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Strongly enhanced visible light photoelectrocatalytic hydrogen evolution reaction in an n-doped MoS$_2$/TiO$_2$(B) heterojunction by selective decoration of platinum nanoparticles at the MoS$_2$ edge sites


Herein, we demonstrate strongly enhanced visible light photoelectrocatalytic hydrogen evolution reaction (HER) in few layer MoS$_2$ grown on a mesoporous TiO$_2$(B) nanobelt (NB) by selective decoration of platinum (Pt) nanoparticles (NPs) on the edge/defect sites of the MoS$_2$ layer.

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Strongly enhanced visible light photoelectrocatalytic hydrogen evolution reaction in an n-doped MoS$_2$ /TiO$_2$(B) heterojunction by selective decoration of platinum nanoparticles at the MoS$_2$ edge sites

Kamal Kumar Paul,a N. Sreekanth,b Ravi K. Biroju,c Alexander J. Pattison,c Daniel Escalera-López,c Anku Guha,b Tharangattu N. Narayanan,b Neil Vaughan Rees,d Wolfgang Theisc and P. K. Giri*a

Herein, we demonstrate strongly enhanced visible light photoelectrocatalytic hydrogen evolution reaction (HER) in few-layer MoS$_2$ grown on a mesoporous TiO$_2$(B) nanobelt (NB) by selective decoration of platinum (Pt) nanoparticles (NPs) on the edge/defect sites of the MoS$_2$ layer. Three catalytically active components are anchored together to increase the photoelectrocatalytic HER activity synergistically, beyond that of commercial Pt/C electrodes (20 wt% Pt). An extremely low concentration of Pt NPs (1.4 wt%) with average size $\sim$3.8 nm was decorated over the preferentially edge-site-exposed few-layer MoS$_2$, with lateral sizes 130–350 nm, as evidenced from high-angle annular dark-field STEM imaging. During the heterojunction formation, S is doped in the TiO$_2$ layer causing a high density of electrons in TiO$_2$ that migrate to the MoS$_2$ layer inducing n-type doping in it and thus TiO$_2$ acts as an efficient photocathode in photoelectrocatalysis. Quantitative XPS analysis reveals that the catalytically active bridging S$_2$ apical S$_2$ increases up to $\sim$72% after the formation of the ternary system Pt@MoS$_2$/TiO$_2$(B). S-enriched MoS$_2$/TiO$_2$(B) selectively loaded with Pt NPs on the edge sites of MoS$_2$ exhibits a giant enhancement in the HER activity in an acidic medium under light. We record a nearly 16 fold higher exchange current density (0.296 mA cm$^{-2}$) for the ternary system as compared to that of the MoS$_2$/TiO$_2$ binary system under visible light excitation. The marginally Pt loaded ternary system exhibits an extremely low charge transfer resistance (14 $\Omega$) and a low overpotential as well as Tafel slope (74 mV and 30 mV dec$^{-1}$, respectively) boosting the overall HER performance under visible light. Chronopotentiometric measurements reveal the high stability of binary and ternary systems to sustain a 10 mA cm$^{-2}$ cathodic current up to 12 hours. The results show that the marginally loaded Pt NPs activate the inert basal plane, edge sites of MoS$_2$ and porous sites of TiO$_2$, forming an integrated network where the photogenerated electrons can easily be injected from the TiO$_2$ to MoS$_2$ and then to Pt NPs, presenting a feasible approach to boost the HER activity under visible light.

1. Introduction

The fast-rising energy crisis and environmental pollution are driving the development of new, sustainable, pollution-free sources that can be used on an industrial scale. Hydrogen is believed to be one of the most promising alternatives to fossil fuels and a source of renewable green energy due to its high energy density and carbon-free combustion emission. Solar-light-driven electrocatalysis using semiconductor TiO$_2$ and its heterostructures (HSs) is one of the most promising sustainable technologies for the generation of hydrogen by water splitting. To make the system commercially viable, the electrocatalyst should be solar light active, efficient and highly stable. To broaden the light harvesting window from UV to visible/NIR
and increase the catalytic activity, numerous strategies have been explored, including impurity doping,\textsuperscript{6-11} staggered-type HSSs,\textsuperscript{12,13} TiO\textsubscript{2}-based plasmonic HSSs with noble metal nanoparticles (NPs),\textsuperscript{14-18} etc. In a heterostructured system, the presence of a heterojunction modifies the band positions as well as the inclination at the interface facilitating the migration of photogenerated charge carriers through the heterojunctions, which makes a highly efficient electrocatalyst.\textsuperscript{19} Though platinum (Pt) group noble metals are the most efficient conventional electrocatalysts, their extremely high cost and scarcity in nature hinder their industrial-scale usage.\textsuperscript{20} Graphene-based two-dimensional (2D) transition metal dichalcogenide nanosheets, especially MoS\textsubscript{2} based heterostructures, have recently received much attention as a noble-metal-free catalyst and an anode material for energy storage devices.\textsuperscript{21-26} Recently, Pi \textit{et al.}\textsuperscript{27} demonstrated an extraordinary catalytic performance by TiO\textsubscript{2} nanostructures decorated with 1T-MoS\textsubscript{2} nanosheets under solar light. Thus, MoS\textsubscript{2} has now been recognized as an efficient co-catalyst incorporated with TiO\textsubscript{2} nanostructures due to its structural anisotropy, chemical inertness, good electroconductivity, and efficient catalytic properties.\textsuperscript{28-30} Theoretical and experimental studies found that the HER ability of MoS\textsubscript{2} mainly derives from the edge sites of its 2D layers, whereas the basal planes are catalytically inert, limiting its overall performance.\textsuperscript{31} Thus, tuning the architecture of MoS\textsubscript{2} to preferentially edge-exposed sites, semiconducting (2H) to metallic (1T) phase transformation, introduction of vacancies and incorporation with metal NPs are the synergistic strategies for the enhancement of HER activity.\textsuperscript{22-33} Recently, edge-site-activated ultra-thin MoS\textsubscript{2} nanostructures with optimum defect density, especially S-vacancies, have been identified as tunable active sites to stimulate the originally inert basal plane for the HER.\textsuperscript{36,37} Although these edge sites and defects in the MoS\textsubscript{2} lattice may introduce additional active sites on its basal plane, their incorporation hampers the electron transport properties, leading to low overall HER activity. Zhou \textit{et al.}\textsuperscript{38} and Li \textit{et al.}\textsuperscript{39} have modified the morphology of TiO\textsubscript{2} from ultra-small spherical NPs to long nanobelts (NBs) and employed few-layer MoS\textsubscript{2} nanosheets on them with high catalytic surface areas, which in turn enhanced the hydrogen generation efficiency synergistically. A few groups considered conductive carbon fiber cloths to decorate vertically aligned and preferentially edge-site-exposed MoS\textsubscript{2} nanostructures, which provide very low catalyst-electrode contact resistance, leading to enhanced HER performance.\textsuperscript{39,40} More recently, Xu \textit{et al.}\textsuperscript{4} demonstrated a smart strategy of utilizing the inert basal plane by loading 2.45 wt% of Pt NPs on the porous MoS\textsubscript{2} nanostructures anchored vertically with the carbon fiber cloths. It was shown that the loaded Pt NPs could both serve as additional active HER sites and enable fast electron transport, which in turn reduce Pt consumption without compromising the HER activity. It may be noted that though there are several reports on the catalytic activity of binary MoS\textsubscript{2}/Pt and TiO\textsubscript{2}/Pt system, there is hardly any report on the TiO\textsubscript{2}/MoS\textsubscript{2}/Pt composite system.\textsuperscript{41,42} Very recently, photocatalytic and electrocatalytic H\textsubscript{2} generation in a TiO\textsubscript{2}/Pt/MoS\textsubscript{2} composite system was reported by Li \textit{et al.}\textsuperscript{44} However, the system was not well characterized and the performance of the composite system was comparable or inferior to that of binary systems. Unlike the earlier reports, we have chosen a porous TiO\textsubscript{2}(B) nanobelt as a novel platform for the growth of edge-site exposed few-layer MoS\textsubscript{2}. Subsequently, Pt NPs are preferentially decorated at the edge sites of MoS\textsubscript{2} and porous sites of TiO\textsubscript{2}(B) with ultralow concentration. To the best of our knowledge, a thorough understanding of such a ternary system and its visible light PEC activity has not been explored in the literature. In particular, the role of individual components in a ternary system needs to be addressed to exploit its application in next-generation photoelectrocatalysis experiments.

Herein, we carried out controlled growth of porous TiO\textsubscript{2}(B) NBs (TB) via a solvothermal method and its \textit{in situ} surface decoration with discrete few-layer MoS\textsubscript{2} by a second stage hydrothermal treatment. Incorporation of a marginal amount of Pt NPs as a suitable co-catalyst on the surface of MoS\textsubscript{2}/TiO\textsubscript{2}(B) (MSTB) can generate additional surface active sites, increasing the overall conductivity and charge separation through the multiple heterojunctions. The ternary catalyst contains the maximum amount of bridging $S^2_\text{apical}$ which are known to be catalytically active. As the Pt NPs are decorated on the edge/porous sites of the MoS\textsubscript{2}/TiO\textsubscript{2} (PMSTB) HS, the photoexcited electrons can easily be transferred from TiO\textsubscript{2} to Pt sites directly as \textit{via} the MoS\textsubscript{2} edge-sites, leading to a remarkable enhancement in the exchange current density ($j_\text{0}$) and thus HER activity compared to that under dark conditions that is much higher than those of the pristine or the other HSs. Thus, a rational design of hierarchical nanostructures with a marginal amount of Pt loading (1.4 wt%) is crucial for achieving superior photoelectrocatalytic systems.

2. Experimental procedure

2.1. Preparation of TiO\textsubscript{2} NBs

Anatase TiO\textsubscript{2} nanopowder, ethylene glycol, and sodium hydroxide (NaOH) pellets were used in our experiments as received from Merck without any further purification. In a typical synthesis, 0.2 g of anatase TiO\textsubscript{2} powder (average particle size $\sim$ 80 nm) was mixed vigorously in a 50 ml aqueous NaOH solution (10 M) with an equal volume of ethylene glycol. Next, the mixed white solution was transferred into a Teflon-lined autoclave (Berghof, BR-100) and the solution temperature was maintained at 220 °C monitored with a thermocouple inserted into the Teflon chamber for 16 h with constant magnetic stirring at 500 rpm. The resultant precipitates were washed thoroughly with DI water and 0.1 N HCl to reduce its pH to 7, which ensures the full exchange of Na\textsuperscript{+} with H\textsuperscript{+} ions. Then, the obtained H-titanate NBs were calcined at 500 °C for 5 h in air to get porous TiO\textsubscript{2}(B) NBs.

2.2. Growth of MoS\textsubscript{2}/TiO\textsubscript{2} NB heterostructures

Typically, 20 mg of TiO\textsubscript{2}(B) NBs powder was homogeneously dispersed in 40 ml of Milli-Q water in bath sonication for 30 min. Next, 60 mg sodium molybdate (Na\textsubscript{2}MoO\textsubscript{4}·2H\textsubscript{2}O) and 120 mg thioacetamide (C\textsubscript{4}H\textsubscript{5}NS) as a source of Mo and S, respectively were dissolved in the above dispersion.\textsuperscript{42} The
mixture was then treated in a Teflon-lined stainless steel autoclave at 240 °C for 24 h with constant magnetic stirring at 250 rpm. The resultant black precipitate was washed thoroughly with DI water to eliminate the additional salts and impurities followed by centrifugation. Uniform decoration of few-layer MoS2 on the TiO2 NB platform with a 1:1 weight ratio of MoS2 and TiO2 was obtained after a drying process at 50 °C for 12 h. For comparison, pure few-layer MoS2 was synthesized under identical conditions but in the absence of a TiO2 NB platform.

2.3. Decoration of Pt NPs on the TiO2 NBs and MoS2/TiO2 NB heterostructures

50 mg of MoS2/TiO2 powder was dispersed in 100 ml of MQ water in an ultrasonic bath for 30 min. 52 mg H2PtCl6 was dissolved in 100 ml of MQ water and added drop-wise into the MoS2/TiO2 dispersion under magnetic stirring. Then, 50 ml of 0.01 M aqueous NaBH4 solution was added slowly to the above mixture to deposit Pt NPs uniformly over the TiO2 as well as MoS2/TiO2 HSs.

2.4. Characterization techniques

The crystal structure of the as-grown catalysts was studied using an X-ray powder diffractometer (XRD) pattern (Rigaku RINT 2500 TTRAX-III, Cu kα radiation). The crystallinity and phase composition of the as-synthesized NRs and the number of layers in MoS2 have been confirmed using micro-Raman measurements (LabRam HR800, Jobin Yvon). The morphology and size of the as-synthesized TiO2 NBs and MoS2 layer on the TiO2 NBs have been studied using a field emission scanning electron microscope (FESEM) (Sigma, Zeiss). The high-magnification surface morphologies and structures of the as-grown samples have been studied using a field emission transmission electron microscope (FETEM) (JEOL-JEM 2100F operated at 200 kV).

Elemental mapping of various samples was recorded using the FETEM equipped with an energy dispersive X-ray (EDX) spectrometer. Samples for TEM analysis were prepared on a carbon-coated Cu grid of 400 mesh size (Pacific Grid, USA). In particular, the edge sites of MoS2 layers and the selective decoration of Pt NPs were identified using bright field scanning transmission electron microscopy (STEM) mode using an aberration-corrected STEM (JEM 2100F, 200 kV) and corresponding energy-dispersive X-ray spectroscopy (EDS) hypermaps were recorded to analyze the local environment of S, Mo, and Pt in TiO2-based MoS2 nanoflowers and Pt NP modified nanostructures. UV-vis diffuse reflectance spectroscopy (DRS) measurements were recorded using a commercial spectrophotometer (SHIMADZU 2600). Room temperature steady state PL spectra of the catalysts were recorded with the help of a spectrophotometer (focal length: 15 cm; blaze wavelength: 500 nm; groove density: 150 g mm⁻¹) equipped with a cooled charge-coupled device (Princeton Instruments, PIXIS 100B) detector using 405 nm diode laser (Coherent, Cube) excitation. X-ray photoelectron spectroscopy (XPS) has been carried out using a PHI X-ray automated photoelectron spectrometer (ULVAC-PHI, Japan) with an Al Kα X-ray beam (1486.6 eV) at a beam current of 20 mA. The shift in the binding energy of various catalysts has been corrected using the C1s spectrum at 284.8 eV as a standard value.²²

2.5. Photoelectrocatalysis measurements under visible light

Photoelectrochemical measurements were performed systematically in a conventional three-electrode electrochemical cell: a commercial Ag/AgCl (saturated KCl) electrode (CH instruments) as the reference electrode, Pt wire or a graphite rod as the counter electrode and the as-grown catalysts supported on a glassy carbon substrate were used as working electrodes. Prior to catalyst loading, the surface of the glassy carbon substrate is polished with 50 μm alumina powder on a polishing cloth and washed with DI water. 4 mg of catalyst was dissolved in 1 ml DI water and the dispersion was sonicated for 1 h. 6 μL of the as-prepared sample was drop cast on the glassy carbon electrode (diameter = 3 mm) and dried in an inert atmosphere. The net loading of each catalyst is ~0.34 mg cm⁻². The electrochemical surface area (ECOSA) of each catalyst was measured using the Randles–Sevcik equation:

\[
I_p = (2.69 \times 105)n^{3/2}AD^{1/2}v^{1/2}C,
\]

where \(I_p\) is the anodic peak current (amperes), \(v\) is the scan rate of potential, \(n\) is the number of electrons involved in the reaction, \(A\) is the active surface area (cm²), \(C\) (mol cm⁻³) is the concentration of electroactive species, and \(D\) is the diffusion coefficient (cm² s⁻¹). Thus, the active surface area \(A\) of the electrode is calculated from the cyclic voltammetry (CV) response of 5 mM [Fe(CN)₆]₃⁻/⁴⁻ in 0.1 M KCl at different scan rates. The calculated ECOSA for the TB, MS, PMS, PTB, MBST and PMSTB are 0.038, 0.042, 0.048, 0.050, 0.052 and 0.045 cm², respectively.

Photo-electrocatalytic studies were performed using a Bio-Logic SP-300 electrochemical workstation. A 250 W Xenon lamp (Lelesil Innovative Systems, India) was used as the visible light source with a wavelength range of ~370–730 nm during the photoelectrochemical measurements. A 0.5 M H₂SO₄ solution was used as an electrolyte, deaerated by N₂ purging until saturation prior to any electrochemical experiment. Linear sweep voltammetry (LSV) was conducted at a scan rate of 5 mV s⁻¹. Electrochemical impedance spectroscopy (EIS) was also performed in 0.5 M H₂SO₄ under dark and light conditions at the HER onset potential of each catalyst over the frequency range 7 MHz–100 Hz with an input sine wave having 10 mV amplitude.

3. Results and discussion

3.1. Morphology studies

Fig. 1(a) shows a FESEM image of pristine TiO2 NBs with a diameter of ~30–100 nm and length of ~ a few μm, while Fig. 1(b) shows uniform decoration of Pt NPs over the TiO2 NBs. During the 2nd stage hydrothermal treatment, self-assembly of few-layer MoS2 nanosheets on the porous TiO2 NB template transforms it into discrete MoS2 nanoflowers (NFs) decorated on the TiO2 NBs with the size distribution of 130–350 nm, as shown in Fig. 1(c). Fig. 1(d) shows the FESEM micrograph of Pt
NP-decorated MSTB HSs. Large Pt NPs can be observed on the TiO2 surface maybe due to the aggregation. Note that, the deposited Pt NPs on the edge-exposed MoS2 NFs have appreciably small size and a narrow size distribution (discussed later), and hence the NPs were not discernable here due to the resolution limit of FESEM.

Fig. 2(a and b) show TEM micrographs of Pt NPs decorated on TiO2 NBs (PTB HS) at two different magnifications, demonstrating overall uniform decoration of Pt NPs, and Fig. 2(c) shows an HRTEM lattice fringe pattern of well-crystalline Pt NPs and TiO2 NBs in PTB. The calculated lattice spacing of 0.22 nm corresponds to the (111) plane of Pt NP, and 0.29 nm and 0.32 nm correspond to the (111) and (002) crystal planes of TiO2(B), respectively, in the PTB HSs. TEM images in Fig. 2(d and e) reveal the in situ growth of MoS2 layers on the porous TiO2 NB platform with a broad size distribution of 100–380 nm, which is in good agreement with the FESEM analysis. As evident from the images, the pure MoS2 crystals with maximally exposed edge active sites appear to be layered wavy petals, and they gather together to form distinct nanosheet-like structures on the porous TiO2 NB platform due to the high autogenous pressure (~45 bar) inside the autoclave. Insets in Fig. 2(d and e) depict the hexagonal diffraction spots and a honeycomb atom arrangement in 2H-MoS2, respectively, grown over TB. Fig. S1(a and b) (ESI†) reveal the bright field STEM images of MSTB with different magnifications, showing the few-layer growth of MoS2 over the porous structure of TiO2 NBs.66 The HRTEM lattice fringe pattern of MSTB HSs shown in Fig. 2(f) clearly reveals the coexistence of few-layer MoS2 in the TiO2 lattice. Fig. 2(f) shows a typically layered nanosheet having ~6 sandwiched S–Mo–S layers with an interlayer spacing of ~0.67 nm. Additional ordered domains with a lattice spacing of 0.28 nm can be assigned to the (100) plane at the basal surface of 2H-MoS2. The lattice spacing of 0.37 nm, 0.39 nm, and 0.64 nm corresponds to the (110), (201) and (001) crystal planes, respectively, for the pure B-phase TiO2. It can be observed from the DF-STEM image of PMSTB shown in Fig. 2(g) that the Pt NPs are selectively decorated at the exposed edge sites of MoS2 over the MSTB HS and the inset shows the size distribution of Pt NPs over the MSTB HSs. It shows a very narrow size distribution (distribution width ~0.19 nm) with an average size of 3.8 nm. Fig. 2(h and i) depict the dark field and bright field STEM images of Pt NPs anchored selectively on edge/defect sites of MoS2 layers supported on the TiO2 NBs, respectively.

In order to estimate the individual contribution of Pt NPs and MoS2 on the HER under dark and light conditions, we performed STEM-EDS elemental mappings on the MSTB HSs before and after the modification with Pt NPs. Fig. 3(a) shows a STEM image of PMSTB on which elemental mapping was performed. EDS elemental mapping reveals that the core of the HS is composed of Ti and O elements, as shown in Fig. 3(b and c), which further confirms the uniform growth of TiO2. Fig. 3(d and e) show the elemental mapping for Mo and S, respectively, which supports our argument that the discrete MoS2 NF grows on the TiO2 platform as an outer layer. The Pt NPs are observed to be dispersed with overall uniformity over the MoS2 NFs as confirmed by the elemental map of Pt shown in Fig. 3(f). Similar results of the elemental distribution of Ti, O as the core layer

Fig. 1  FESEM images of (a) pristine TiO2 NBs, (b) Pt NP decorated TiO2 NBs, (c) MoS2 NFs decorated on TiO2 NBs, and (d) Pt NP decorated MoS2/TiO2 HSs.
and Mo and S as an outer layer were observed in the case of MSTB, as shown in Fig. S2(a–f) (ESI†). EDS spectra corresponding to MSTB and PMSTB shown in Fig. S2(g and h) (ESI†) confirmed that the ratio of S and Mo is found to be similar before and after Pt loading onto the MSTB HS (see Fig. S2(g and h), ESI†). It is clear that the majority of the Pt NPs is embedded at the edge sites of the 2H phase MoS2 layers. The weight% of S is found to be high indicating S-rich MoS2 layers in all the catalysts MS to MSTB to PMSTB, as evident from the EDS analysis of pristine samples (see Fig. S3, ESI†) which is reported to be beneficial for the enhanced HER activity.22 However, in the case of PTB, most of the Pt NPs are preferentially attached to the porous sites of TiO2 nanostructures.

3.2. Structural analysis

3.2.1. XRD analysis. Fig. S4 (ESI†) depicts the XRD pattern of the as-grown catalysts. The diffraction peaks for pristine MoS2 (marked with “*”) in Fig. S4(a) (ESI†) detected at 2θ = 14.5°, 32.9° and 56.5° can be attributed to the (002), (100) and (106) crystal planes, respectively (JCPDS card no. 37-1492). XRD peaks corresponding to pristine TiO2 NBs (labeled with “+” mark) match with the standard values of the TiO2 monoclinic structure.12 Fig. S4(c) (ESI†) shows the diffraction pattern of few-layer MoS2 designed on porous TiO2 HSs (MSTB). It can be noted that the diffraction peak of pristine MoS2 at ~14.5° corresponding to the c-plane was not detected in the case of MSTB. Thus, the absence of this peak confirms the coating of TiO2 NBs with extremely thin few-layer MoS2 nanosheets, which may prevent the crystal growth along the c-axis. Fig. S4(d) (ESI†) shows the XRD pattern of PMSTB, which clearly confirms the coexistence of Pt, MoS2, and TiO2(B) crystals. In the figure, Pt has been depicted by circles (filled). The diffraction peaks of Pt are relatively sharp, clearly implying its highly crystalline nature.

3.2.2. Raman analysis. In order to investigate the crystallinity, phase and layer numbers in the as-grown catalysts, micro-Raman analysis has been conducted, as shown in Fig. 4. Each of
the phonon modes of TiO$_2$ NBs correspond to the monoclinic structure of B-phase TiO$_2$, see Fig. 4(a). The pristine MoS$_2$ exhibits two active Raman modes attributed to E$_{2g}^{1}$ and A$_{1g}$ having a separation of 25.1 cm$^{-1}$, as shown in Fig. 4(a). However, MSTB exhibits a combination of B-phase TiO$_2$ and MoS$_2$. In MSTB, these Raman modes are observed with a reduced separation of 22.3 cm$^{-1}$, as clarified by the vertical dotted lines. After loading the Pt NPs on MSTB, the intensity of the characteristic MoS$_2$ peaks is significantly reduced, while that of TiO$_2$ is not affected much. This may be due to the screening effect of Pt NPs decorated over the edge-rich MoS$_2$ NFs. Fig. 4(b) shows the B$_g$ and A$_g$ Raman modes for B-phase TiO$_2$ in the pristine TB, MSTB, and PMSTB, and their corresponding Lorentzian fittings. It is evident that the intensity of TiO$_2$ Raman modes decreases after the decoration of MoS$_2$, which may be due to the bonding of MoS$_2$ at the porous sites of
TiO$_2$ NBS. The $B_g$ and $A_g$ Raman modes of TiO$_2$ NBS at 123.1 cm$^{-1}$ and 146.7 cm$^{-1}$, respectively, are broadened and blue shifted after the MoS$_2$ growth, as shown in Fig. 4(b). The MSTB shows a blue shift of 3.2 cm$^{-1}$ in $B_g$ mode with broadening in the FWHM from 10.8 cm$^{-1}$ to 12.9 cm$^{-1}$. Similarly, for $A_g$ mode, the MSTB HS exhibits a huge blue shift of 6.8 cm$^{-1}$ with an increment in the FWHM from 11.7 cm$^{-1}$ to 22.4 cm$^{-1}$. Such a large blue shift and broadening are mostly due to a surface strain (compressive type) induced by the MoS$_2$ nanosheets covered on the TiO$_2$ surface originating from the non-stoichiometric oxygen vacancy (O$_v$) defects resulting possibly from the S-doping at the O-site in the TiO$_2$ lattice. After the loading of Pt NPs over MSTB, no further increase of defect concentration in the TiO$_2$ lattice is observed. Fig. 4(c) shows the $E_{2g}$ and $A_{1g}$ Raman modes for MoS$_2$ in the pristine MS, MSTB, and PMSTB, and the corresponding Lorentzian fittings are also shown. The pristine MoS$_2$ exhibits two active Raman modes centered at 379.7 cm$^{-1}$ and 404.8 cm$^{-1}$, which are attributed to $E_{2g}$ and $A_{1g}$ modes, respectively, as shown in Fig. 4(c). However, in MSTB, these Raman modes are observed at 380.1 cm$^{-1}$ and 402.4 cm$^{-1}$, respectively. The former peak ($E_{2g}$) is attributed to the in-plane vibrations and the latter one ($A_{1g}$) to the vertical-plane vibrations in the Mo–S bond of MoS$_2$ and the separation between these two peaks is mainly determined by the layer number in MoS$_2$ nanosheets. The estimated frequency differences between these two modes are $\Delta \nu \approx 25.1$ cm$^{-1}$ and 22.3 cm$^{-1}$ for pristine MS and MSTB, respectively. Thus, the growth of few-layer pristine MoS$_2$ is confirmed and the reduction in $\Delta \nu$ for MSTB may be interpreted as follows: first, the overall growth of layered MoS$_2$ on the TiO$_2$ platform leads to a reduced number of layers (bilayer/few-layer); this is due to the presence of numerous porous nucleation sites in TiO$_2$ NBS which not only act as the nucleation sites for the growth of layered MoS$_2$, but also constrain their aggregation to yield bilayer/few-layered structures. In contrast, the bare MoS$_2$ NFs aggregate during the hydrothermal growth due to the absence of any anchoring support, resulting in multilayered MoS$_2$. Second, in MSTB, the only $A_{1g}$ peak is observed to be redshifted (by $\approx 2.4$ cm$^{-1}$), whereas the $E_{2g}$ peak remained unchanged. This may be due to the softening of $A_{1g}$ vibrations at high electron concentrations, which results from the n-type doping in MoS$_2$ grown in the catalysts. In the present case, pristine MoS$_2$ layers contain S atoms with electron binding energies at $\approx 161.9/163.1$ eV and $\approx 163.4/164.6$ eV, respectively (two sets of doublets), as shown in Fig. 5(a). The lower binding energy doublets are assigned to unsaturated S$^{2-}$ and terminal S$^{2-}$, while the higher binding energy doublets are assigned to bridging S$^{2-}$ and apical S$^{2-}$. In addition to the formation of MoS$_2$, the presence of S$^{2-}$ in the HS sample may correspond to the Ti–S bond formed during the substitution of O-atoms by S-atoms in the TiO$_2$ crystal lattice, resulting in S-doped TiO$_2$, which is consistent with the large blue shift in TiO$_2$ Raman spectra and enhancement of O$_v$ concentration in the TiO$_2$ lattice after the in situ growth of MoS$_2$ over TiO$_2$ (discussed later). Ting et al. demonstrated that the catalytic reactivity, as well as the turnover frequency of hydrogen production, increases almost linearly with increasing the amount of S$^{2-}$/apical S$^{2-}$ in the catalysts. In the present case, pristine MS exhibits S atoms with bridging S$^{2-}$/apical S$^{2-}$ as 39.1% which is found to be increased to 54.4%, after its growth on porous TB, as shown in Fig. 5(a and b). Therefore, the TB NBS not only facilitate the few-layer growth of MoS$_2$ with edge-exposed sites but also serve as an effective platform for mediating the evolution of MoS$_2$ with more bridging S$^{2-}$/apical S$^{2-}$ to promote the enhanced HER activity. It is noteworthy that after Pt NP decoration on MSTB, the bridging S$^{2-}$/apical S$^{2-}$ increases dramatically to 72.2%, as shown in Fig. 5(c). Thus, it is
clear that the Pt NPs plays a crucial role to increase the bridging $S_{2}\ ^{2-}$/apical $S^{2-}$ amount in the HS and eventually in the superior HER performance.\textsuperscript{35} Fig. 6(a–d) displays the O 1 s XPS spectra of TB, MSTB, PTB and PMSTB, respectively. The spectra corresponding to pristine TB and PTB possess a long tail towards the higher-energy region making the spectra asymmetric in nature. In addition, MSTB and PMSTB exhibit exceptionally broad O 1s spectra implying the presence of defects or impurities on its surface. Each O 1s spectra can be fitted with three symmetric Gaussian peaks, as reported in the literature.\textsuperscript{36} The first peak at $\sim$530.1 eV is attributed to the TiO$ _2$ crystal lattice and its relative percentages are calculated to be 66.6%, 61.4%, 21.2% and 21.3% for TB, PTB, MSTB, and PMSTB, respectively. Thus, it is clear that the relative percentage of lattice oxygen in TiO$_2$ decreases marginally after the Pt decoration, but it decreases dramatically after the decoration of MoS$_2$. The second peak at $\sim$531.2 eV can be assigned to the Ti–O bond (O$_{\text{Ti}}^{3+}$) and the relative O$_{\text{Ti}}^{3+}$% calculated from the O 1 s XPS spectra is tabulated in Table 1. After the decoration of MoS$_2$, the O$_v$ concentration in the TiO$_2$ lattice is observed to be more than doubled from 21.1% to 46.1%, which may be due to the substitution of O-atoms in TiO$_2$ with the S-atoms during the \textit{in situ} growth of MoS$_2$ over the TiO$_2$ platform. This is consistent with the large blue shift in the Raman spectrum. Loading of Pt NPs on TB or MSTB results in the decrease in O$_v$ concentration from its initial value, perhaps due to the presence of Pt$^{2+}$ species, which reduce the vacancy concentration. The third peak at $\sim$532.7 eV is attributed to the hydroxyl group adsorbed on the HS surfaces and its relative percentages are shown in Table 1. Thus, it is observed that introduction of Pt NPs into the nanostructures enhances the relative percentage of the adsorbed hydroxyl group from 12.3% to 23.1% for pristine TB and from 32.7% to 47.3% for MSTB. Thus, it can be concluded that the Pt NPs introduce the hygroscopic nature in the nanostructure and also increase the adsorption capability in the system. These exceptionally high defect states may serve as shallow donors and enhance the charge transfer at the multiple interfaces, which in turn improves the overall photoelectrocatalytic water splitting under solar light, as discussed later.

### Table 1 Summary of the samples, their effective band gap, the relative percentage of oxygen vacancies (O$_v$), hydroxyl groups (O$_{\text{OH}}$), lower and higher binding energy (BE) S present in the samples

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Sample</th>
<th>O$_v$</th>
<th>O$_{\text{OH}}$</th>
<th>Lower BE S (terminal and unsaturated)</th>
<th>Higher BE S (bridging and apical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB</td>
<td>TiO$_2$(B)</td>
<td>22.2</td>
<td>18.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MS</td>
<td>MoS$_2$</td>
<td>—</td>
<td>—</td>
<td>60.9</td>
<td>39.1</td>
</tr>
<tr>
<td>MSTB</td>
<td>MoS$_2$/TiO$_2$</td>
<td>46.1</td>
<td>32.7</td>
<td>45.6</td>
<td>54.4</td>
</tr>
<tr>
<td>PMS</td>
<td>Pt@MoS$_2$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>PTB</td>
<td>Pt@TiO$_2$</td>
<td>15.5</td>
<td>23.1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>PMSTB</td>
<td>Pt@MoS$_2$/TiO$_2$</td>
<td>31.4</td>
<td>47.3</td>
<td>27.8</td>
<td>72.2</td>
</tr>
</tbody>
</table>
corresponding to their DRS spectra. The pure TiO$_2$(B) NBs exhibit a sharp rise in absorption (edge) at ~360 nm (the indirect bandgap estimated from the Tauc plot is ~3.25 eV), which is attributed to their intrinsic band gap absorption. Pristine few-layer MoS$_2$ NFs exhibit a broad absorption band having a peak at ~670 nm (direct bandgap estimated from the Tauc plot: ~1.63 eV) showing a large blue shift compared to their bulk counterpart. This may be attributed to the strong quantum confinement effect of the thin and layered MoS$_2$ nanosheets, which makes the MoS$_2$ a promising candidate for visible light photocatalysis.  

Incorporation of few-layer MoS$_2$ on TiO$_2$ NBs enhances the absorption intensity significantly over the wide UV-visible-IR range, as shown in Fig. 7(a). Introduction of Pt NPs on the TiO$_2$ NBs further enhances the visible light absorption efficiency, with a new absorption band centered at ~415 nm, besides its enhanced UV and visible-NIR absorption. Cueto et al.$^{58}$ have shown that Pt NPs with a size of 5–35 nm exhibit a plasmonic absorption covering a narrow band in the range 200–320 nm, and a broader band with a tail extending up to the NIR region. However, in the case of large Pt NPs the absorption band becomes intense and broad enough as a consequence of stronger plasmonic excitation due to the formation of numerous hotspots between two or more Pt NPs close to each other. In the present work, the Pt NPs decorated over the MoS$_2$ NFs are closely spaced, which enables high plasmonic excitation generation in the numerous hotspots, and results in high absorption. Interestingly, the absorption edge of the TiO$_2$ NBs is observed to be red shifted after decoration of MoS$_2$ NFs as well as Pt NPs. With Pt NPs, the absorption edge of the TiO$_2$ is red shifted to ~380 nm from ~360 nm. In the case of MSTB, it is further redshifted to ~402 nm, which implies an efficient band bending at the interface arising from the strong coupling between the porous TiO$_2$ and wrapped MoS$_2$ layers. S-
doping in the TiO2 lattice may also be attributed to this red shift. However, the maximum red shift is observed in PMSTB (~471 nm), which may be attributed to the strong coupling between each pair of the components MoS2–Pt, MoS2–TiO2, and Pt–TiO2. Thus, the HSs are expected to be extremely sensitive to the visible-NIR light and would be beneficial for the efficient visible light photocatalytic hydrogen evolution.

Fig. 7(b) shows a comparison of room temperature PL spectra of TB, MSTB, and PMSTB. pristine TiO2 NBs exhibit very weak and broad PL emission having an emission peak at ~515 nm, which is attributed to the single electron trapped oxygen vacancy (OV) defects (F’ center). After the growth of the MoS2 layer on TiO2 NBs, the PL intensity corresponding to the F’ center increases strongly, indicating an increase in the concentration of OV defects. During the in situ hydrothermal growth of MoS2 on TiO2, S-atoms may diffuse and substitute the O-atoms in the TiO2 lattice, causing S-doping in TiO2. This causes an increase in the OV concentration and an eventual increase in electron density in TiO2. Due to the high optical absorption and OV defects in MSTB HS, the PL intensity corresponding to the F’ center increases substantially. After loading of Pt NPs over MSTB, the PL intensity reduces, which is due to the fast interfacial electron transfer from TiO2 to Pt NPs via MoS2. Additionally, PMSTB shows a relatively broader PL spectrum indicating the contribution from the hydroxyl group attached to the TiO2 surface, which is consistent with the XPS analysis.

3.4. Hydrogen evolution reaction (HER) study

The visible light HER performance of various catalysts, such as TB, MS, MSTB, PMS, PTB and PMSTB as working electrodes made on a glassy carbon disk was investigated in an N2-saturated 0.5 M H2SO4 solution using a typical three-electrode linear sweep voltammetry (LSV) method. For a better comparison, each measurement has been repeated under dark conditions as well. The electrochemical HER activities (LSVs) of various catalysts under dark and light conditions (wavelength range 370–730 nm) are shown in Fig. 8(a and b) and the corresponding Tafel slopes are shown in Fig. 8(c and d), respectively. Note that the results are nearly independent of scan rates in the range 2–10 mV s⁻¹ (see Fig. S9 and Table S1, ESI†) and the presented data correspond to a scan rate of 5 mV s⁻¹. As shown in Fig. 8(a), the HER for pristine TiO2 NBs starts at a potential of ~623 mV and ~616 mV (versus RHE) under dark and light conditions, respectively, above which the current increases drastically. In spite of very low overall current density, TB presents a HER overpotential (to attain ~10 mA cm⁻² current density) of ~796 mV under light at a current density of 10 mA cm⁻², which is positively shifted by 87 mV as compared to that in the dark. The pristine few-layer MoS2 exhibits much enhanced current density with a low onset potential of ~246 mV, which reduces to ~193 mV after light illumination. The overpotential is observed to be ~425 mV and ~395 mV under dark and light conditions, respectively (see Table 2). Interestingly, in MSTB the uniform decoration of edge-exposed few-layer MoS2 on the porous sites...
of TiO2 NBs decreases the onset potential to −215 mV in the dark, which further reduces to −178 mV after irradiation with visible light as compared to those of bare TiO2 and MoS2 nanostructures. In MSTB, the overpotentials are calculated to be −336 mV and −305 mV under dark and light conditions, respectively. Thus, it can be concluded that more carriers are being generated in MSTB with light irradiation, which augments the reduction process of electroadsorbed protons. The introduction of merely 0.6 wt% Pt NPs on the TB, MS, and MSTB results in a dramatic reduction in the onset potential towards the HER. For PMS, it is measured to be −76 mV and −66 mV, while for PTB it is observed at −45 mV and −41 mV, under dark and light conditions, respectively. In the case of PMSTB, the onset potential in the dark is measured to be −40 mV, which is dramatically reduced to −9 mV after light irradiation, which essentially outperforms the commercial Pt/C electrode (−48 mV) with much higher Pt content. The summary of the performance of various catalysts is presented in Table 2.

As evident from the table, the PMSTB exhibits exceptionally low overpotential under light, −74 mV, which is much lower (by 23 mV) than the value measured in the dark (−97 mV) and this is further lower than that of the commercial Pt/C electrode (−106 mV). Thus, a dramatic enhancement in the photogenerated charge carriers, as well as reduced charge transfer resistance, is expected in the systems after the Pt NP decoration, which serve as favorable nodes with large electron-accepting and buffering properties to facilitate electron transport, which in turn improves the overall conductivity.4

Tafel slopes of all the samples under both dark and light conditions (in mV per decade), estimated from the linear fit of the overpotential and logarithmic function of current density (log|j|), are shown in Fig. 8(c and d) and tabulated in Table 2. Lower Tafel slopes not only reveal about the rate-determining step of the hydrogen evolution electrocatalysis mechanism but are also desirable to minimize the energy input required to achieve a targeted HER current density. From Fig. 8(c and d), it is evident that in each catalyst the Tafel slope decreases after the illumination with light compared to their respective dark values, which eventually confirms the acceleration of the electron transfer kinetics upon irradiation. In the dark, a much lower Tafel slope is estimated for pristine MS (119 mV dec⁻¹) than for pristine TB (170 mV dec⁻¹), which further decreases in their composite system (MSTB) to 112 mV dec⁻¹. Under visible light illumination, their corresponding values are calculated to be 135 mV dec⁻¹ (TB), 107 mV dec⁻¹ (MS) and 92 mV dec⁻¹ (MSTB), as shown in Table 2. After Pt NP loading on MS, TB, and MSTB, the Tafel slope is observed to be decreased drastically, as shown in Fig. 8(d). Tafel slopes for PMS and PTB are 59 and 53 mV dec⁻¹ in the dark, and 56 and 50 mV dec⁻¹ under light, respectively. PMSTB exhibits an exceptionally low Tafel slope (30 mV dec⁻¹) under light, which is much lower (19 mV dec⁻¹) than the value measured in the dark (49 mV dec⁻¹) and our values are comparable/better than that of a commercial Pt/C electrode (32 mV dec⁻¹). Two main reaction pathways are widely accepted in HER electrocatalysis, commencing with a primary discharge step (i.e., Volmer reaction: H₂O + e⁻ → H_adsorbed), followed by either an electrochemical desorption step (i.e., Heyrovsky reaction: H₂O + e⁻ + H_adsorbed → H₂) or a monoatomic hydrogen recombination step (i.e., Tafel reaction: H_adsorbed + H_adsorbed → H₂). As broadly reported in the literature, Tafel slopes of ~120 mV dec⁻¹, ~40 mV dec⁻¹, and ~30 mV dec⁻¹ are allocated to Volmer, Heyrovsky and Tafel reactions being the HER rate-determining step, respectively.60,61 In our case, the Tafel slopes of all the HS photocatalysts (MSTB, PMS, PTB, and PMSTB) fall between the Volmer mechanism and the Tafel mechanism indicating that the Volmer–Tafel mechanism plays the predominant role in the catalysts’ HER kinetics.62 The lowest Tafel slope found for PMSTB under visible light illumination (i.e. enhanced HER kinetics) consequently supports its high HER performance.

Electrochemical impedance spectroscopy (EIS) is a powerful technique to characterize interface reactions and the heterogeneous electron transfer process in HER.63 Fig. 9(a-d) and S7(a and b) (ESI†) show the Nyquist plots of all the samples corresponding to their EIS response. The charge transfer resistance (Rct) values have been calculated for all the samples estimated from the Randles circuit (see Fig. S7(c), ESI†) under dark and light conditions.64 In the dark, the Rct is calculated to be lower for MSTB (102 Ω) as compared to those of the pristine TB (527 Ω) and MS (132 Ω). Interestingly, after the Pt NP decoration, the Rct dramatically reduces to 36 Ω, 33 Ω and 27 Ω for PMS, PTB, and PMSTB, respectively, in the dark. The Rct values of all catalysts are decreased even further upon illumination, indicating the presence of photogenerated carriers in these

<table>
<thead>
<tr>
<th>Catalyst code</th>
<th>Onset potential (at −0.5 mA cm⁻²) (mV V RHE)</th>
<th>Overpotential (at −10 mA cm⁻²) (mV V RHE)</th>
<th>Tafel slope (mV dec⁻¹)</th>
<th>Charge transfer resistance, Rct (Ω)</th>
<th>Exchange current density, j0 (mA cm⁻²)</th>
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<tbody>
<tr>
<td>TB</td>
<td>−623</td>
<td>−616</td>
<td>170</td>
<td>135</td>
<td>527</td>
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<tr>
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<td>−246</td>
<td>−193</td>
<td>119</td>
<td>107</td>
<td>132</td>
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<tr>
<td>MSTB</td>
<td>−215</td>
<td>−178</td>
<td>112</td>
<td>92</td>
<td>102</td>
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<td>PMS</td>
<td>−76</td>
<td>−66</td>
<td>59</td>
<td>56</td>
<td>36</td>
</tr>
<tr>
<td>PTB</td>
<td>−45</td>
<td>−41</td>
<td>53</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>PMSTB</td>
<td>−40</td>
<td>−9</td>
<td>49</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>Pt/C</td>
<td>−48</td>
<td>—</td>
<td>32</td>
<td>—</td>
<td>6</td>
</tr>
</tbody>
</table>
electrodes, as tabulated in Table 2 and Fig. 9(e). Under illumination, the $R_{ct}$ for PMSTB decreases to the minimum value of 14 $\Omega$ indicating the augmented charge transfer process in the presence of light. The heavy n-type doping in the catalytically active edge-exposed MoS$_2$ NFs (as demonstrated from Raman analysis, see Fig. 4(c)) provides a fast electron transfer from the TiO$_2$ side to the MoS$_2$ side and results in superior HER kinetics, which is dramatically enhanced after the introduction of metallic and highly active catalyst Pt NPs into the MSTB system.

Further insight into the intrinsic activity of the HER electrocatalysts can be obtained by comparison of exchange current density ($j_0$) values, which is determined by the ability to exchange electrons from the working electrode to the counter electrode through the electrolyte solution at null potential. Fig. 9(f) compiles exchange current density, $j_0$, values obtained under dark and light conditions for all studied samples. It is noteworthy that a dramatic enhancement (~10-fold) in $j_0$ value is observed in TB under visible light after the decoration with MoS$_2$ layers. Furthermore, for all samples tested, there is a significant increase in $j_0$ values after visible light illumination, consistent with the lower $R_{ct}$ and Tafel slope values found after light irradiation. Among the various electrodes studied here, PMSTB showed the highest $j_0$ (~0.182 mA cm$^{-2}$ in the dark and 0.296 mA cm$^{-2}$ under visible light). Thus, the aforementioned enhanced HER performance of MSTB is a result of the efficient charge transport and favorable HER kinetics at the interface of the HS components, which is further enhanced after decoration with Pt NPs, widely regarded as the best performing noble metal catalyst for the HER.

To evaluate the durability of the as-prepared catalyst, the cyclic durability, as well as long term stability, was investigated, and the results are presented in Fig. 10(a). A long-term cycling
experiment (up to 22 hours) was performed for PMSTB by recording 10 000 CV cycles from 0 V to −0.2 V vs. RHE. As shown in Fig. 10(a), the polarization curve shows no loss in current density after 10 000 CV cycles, though the performance marginally improves with time, which may be due to the improved interfacial contact and possible Pt dissolution/redeposition at the PMSTB surface, which may yield an increase in the HER active sites. The long term stability test was performed by chronopotentiometry measurements to evaluate the catalyst capability of sustaining a 10 mA cm\(^{-2}\) cathodic current over a 12 h period (see inset of Fig. 10(a)). The catalyst PTB shows the initial decay of HER performance up to 3 h of operation (−0.270 V@3 h vs. −0.123 V@0 h), indicating the stabilization of the anchoring effect of MoS\(_2\) with respect to the decorated Pt NPs. Beyond 3 h, PTB performance marginally improves with time up to 12 h (−0.238 V@3 h), PMSTB shows a similar trend with an initial decay of HER performance with time up to 3 h, as shown in the inset of Fig. 10(a). Eventually, it reaches a HER performance of −0.195 V@12 h, which is better than that of PTB. Note that after 12 h of continuous galvanostatic operation at 10 mA cm\(^{-2}\), the HER performance of PMSTB decays by ~90 mV. Additionally, some intermittent fluctuation in the potential values is observed for PMSTB beyond ~4 h of continuous operation, which may be due to the mild oxidation of the MoS\(_2\) sites accelerated by the anchored Pt NPs and the H\(_2\) bubble movement. We cannot rule out the effect of leaching of the samples in MoS\(_2\) and Pt-based ternary systems, which necessitates a more careful sample preparation for such experiments. Interestingly, the performance of MSTB initially improves with time and then reaches a saturation value. Possible coarsening of the MoS\(_2\) layer along with electrochemical activation of the high binding energy S\(_2\)\(^2-\) sites upon irreversible HER cathodic cleaving may explain the observed enhancement.\(^{25,65}\) To understand the structural stability of the catalyst, the Raman spectra of MSTB were recorded before and after the PEC reaction. The crystallinity and stability of both TiO\(_2\)(B) and MoS\(_2\) components are observed to be retained under the PEC reaction, as evident from Fig. S6 (ESI†). However, the relative intensity of MoS\(_2\) characteristic peaks slightly decreases after the reaction, which may be due to oxidation and associated introduction of defects in the MoS\(_2\) layers. One additional Raman peak is detected at ~820 cm\(^{-1}\) after the PEC reaction, which may be assigned to the M=O bond\(^{66,67}\) resulting from the marginal oxidation of MoS\(_2\) in the acidic media. However, chronopotentiometric measurements show that the MSTB catalyst exhibits excellent stability towards HER activity up to 12 h, confirming the non-photocorrosive nature of our catalyst. We believe that the interplay between Pt and MoS\(_2\) interfaces, which ultimately results in enhanced HER performances, is not just the synergistic effect of Pt promotion of initially inactive MoS\(_2\) sites and reduction in the TiO\(_2\) bandgap, but also the mechanical anchoring provided by MoS\(_2\) and the inherently high Pt HER electroactivity and conductivity. In addition, appropriate band bending at the multiple interfaces sweeps away the charge carriers and allows them to participate in the enhanced HER activity.

3.5. Mechanism of enhanced HER activity

Though MoS\(_2\) is known as a catalytically active material, poor charge transport in the basal plane is often responsible for its inferior HER performance. Fabrication of edge-exposed MoS\(_2\) and activation of the inert basal plane through Pt doping or extrinsic S vacancy generation have proven to be successful strategies to trigger superior HER electrocatalytic activities.\(^{68–70}\) In this study, few-layer MoS\(_2\) with a high density of catalytically active edge-exposed sites is tightly coupled with the porous surface of S-doped TiO\(_2\) NBs. Structural analysis by HRTEM and STEM imaging of the as-grown MoS\(_2\) layers on the TiO\(_2\) NBs confirms their edge-rich nature, and the presence of surface defects. This defect-rich structure leads to a higher exposure of unsaturated sulfur edge sites, which are widely regarded as the active sites responsible for the overall HER activity.\(^{22,55}\) Additionally, the MoS\(_2\) layers grown onto the TiO\(_2\) NB surface present an n-type doping of MoS\(_2\), contributing to maximize HER activities after MoS\(_2\) basal plane activation.

Upon illumination with visible light, electrons in TiO\(_2\), as well as MoS\(_2\) in the HSs, may be excited, as confirmed by the UV-
visible absorption analysis. Due to the appropriate band alignment at the interface, the photogenerated electrons at the TiO2 NBs can easily be transferred to the MoS2 layer, avoiding possible recombination loss of carriers and it induces n-doping of the MoS2 layer, as depicted in Fig. 10(b). The photo action spectra of different samples are shown in Fig. S8, confirming the visible light activation of electron–hole pairs and their efficient separation. Consequently, this efficient charge transfer occurring at the heterojunction (MSTB) greatly reduces the charge transfer resistance under visible light (88 Ω) and accounts for the enhanced exchange current density ($j_0$) under illumination, which is measured to be 0.019 mA cm$^{-2}$. A marginal amount of Pt NP (1.4 wt%) loading on the MSTB is found to decorate the catalytically active edge sites of MoS2 as well as the porous sites of TiO2 with Pt NPs. The enhanced HER activities obtained after Pt decoration onto porous MoS2 NFs/TiO2 NBs indicate an even higher density of proton-accepting sites compared to MoS2 NFs/TiO2 NBs, which presumably arises from further activation of initially electrocatalytically inert MoS2 basal planes and S-edge sites. In addition, the presence of Pt NPs can also serve as advantageous metallic current collector nodes to facilitate lower resistance transport pathways of photoexcited carriers from TiO2 domains to Pt NPs through MoS2 (see Fig. 10(b)), improving the overall conductivity. Hence, significantly enhanced HER activity was observed using PMSTB with a minimum charge transfer resistance of 14 Ω and a maximum exchange current density of 0.296 mA cm$^{-2}$. Additionally, the modification by H2SO4 decreases the work function of TiO2, which changes its conduction band offset. A schematic illustration of the excitation of electrons and their separation through two interfaces under the light irradiation is shown in Fig. 10(b) and this results in the superior HER performance of the composite system. The structural defects and porous S-doped TiO2 surface also promote a closer interaction between MoS2 and TiO2 during solvothermal synthesis (i.e. higher availability of nucleation sites), which may be responsible for the catalytically active n-type doped structure of MoS2 NFs. The detection of hydrogen gas during the electrocatalysis experiment and its quantification was made by the gas chromatography measurement and the results are presented in Fig. S10 and S11, respectively (ESI†).

On a separate note, the adsorbed hydroxyl group in the TiO2 lattice increases greatly after the decoration of MoS2 layers (32.7%), which further enhances to 47.3% after the loading of Pt NPs on MSTB, as confirmed from XPS analysis. As the Volmer–Tafel HER mechanism governs the HER performance in our HS catalysts, the higher presence of hydroxyl groups at the PMSTB electrode, known to facilitate electroadsorbed hydrogen desorption, may promote the rate-limiting electrochemical desorption step involving hydrogen gas formation.

4. Conclusion

In summary, a hierarchical Pt@MoS2/TiO2 HS has been successfully grown via a three-step chemical process, which consists of solvothermal fabrication of TiO2(B) NBs, its surface decoration by discrete few-layer MoS2 by a hydrothermal method followed by in situ decoration of Pt NPs onto it. Uniform decoration of MoS2 layers on the porous sites of TiO2 as well as preferential decoration of Pt NPs on edge-sites/defect-sites of MoS2 and porous sites of TiO2 NBs has been evidenced by the FETEM and STEM analyses. The maximally edge-exposed MoS2 NFs grown on and supported by the porous TiO2 platform exhibit overall reduced layer numbers compared to the pristine MoS2 layers and the MoS2 NFs likely to be n-type doped, as revealed from the Raman analysis. In the HSs, MoS2 exhibits exposed edge-sites, considered as the active nodes towards the HER. The formation of O V rich MSTB and PMSTB with extremely high and broad visible to NIR absorption has been evidenced by the XPS and UV-visible absorption spectra, respectively. XPS analysis shows that the catalytically active bridging S$_2^{2-}$/apical S$_2^{2-}$ increases up to ~72% after the formation of the ternary system, PMSTB. Formation of a well-coupled heterojunction between MoS2 and S-doped TiO2 accelerates the charge transfer rate from the TiO2 to the MoS2 side through the interfaces. Interestingly, Pt NPs anchored with the edge-sites of MoS2 and porous sites of TiO2 collect the photo-excited carriers making the HSs superior for HER activity than their individual counterparts. Under visible light illumination, the onset potential of MSTB is observed to be much lower (~178 mV) than that of the TiO2 (~616 mV) and MoS2 (~193 mV) layer, with significant enhancement in the exchange current density. With the loading of 1.4 wt% Pt NPs on MSTB, the onset potential and the corresponding Tafel slope are reduced drastically to ~9 mV and 30 mV dec$^{-1}$, respectively, with dramatically improved exchange current density (0.296 mA cm$^{-2}$). The Pt NP-supported HSs exhibit a giant enhancement in HER activity as evidenced by the EIS spectra. The presence of edge-defect enriched few-layer MoS2 NFs on porous TiO2 NBs, supported by a marginal amount of Pt NPs exhibit extremely high hydrogen generation with high-performance stability at the working electrode through the Volmer–Tafel mechanism. Our results are very significant for the development of multi-component catalysts.

Conflicts of interest

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References


