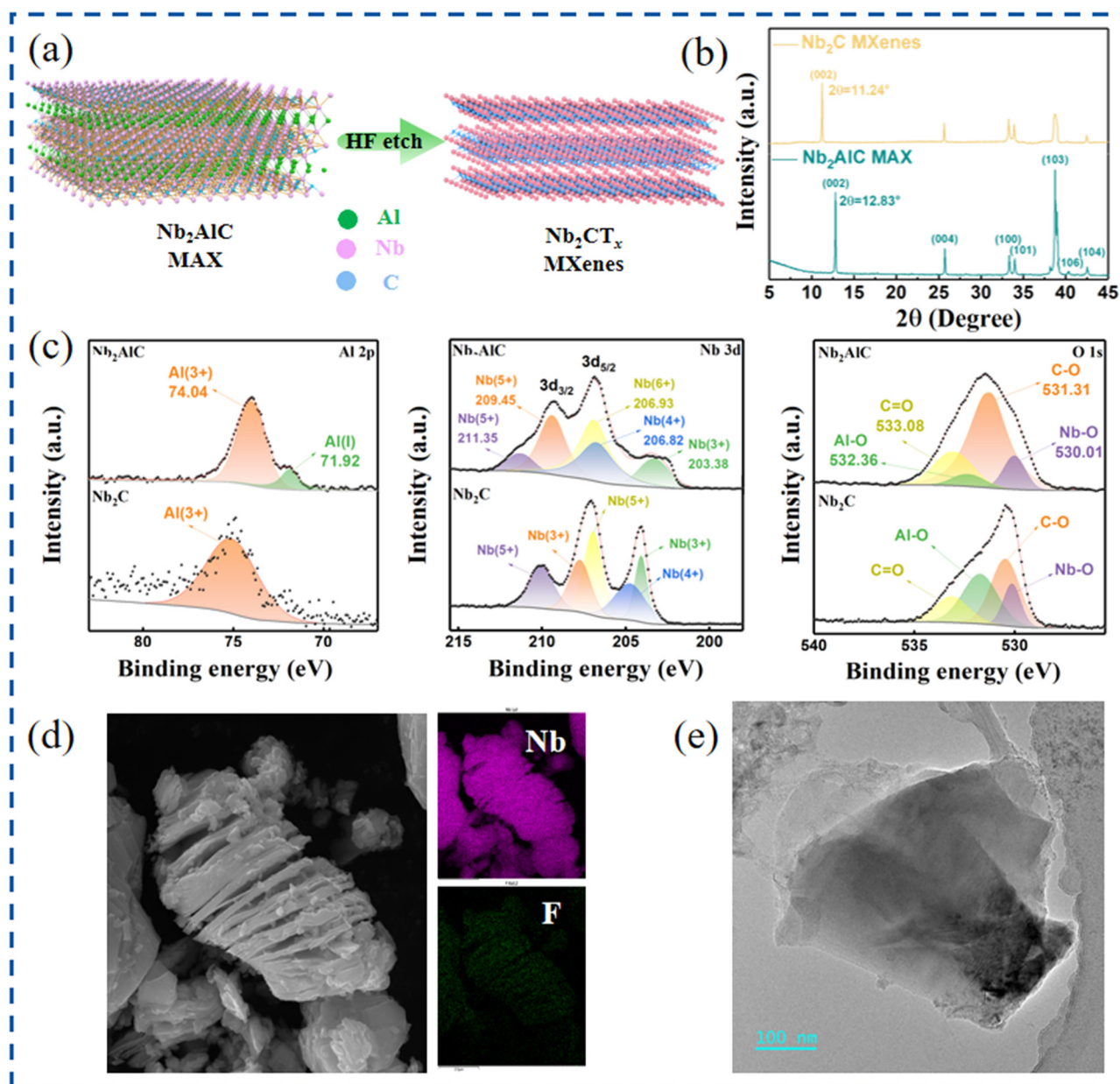


Fig. 1 (a) Etching process schematic of the Nb₂CT_x MXenes phase material obtained via HF acid etching of the Nb₂AlC MAX phase precursor. (b) XRD images of the Nb₂AlC MAX phase and Nb₂CT_x MXenes phase before and after etching. (c) XPS images, (d) SEM images, EDS images and (e) TEM images of the etched Nb₂CT_x MXenes phase.

confirms the formation of a layered structure. The structural stability of the Nb₂CT_x MXenes in HI aqueous solution was evaluated via X-ray diffraction (XRD). Minimal changes in the XRD patterns before and after HI immersion (Fig. S3) demonstrated the excellent chemical stability of the Nb₂CT_x MXenes under HI treatment.

3.2 Characterization of the structure and morphology of MAPbI₃/Nb₂CT_x MXenes

The heterojunction photocatalysts of MAPbI₃ and Nb₂CT_x MXenes nanosheets (MAPbI₃/Nb₂CT_x MXenes) were fabricated

via an *in situ* coupling method. Specifically, various quantities (20 mg, 40 mg, 80 mg, 100 mg, and 120 mg) of synthesized Nb₂CT_x MXenes were introduced into the precursor solution for MAPbI₃ perovskite synthesis. The resulting composites were designated MAPbI₃/20MX, MAPbI₃/40MX, MAPbI₃/80MX, MAPbI₃/100MX and MAPbI₃/120MX, respectively. The as-prepared MAPbI₃/Nb₂CT_x MXenes composites exhibited a structural configuration in which multiple small-sized Nb₂CT_x MXenes nanosheets were anchored onto larger MAPbI₃ substrates (Fig. 2(a)). This architecture endows the composites with enhanced charge separation efficiency and superior photocatalytic performance for HI decomposition.



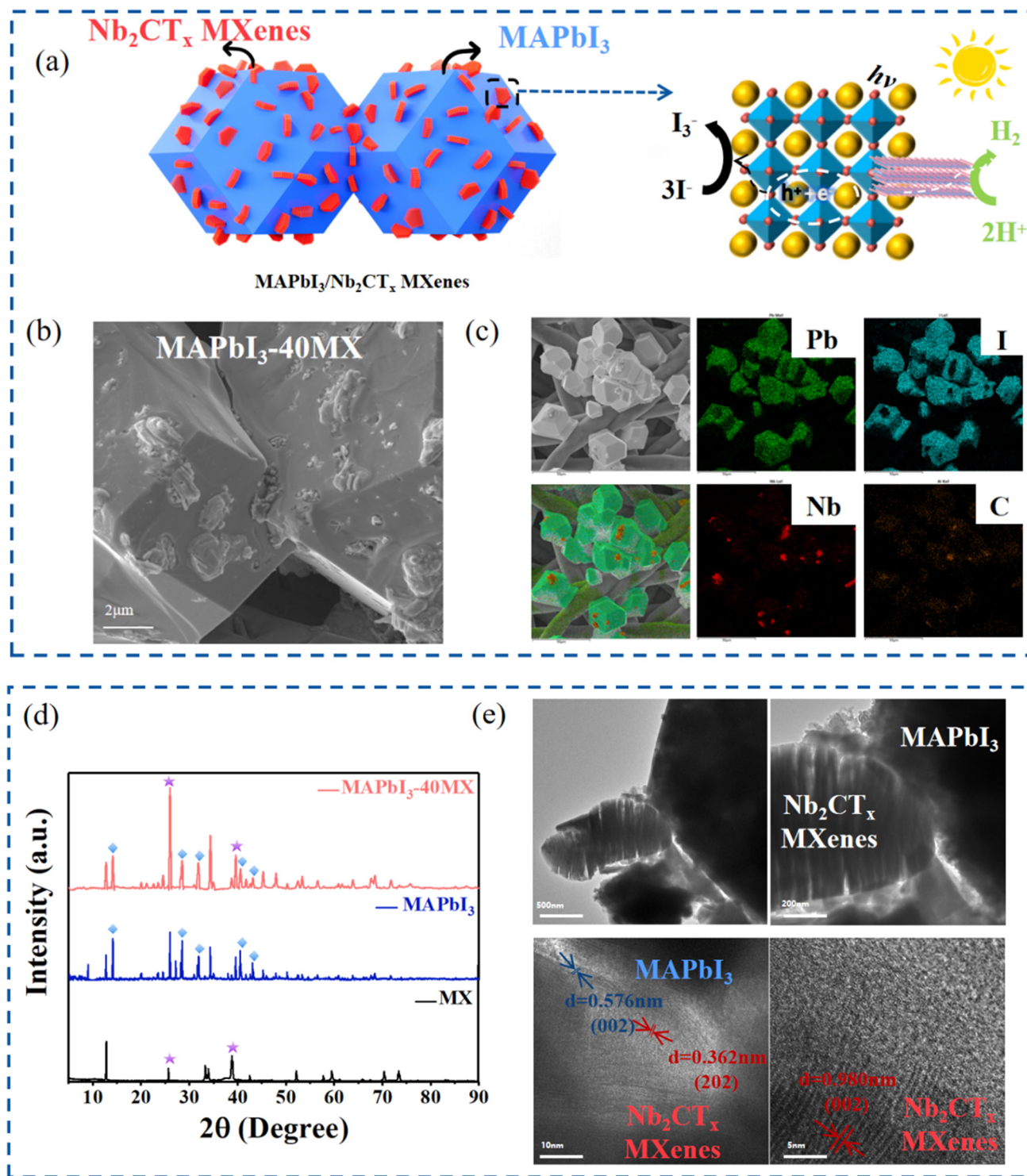


Fig. 2 (a) Schematic illustration of the structural configuration and redox processes of MAPbI₃/Nb₂CT_x MXenes. (b) SEM images of the MAPbI₃/Nb₂CT_x MXenes composite photocatalyst with 40 mg of Nb₂CT_x MXenes added. (c) SEM images and corresponding EDX maps of MAPbI₃/Nb₂CT_x MXenes. (d) XRD images of pure MAPbI₃, pure Nb₂CT_x MXenes and MAPbI₃/Nb₂CT_x MXenes composites with 40 mg of Nb₂CT_x MXenes added. (e) TEM/HRTEM images of MAPbI₃/Nb₂CT_x MXenes after compositing.

SEM characterization revealed the morphological features of the composite materials. Smooth rhombic dodecahedral MAPbI₃ crystals were densely decorated with multilayered Nb₂CT_x MXenes nanosheets, forming well-integrated MAPbI₃/

Nb₂CT_x MXenes composites (Fig. 2(b)). SEM images of the MAPbI₃/Nb₂CT_x MXenes composites modified with different masses of Nb₂CT_x MXenes are shown in Fig. S4. EDS elemental mapping confirmed the homogeneous distribution

of Pb, I, Nb, and C throughout the composite structure, verifying the successful incorporation of Nb₂CT_x MXenes into the MAPbI₃ matrix (Fig. 2(c)).

XRD was employed to investigate the crystalline structures of the MAPbI₃ and Nb₂CT_x MXenes and their composites (Fig. 2(d)). The XRD pattern of pristine MAPbI₃ exhibits characteristic peaks at 14.1, 28.4, 31.8, 40.4, and 43.0 nm, which are indexed to the (110), (220), (310), (400), and (314) crystallographic planes of the tetragonal perovskite structure, respectively.¹⁰ The XRD patterns of the MAPbI₃/Nb₂CT_x MXenes composites modified with different masses of Nb₂CT_x MXenes and the MAPbI₃/Nb₂CT_x MXenes composites modified with different sizes are shown in Fig. S5 and S6. Notably, the MAPbI₃/Nb₂CT_x MXenes composite material retains the characteristic diffraction peaks corresponding to both Nb₂CT_x MXenes and pure MAPbI₃ components. Furthermore, XRD analysis confirmed that the MAPbI₃/Nb₂CT_x MXenes hybrid maintains a tetragonal perovskite phase identical to that of pristine MAPbI₃, demonstrating the structural integrity of the perovskite framework during composite formation.

TEM observations further confirmed the successful coupling between the Nb₂CT_x MXenes nanosheets and MAPbI₃ (Fig. 2(e)). HRTEM imaging revealed interplanar spacings of 0.576 nm, 0.362 nm, and 0.980 nm, which correspond to the (110) plane of MAPbI₃ and the (202)/(002) planes of Nb₂CT_x MXenes, respectively. These structural characterizations collectively demonstrate the successful fabrication of MAPbI₃/Nb₂CT_x MXenes heterojunction photocatalysts with well-defined interfacial contacts.

3.3 Photocatalytic HER activities of MAPbI₃/Nb₂CT_x MXenes

Fig. 3(a) shows the photocatalytic hydrogen production rates and corresponding hydrogen production rates of the MAPbI₃/Nb₂CT_x MXenes composites with different masses of Nb₂CT_x MXenes. Fig. 3(b) shows the photocatalytic hydrogen production and corresponding hydrogen production rates of the MAPbI₃/Nb₂CT_x MXenes composites with different sizes of Nb₂CT_x MXenes. The HER performance of the MAPbI₃/Nb₂CT_x MXenes photocatalysts in a 20 mL aqueous HI solution was evaluated under visible light irradiation ($\lambda \geq 420$ nm) using H₃PO₂ as a sacrificial electron donor. As shown in Fig. 3a, although pure MAPbI₃ exhibits photocatalytic activity, its HER rate remains as low as 35 $\mu\text{mol h}^{-1} \text{g}^{-1}$ because of the rapid recombination of photogenerated carriers. After anchoring HF-etched Nb₂CT_x MXenes nanosheets (predominantly 2 μm in lateral size) onto MAPbI₃, the HER activity for HI splitting was significantly enhanced. Compared with pristine MAPbI₃, MXenes with varying mass ratios demonstrated substantially higher H₂ evolution rates. Specifically, MAPbI₃-20MX, MAPbI₃-40MX, MAPbI₃-80MX, MAPbI₃-100MX and MAPbI₃-120MX presented H₂ production rates of 4251.97, 7294.53, 2633.26, 729.53, and 1078.75 $\mu\text{mol h}^{-1} \text{g}^{-1}$, respectively, corresponding to 121-, 208-, 75-, 20-, and 31-fold enhancements over those of pure

MAPbI₃. This confirms the critical role of Nb₂CT_x MXenes loading in boosting HER performance for HI splitting. Further optimization was achieved by reducing the lateral size of the optimal 40 mg of Nb₂CT_x MXenes (initially 2 μm) to ~ 1 μm through thermal agitation and ultrasonication. The resulting MAPbI₃-40MX-1 μm photocatalyst delivered a remarkable HER rate of 12046.77 $\mu\text{mol h}^{-1} \text{g}^{-1}$ (200.78 $\mu\text{mol h}^{-1}$), representing 344-fold and 1.65-fold improvements over those of pristine MAPbI₃ (ref. 61) (35 $\mu\text{mol h}^{-1} \text{g}^{-1}$) and MAPbI₃-40MX (7294.53 $\mu\text{mol h}^{-1} \text{g}^{-1}$), respectively (Fig. S7). This enhancement arises from the exposure of unsaturated coordination sites at active edges and improved electron transfer properties in smaller MXenes nanosheets.^{62,63} However, excessive size reduction to ~ 500 nm (MAPbI₃-40MX-500 nm) drastically decreased the HER performance due to synergistic effects, including quantum confinement, increased surface defects, and nanosheet aggregation.

To assess practical applicability, five consecutive recycling tests (5 h per cycle) were conducted under identical conditions (Fig. 3(c)). MAPbI₃-40MX maintained stable HER activity throughout the cycles, demonstrating excellent photostability. The minor activity decline in later cycles likely originated from catalyst deposition on magnetic stir bars. Postreaction characterization revealed nearly identical XRD patterns (Fig. S8(a)) and SEM images (Fig. S8(b)) before and after cycling, confirming the structural integrity and compositional stability of MAPbI₃-40MX during photocatalytic operation. These results highlight the exceptional photocatalytic durability and structural robustness of the MAPbI₃/Nb₂CT_x MXenes composite system.

Compared with the current literature data, as shown in Fig. S9, the pink bars represent the HER yields of MXenes-based composites, whereas the orange bars represent those of perovskite MAPbI₃-based composites. The figure shows that the HI-splitting HER efficiency of the MAPbI₃/Nb₂CT_x MXenes composite developed in this work is in the upper-middle range, indicating its promising potential as an excellent photocatalytic hydrogen production material.

Further investigation into the photocatalytic performance of MAPbI₃ composites with other MXenes (Ti-, Mo-, W-, and Ta-based MXenes) under identical conditions (1 μm particle size) is presented in Fig. S10. Notably, the Nb₂CT_x-MAPbI₃ composite demonstrates the highest HER activity among all tested MXenes-based composites. To validate the role of the Z-scheme heterojunction in enhancing performance, control experiments were conducted using pure Nb₂CT_x MXenes as the photocatalyst (Fig. S11). Strikingly, the HER efficiency of the Nb₂CT_x-MAPbI₃ composite exceeds that of pure Nb₂CT_x MXenes by over ninefold. This significant enhancement provides strong evidence for the formation and efficacy of the Z-scheme heterojunction structure in facilitating charge separation and boosting photocatalytic hydrogen evolution.

The solar light harvesting capabilities of the Nb₂CT_x MXenes nanosheets, MAPbI₃, and MAPbI₃/Nb₂CT_x MXenes composites were evaluated through UV-vis diffuse reflectance spectroscopy (Fig. 4(a) and S12). The Nb₂CT_x MXenes (black



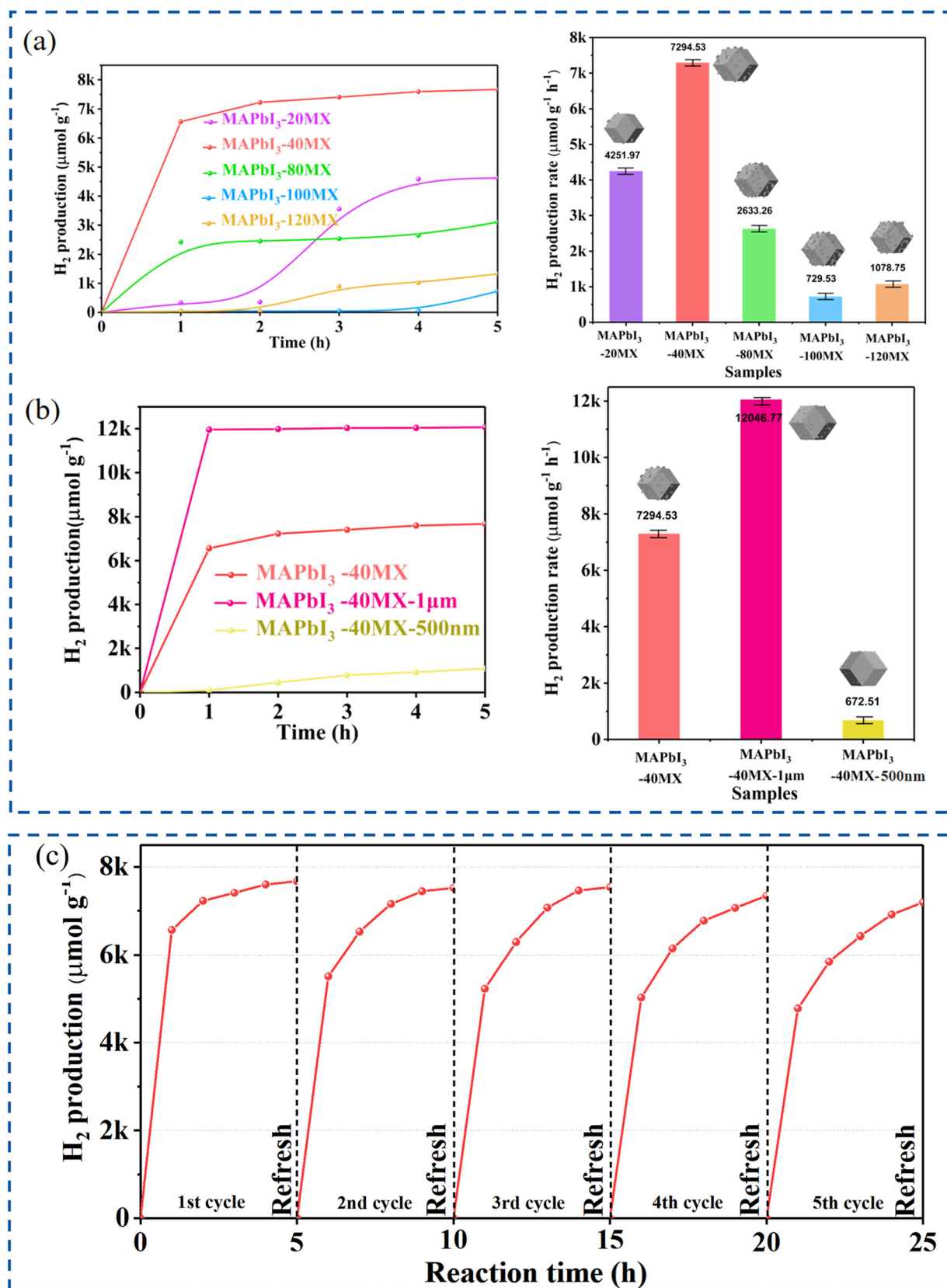


Fig. 3 (a) Photocatalytic hydrogen production rates and corresponding hydrogen production rates of MAPbI₃/Nb₂CT_x MXenes composites with different masses of Nb₂CT_x MXenes (under visible light, the photocatalytic hydrogen production of the sample within 5 h). (b) Photocatalytic hydrogen production rates and corresponding hydrogen production rates of MAPbI₃/Nb₂CT_x MXenes composites with different sizes of Nb₂CT_x MXenes (under visible light, the photocatalytic hydrogen production of the sample within 5 h). (c) Cycling tests of the H₂ production performance of MAPbI₃/40MX.

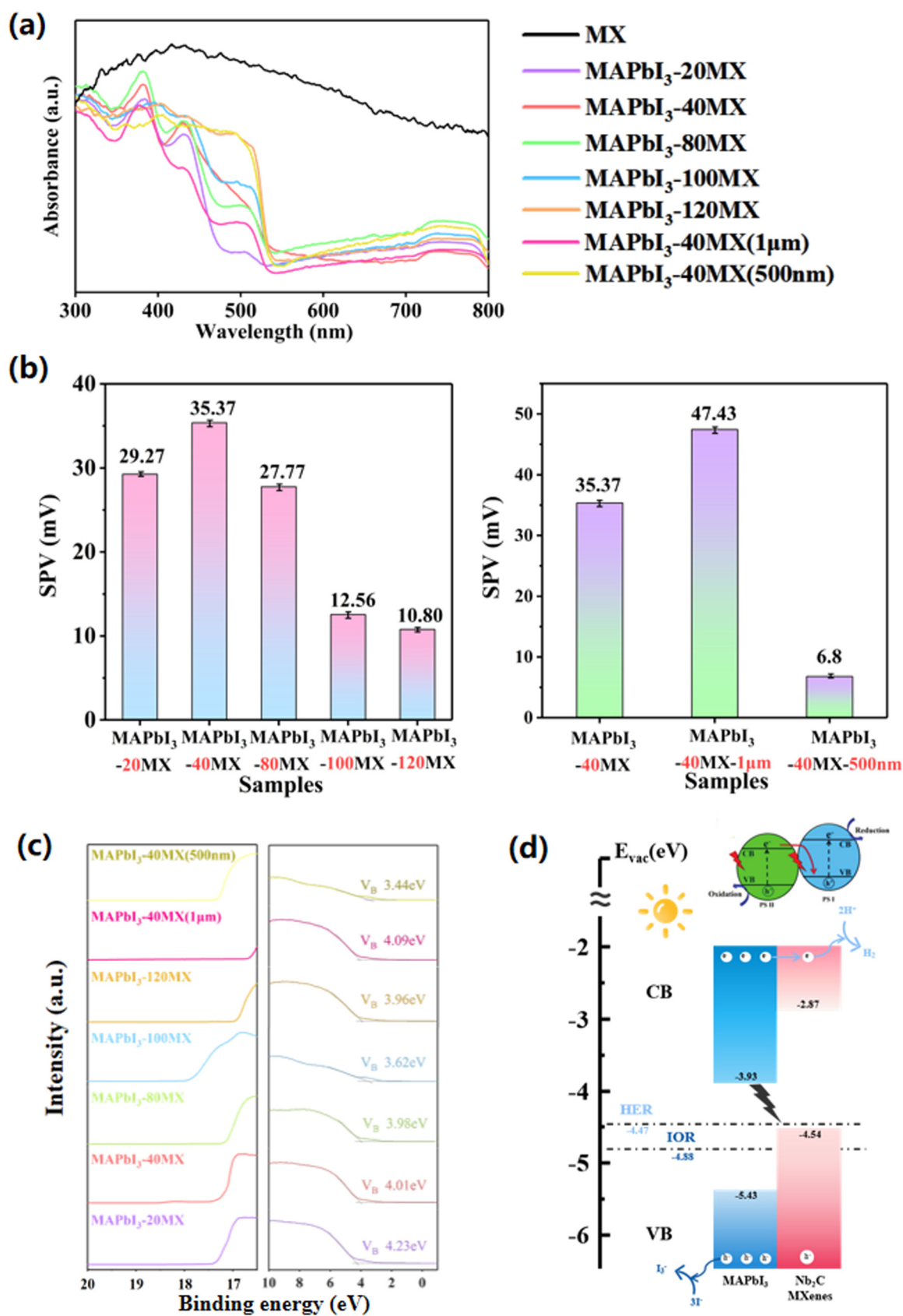


Fig. 4 (a) UV-vis spectra and band gap energies of composite Nb₂CT_x MXenes and MAPbI₃ at different ratios. (b) SPV signals of composite Nb₂CT_x MXenes and MAPbI₃ at different ratios. (c) UPS spectra of composite Nb₂CT_x MXenes and MAPbI₃ at different ratios. (d) Schematic band diagram of MAPbI₃/Nb₂CT_x MXenes for photocatalytic H₂ splitting reactions.

curve) exhibit a broad absorption spectrum without distinct absorption edges, demonstrating full-spectrum absorption characteristics consistent with their metal-like properties. MAPbI₃ displays visible light absorption due to its semiconductor nature. Consequently, the MAPbI₃/Nb₂CT_x MXenes composite shows strong absorption between 200 and 520 nm, enabling efficient harvesting of visible light for photocatalytic HI splitting toward hydrogen generation.

The carrier separation efficiency was investigated *via* surface photovoltage (SPV) spectroscopy, which directly detects the photogenerated voltage under illumination, with the SPV signal intensity reflecting the charge separation capability. As shown in Fig. 4(b), the SPV signals of MAPbI₃/40MX (35.37 ± 2.6 mV) and MAPbI₃/40MX-1 μm (47.43 ± 3.1 mV) significantly surpassed those of MAPbI₃/20MX (29.27 ± 1.8 mV), MAPbI₃/80MX (27.77 ± 3.0 mV), MAPbI₃/100MX (12.56 ± 3.0 mV), MAPbI₃/120MX (10.80 ± 1.4 mV), and MAPbI₃/40MX-500 nm (6.8 ± 0.8 mV). This clearly demonstrates enhanced charge separation in MAPbI₃ modified with 40 mg of Nb₂CT_x MXenes. Notably, MAPbI₃/40MX-1 μm has the highest SPV response, suggesting an optimal charge distribution that contributes to its superior hydrogen evolution performance.

Fig. 4(c) shows the ultraviolet photoelectron spectroscopy (UPS) spectra of the crystal, whereas Fig. 4d shows the energy level diagram of the MAPbI₃/Nb₂CT_x MXenes-based HI-splitting hydrogen production system constructed from the UPS data. The inset in the upper right corner of Fig. 4(d) schematically depicts the electron-hole separation in the Z-scheme heterojunction photocatalyst under light irradiation.⁶⁴ As revealed in Fig. 4(d), the Z-scheme heterojunction formed between the MAPbI₃ and Nb₂CT_x MXenes enables more efficient photoinduced charge separation and enhanced reduction capacity than conventional type II heterojunction photocatalysts do. In this Z-scheme configuration, the conduction band (CB) and valence band (VB) of the perovskite material exhibit lower energy levels than those of typical semiconductor materials. The experimental results demonstrate that the MAPbI₃/40MX-1 μm heterojunction (with the incorporation of 1 μm-sized Nb₂CT_x MXenes) achieves optimized band alignment, with a valence band maximum (VBM) of -4.61 eV and a conduction band minimum (CBM) of -2.49 eV. Notably, the more negative VB position of this heterojunction compared with that of pristine MAPbI₃ (-4.47 eV *vs.* vacuum level (VAC) for the H⁺/H₂ redox potential) meets the thermodynamic requirements for the photocatalytic HER. In the Z-scheme heterojunction, photogenerated electrons spontaneously transfer from the CB of MAPbI₃ to the VB of Nb₂CT_x MXenes for hole recombination. This directional charge migration results in electron accumulation on the higher-reduction-potential CB of the MXenes and hole retention on the stronger-oxidation-capacity VB of MAPbI₃. Such charge separation dynamics not only suppress electron-hole recombination but also preserve the superior reduction capability of MXenes and the robust oxidation capacity of

perovskite, thereby synergistically driving H⁺ reduction and HI oxidation reactions. Furthermore, the high conductivity and abundant surface active sites of the Nb₂CT_x MXenes provide efficient reaction sites for H₂ evolution while accelerating interfacial charge transfer. The strengthened built-in electric field significantly enhances the carrier separation efficiency. Concurrently, the photogenerated holes in the VB of MAPbI₃ oxidize I⁻ to I₃⁻, which is subsequently consumed by H₃PO₂ during photocatalytic processes, maintaining solution stability. Stability tests confirmed the structural integrity of MAPbI₃/40MX-1 μm after 12 hours of continuous photocatalytic operation, with SEM images and XPS analysis showing no significant perovskite degradation or MXenes oxidation (Fig. S13), demonstrating the synergistic stabilization effect of the Z-scheme heterojunction.

To further elucidate the photogenerated carrier transfer pathway in the MAPbI₃/Nb₂CT_x MXenes composite, *in situ* XPS characterization was performed under illumination. As shown in Fig. 5(a), upon light irradiation, the binding energies of the Pb 4f peaks in the MAPbI₃/Nb₂CT_x MXenes composite shifted from 143.02, 138.14, and 134.92 eV to 143.33, 138.44, and 135.38 eV, respectively. Similarly, the I 3d peak shifted from 618.85 and 630.36 eV to 619.21 and 630.69 eV. This positive shift in binding energies suggests the accumulation of holes within the MAPbI₃ component following photoexcitation.

Conversely, the binding energies of the Nb 3d peaks decreased from 204.65 and 207.28 eV to 204.44 and 207.11 eV, whereas the C 1s peaks shifted from 286.44 and 288.75 eV to 286.29 and 288.35 eV. This negative shift is attributed to the accumulation of negatively charged photogenerated electrons within the Nb₂CT_x MXenes component.

Considering the band alignment of the MAPbI₃ and Nb₂CT_x MXenes, these observations collectively indicate that, upon illumination, photogenerated electrons from MAPbI₃ transfer to the Nb₂CT_x MXenes. This electron transfer serves two critical functions: suppressing electron-hole recombination within the Nb₂CT_x MXenes by annihilating holes. Facilitates spatial charge separation, leading to the accumulation of a high density of photogenerated electrons in the Nb₂CT_x MXenes and a corresponding accumulation of photogenerated holes in the MAPbI₃.

Consequently, the observed XPS shifts and the proposed charge transfer mechanism provide compelling evidence for a direct Z-scheme (or Z-type) heterojunction within the MAPbI₃/Nb₂CT_x MXenes composite, where the photogenerated electrons follow a Z-scheme transfer pathway.

Following the formation of the MAPbI₃/Nb₂CT_x MXenes heterojunction, the lower work function and higher Fermi level of MAPbI₃ MXenes than of Nb₂CT_x MXenes (Fig. 5(b)) create thermodynamically favorable conditions for spontaneous electron transfer from MAPbI₃ to Nb₂CT_x MXenes. This electron migration persists until the Fermi levels of the two components equilibrate. Consequently, electron depletion and accumulation layers are established at the interface under equilibrium conditions. This results in a



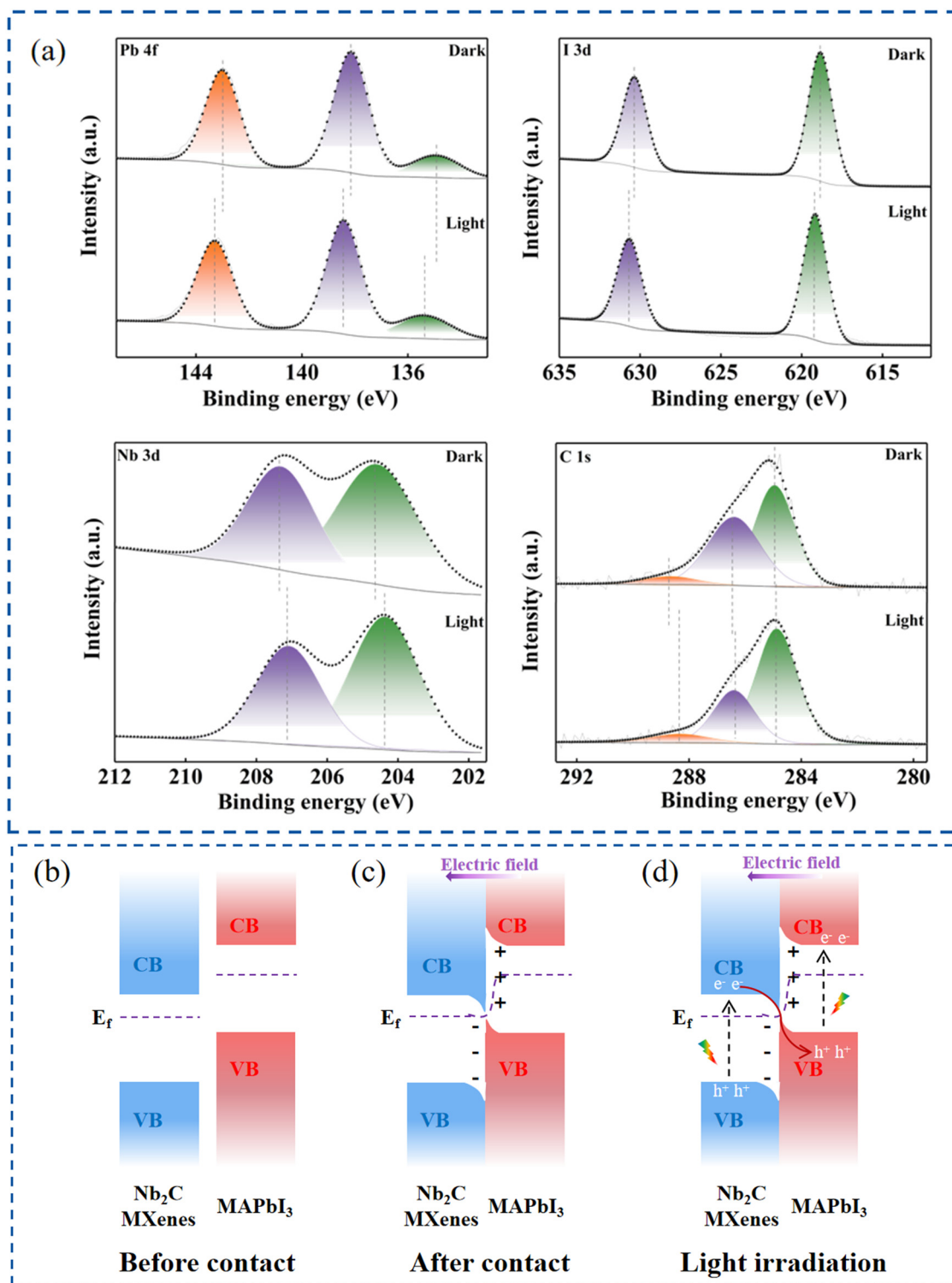


Fig. 5 (a) High-resolution XPS spectra of Pb 4f, I 3d, Nb 3d and C 1s of MAPbI₃/Nb₂CT_x MXenes before and after illumination. Illustration of the band structures between Nb₂CT_x MXenes and MAPbI₃. (b) before contact, (c) in the dark, and (d) under light irradiation. The E_f bending at the interface was considered in (c) and (d).

positively charged surface on MAPbI₃ and a negatively charged surface on Nb₂CT_x MXenes, inducing the formation of a robust interfacial electric field (IEF) and band bending at the MAPbI₃/Nb₂CT_x MXenes interface (Fig. 5(c)). This

configuration provides a potent driving force for interfacial charge transfer.

Under light illumination, the IEF promotes the recombination of photogenerated electrons in the CBM of



Nb₂CT_x MXenes with photogenerated holes in the VBM of MAPbI₃ via an S-shaped electron transfer pathway (Fig. 5(d)). Consequently, photogenerated electrons are preserved in the CBM of MAPbI₃, whereas photogenerated holes accumulate in the VBM of Nb₂CT_x MXenes. Thermodynamically, the estimated redox potentials of the MAPbI₃/Nb₂CT_x MXenes heterojunction exhibit overlapping regions with the theoretical potentials required to simultaneously drive reduction reactions on the Nb₂CT_x MXenes side and oxidation reactions on the MAPbI₃ side under visible light irradiation.

3.4 Photocatalytic mechanism

The interfacial charge transfer characteristics between the MAPbI₃ and Nb₂CT_x MXenes were systematically investigated via DFT calculations. Fig. S14 presents the optimized configurations of pristine MAPbI₃ and Nb₂CT_x MXenes and their heterostructures (denoted MAPbI₃/Nb₂CT_x MXenes). DFT-derived electronic band structures (Fig. S15) and density of states (DOS) profiles (Fig. 6(a)) reveal distinct semiconductor characteristics in MAPbI₃ and quasi-metallic behavior in Nb₂CT_x MXenes. To elucidate the interfacial charge redistribution, differential charge density analysis was performed at the MAPbI₃/Nb₂CT_x MXenes interface (Fig. 6(b)). The planar-averaged charge density difference along the Z-axis demonstrates significant electron accumulation (yellow regions) localized on the Nb₂CT_x MXenes component, whereas electron depletion (cyan regions) predominantly occurs in the MAPbI₃ region, indicative of directional electron transfer from MAPbI₃ to Nb₂CT_x MXenes. This charge transfer mechanism is further

corroborated by work function calculations (Fig. 6(c)), which yield values of 4.571 eV for MAPbI₃ and 5.77 eV for the Nb₂CT_x MXenes. The higher work function of the Nb₂CT_x MXenes establishes an electron-driving force at the interface, which is consistent with the observed differential charge distribution and confirms the formation of a Z-scheme heterojunction architecture. Furthermore, hydrogen adsorption Gibbs free energy (ΔG_{H^*}) calculations (Fig. 6(d)) demonstrated remarkable catalytic enhancement in the composite system. The optimized MAPbI₃/Nb₂CT_x MXenes heterostructure exhibited near-zero $|\Delta G_{H^*}|$ values, suggesting a significantly reduced overpotential and improved HER activity during HI photocatalytic decomposition. This synergistic effect arises from the Z-scheme charge transfer pathway, which effectively suppresses carrier recombination while maintaining strong redox potentials.⁶⁵

Conclusions

This study successfully constructed a Z-scheme heterojunction-based MAPbI₃/Nb₂CT_x MXene composite photocatalyst for hydrogen production via HI splitting. An *in situ* coupling strategy enabled uniform anchoring of Nb₂CT_x nanosheets onto MAPbI₃ with interfacial chemical bonding, establishing intimate contact and directional charge-transfer channels. The composite achieved exceptional photocatalytic hydrogen evolution (12 046.77 $\mu\text{mol h}^{-1} \text{g}^{-1}$), representing a 344-fold enhancement over pristine MAPbI₃, while retaining 85% activity after cycling-overcoming the efficiency–stability trade-off typical of perovskite photocatalysts. Theoretical analyses reveal the synergistic mechanism: a robust

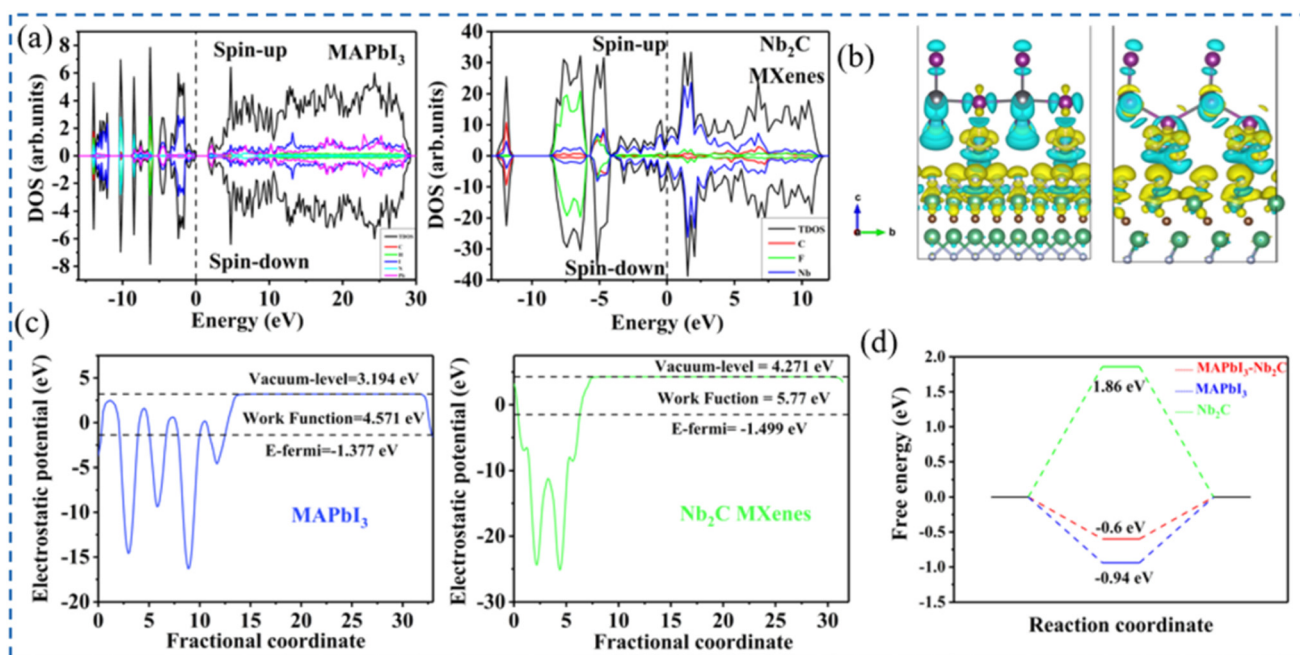


Fig. 6 (a) The densities of states of the MAPbI₃ and Nb₂CT_x MXenes are calculated. (b) The differential charge density distribution at the interface of the MAPbI₃/Nb₂CT_x MXenes complex was simulated. (c) Work function calculation of pure MAPbI₃, pure Nb₂CT_x MXenes and MAPbI₃-MX. (d) Gibbs free energy calculation of H atom adsorption on pure MAPbI₃, pure Nb₂CT_x MXenes and MAPbI₃-MX.

interfacial built-in electric field drives Z-scheme charge migration, facilitating the participation of highly reductive electrons from the Nb₂CT_x conduction band and oxidative holes from the MAPbI₃ valence band in surface reactions. The metallic conductivity of MXenes accelerates charge kinetics, while their abundant active sites optimize proton reduction. This work demonstrates Nb₂CT_x as an efficient noble-metal-free cocatalyst and establishes a structure-interface-property paradigm for designing stable, high-performance photocatalytic systems.

Author contributions

Ruiyan Sun: conceptualization, data curation, formal analysis, and writing – original draft. Lili Gao: funding acquisition, investigation, methodology, project administration, resources, supervision, and writing – review & editing. Deng Li: data curation, formal analysis, investigation, supervision, and writing – review & editing. Hua Wang: investigation, supervision, and writing – review & editing. Fan Yang: investigation, methodology, supervision, and writing – review & editing. Jin Wang: investigation, methodology, project administration, and writing – review & editing. Ke Hao: data curation, formal analysis, and writing – original draft. Haijiao Xie: data curation, and formal analysis. Ping Hu: funding acquisition, investigation, methodology, project administration, resources, supervision, and writing – review & editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

Supplementary information: Figures: XPS survey spectrum of Nb₂CT_x MXenes after etching; SEM patterns and TEM patterns before and after HF-etched; XRD patterns before and after HI immersion; SEM images of Nb₂CT_x MXenes modified MAPbI₃/Nb₂CT_x MXenes composites with different mass; XRD patterns of MAPbI₃/Nb₂CT_x MXenes composites modified with different mass of Nb₂CT_x MXenes; XRD patterns of Nb₂CT_x MXenes modified MAPbI₃/Nb₂CT_x MXenes composites with different sizes; the HER rates of the original MAPbI₃, MAPbI₃/40MX and MAPbI₃/40MX-1 μm photocatalysts were compared; XRD patterns of MAPbI₃/40MX before and after cycling; compared with other MXenes-based (pink) and MAPbI₃-based (orange) photocatalytic hydrogen evolution systems; the photocatalytic hydrogen evolution results of MAPbI₃ doped with different particle sizes of 1 μm MXenes (Ti-, Mo-, W-, Ta-based); the photocatalytic hydrogen evolution performance of pure Nb₂CT_x MXenes and Nb₂CT_x-MAPbI₃ (40MX-1 μm) after compounding with MAPbI₃ was compared; UV-vis diffuse reflectance spectra of Nb₂CT_x MXenes nanosheets and MAPbI₃/Nb₂CT_x MXenes composites; SEM image and XPS analysis of MAPbI₃/40MX-1 μm before and after 12 hours of continuous photocatalytic hydrogen production; the

configuration diagrams of pure MAPbI₃, pure Nb₂CT_x MXenes and MAPbI₃-MX after compounding; the band structure of MAPbI₃ and Nb₂CT_x MXenes are calculated. See DOI: <https://doi.org/10.1039/D5LF00214A>.

All data supporting the findings of this study are fully presented within the manuscript text and figures. No additional external datasets were generated or analyzed, except for the comparative data used in Fig. S9. The data for Fig. S9 were derived from the study by Li *et al.* 2022 (DOI: <https://doi.org/10.1016/j.jpowsour.2022.231006>) and Nemamcha *et al.* 2024 (DOI: <https://doi.org/10.1016/j.scitotenv.2024.172816>).

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