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Tailored performance of layered transition metal dichalcogenides *via* integration with low dimensional nanostructures

Transition metal dichalcogenides (TMDs) with a unique sandwich structure have attracted tremendous

attention in recent years due to their distinctive electrical and optical properties. The performance of TMDs

can be tailored by integration with low dimensional nanostructures which possess guantum size effects and

large specific surface areas. In this review, we give a brief description of integrated structures, their synthesis methods, and highlight the applications in hydrogen production, lithium batteries, sensors and detectors.

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1. Introduction

Since the advent of graphene in 2004, two-dimensional (2D) materials with large specific surface areas and excellent electronic and optical properties have attracted significant attention in various fields such as energy storage, sensing, electronic and optoelectronic devices.1-7 Among them, transition metal dichalcogenides (TMDs, e.g. MoS₂, MoSe₂, WS₂, WSe₂) are gradually becoming hotspots of research due to their novel structure and remarkable properties.8,9 These materials present a MX₂ stoichiometry, where M is a transition metal and X is a chalcogenide.¹⁰ They possess a unique 2D X-M-X structure, in which the monolayer consists of transition metal atoms and chalcogen atoms interacting with strong covalent bonds, while adjacent TMDs layers are formed by weak van der Waals forces.11,12 TMDs with semiconducting properties have a tuneable bandgap around 1-2 eV, and the bandgap becomes direct when the thickness of crystals decreases to a single layer, indicating that TMDs are promising materials in optoelectronic applications.13-15

TMDs-based heterostructures with outstanding properties and novel phenomena have been widely investigated.^{16,17} These heterostructures not only inherit the properties of individual components, but also present innovative properties, such as Moiré pattern-induced wave function localization in MoS₂/MoSe₂ heterostructures and larger on/off ratio in graphene/MoS₂ heterostructures-based transistor.¹⁸⁻²⁰ With the development of these heterostructures, new properties can be designed and tailored beyond the capability of conventional TMDs.²¹ These TMDs-based heterostructures can be integrated *via* various routes, including 0D quantum dots (QDs) and 1D nanotubes (NTs),²² or 0D QDs and 2D nanosheets (NSs),²³ or 1D nanorods (NRs) and 2D NSs as well.²⁴ Here, we focus on heterostructures composed of 2D TMD NSs and low dimensional nanostructures (LDNs).

LDNs such as nanodots (NDs), nanoparticles (NPs), nanowires (NWs) and nanobelts (NBs) with quantum size effects and large specific surface areas usually exhibit novel properties differ from their bulks.^{25–27} For instance, Nb₂O₅ shows an increased band gap from 3.4 eV to 4.2 eV when its particle size decreases to nanoscale.²⁸ Owing to tuneable optical properties and the effect of surface chemistry, some materials in low dimension show enhanced photoluminescence (PL), high sensitivity to detect gas or biological molecules, absorptivity of dye molecules, and improved charge transport ability.^{29–32} Therefore, a method of fabricating TMD-based heterostructures *via* integrating with LDNs is a potential approach to enhance performance in corresponding devices.^{21,33,34}

Although many comprehensive reviews regarding TMDs have been reported,^{16,17,35–38} there is still no systematic review with respect to LDNs/TMDs integration. In this review, we began with a brief description of integrated structures. We then outlined the synthesis methods of TMDs NSs and provided two main routes: self-assembly and hydrothermal/solvothermal to prepare LDNs/TMDs nanostructures. Subsequently, we highlight their applications and device performance. In the last part, a short summary is given.

2. Integrated structures

2.1 Low dimensional nanostructures

When the material size shrinks into nanoscale, the number of atoms or molecules forming the material becomes an



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influential role to the physicochemical properties and reactivity.³⁹ In order to simplify the size and dimensional effects, it is preferable to classify the materials according to the number of dimension with expansion freedom (not restricted in nanosize). For example, NDs and NPs, of which all dimensions are in the range of a few nanometres, belong to 0D category; and 3D materials usually refer to bulk materials. For the same material, the allotropes usually exhibit dimension-dependent distinctive properties. One of the typical instances is the allotropes of carbon materials. For a given carbon concentration, 1D multiwall carbon nanotubes (MWNTs) has higher photomechanical stress response and energy conversion efficiency than 2D single layer graphene and 3D graphite under illumination of nearinfrared (NIR) light.40 In another case, silicon materials with different dimension show different optical properties. While the bulk silicon does not emit visible light due to the indirect bandgap, the low dimensional Si nanostructures with the quantum-confinement effect are able to emit visible light.41,42 Besides, Si NWs structures have a small reflection in a wide spectrum range compared to 2D thin films, which improves the optical absorption in the high-frequency regime.43 In some metal materials, such as Au and Ag, when the dimension of metal crystals decreases to nanoscale, these nanostructures arrays demonstrate surface plasmon resonance phenomenon under light illumination.44,45 The collective motion of conduction band electrons related to fixed positive ions give rise to a plasmon oscillation in a metal under incident light.⁴⁶ This unique optical property provides some inspirations for applications such as biosensors and solar cells.47

In LDNs materials, a small change of size will alter its optical properties due to quantum confinement effect.48-50 For instance, Xue et al. demonstrated that the TiO₂ NPs with a size varied from 6.8 nm to 14.2 nm have a large difference on Raman intensity, which can be attributed to the charge-transfer resonance between the TiO₂ and the adsorbed molecules.⁵¹ Similarly, owing to the size effect, an absorption peak redshifts of Au NPs is observed when the particle diameter increased from 20 nm to 100 nm.52 Therefore, the metal NPs with localized surface plasmon resonances can be employed to develop refractive index sensors through combining with microfiber.53 In addition, some LDNs materials also exhibit distinct chemical, electrical or biological properties due to the size effect.54-56 For example, CdSe QDs employed for biological application, the smaller sized QDs have a greater improvement in enzymatic activity compared with the larger QDs.57 In general, these materials in low dimension with unique characteristics are applied in a range of fields such as catalysis, sensing, electronic and optoelectronic.58,59

2.2 Electronic and optical properties of 2D TMDs

TMDs materials are comprised of a transition metal element of groups IV – X and a chalcogen element such as sulfur (S) and selenium (Se).⁶⁰ Bulk TMDs exhibit a wide variety of polymorphs as compared to other 2D counterparts, and they cover a wide spectrum of properties such as semiconductivity, half-metallic magnetism and superconductivity.⁶¹ When the d-orbitals of

transition metal are partially occupied, TMDs display metallic conductivity properties, whereas these materials are semiconductors when the orbitals are fully occupied.¹⁰ In bulk phase of TMDs, there are three possible stacking structures: 1T, 2H and 3R with tetragonal symmetry, hexagonal closed packing and rhombohedral symmetry, respectively.⁹ However, monolayer TMDs are demonstrated to possess two polytypes, metallic 1T phase and semiconducting 2H phase, and the stacking structures are shown in Fig. 1.⁶² It has been demonstrated that the 2H stacking structure can be converted into 1T stacking structure by Li intercalation or plasmonic hot electron induced structure phase transition.^{5,63} The metallic 1T MoS₂ employed as electrode materials exhibits outstanding capacitive behaviour in both aqueous and organic electrolytes due to their intrinsic hydrophilicity and high electrical conductivity.⁶⁴

Semiconducting TMDs such as MoS₂ and WS₂ with a tuneable band gap promote their applications in photoelectric field.9,65,66 With decreasing layer number, the band gap present an increasing trend, and the indirect band gap of bulk TMDs gradually shift to be direct when reduced to single layer.67 Fig. 2 shows a band structure of bulk and monolayer MoS₂ calculated from first principles.68 At the Γ-point, bulk MoS₂ has an indirect band gap of 1.2 eV, which can be transferred to a direct band gap of 1.9 eV in monolayer form. This phenomenon can be explained by quantum confinement effect.14,69 Owing to the direct band gap, a strong PL is observed in monolayer MoS₂, and the PL quantum yield (QY) has a 10⁴ fold enhancement compared with their bulk crystal.70 Moreover, the PL of monolayer MoS₂ can be effectively improved via an air-stable, solution-based chemical treatment and the consequent QY is more than 95%.71 Therefore, single layer semiconducting TMDs with direct band gap indicates that they are promising candidates in optoelectronic applications.72

2.3 LDNs/TMDs heterostructures

The integration of materials in different dimensionalities is able to combine the inherent advantages and mitigate the genetic disadvantages in terms of fundamental properties.⁷³ Noble metals, metal oxides, graphite derivatives crystals with sizes in nanoscale such as Au NPs and carbon NTs (CNTs) can be integrated with 2D TMDs NSs. The as-prepared heterostructures present an obviously enhanced performance in



Fig. 1 Crystal structures of (a) 1T and (b) 2H crystal structures of the TMDs. Adapted with permission from ref. 6. Copyright 2013 American Chemical Society.



Fig. 2 Band structures of bulk MoS₂ and its monolayer. The arrows indicate the smallest value of the band gap (direct or indirect) for a given system. The top of valence band (blue) and bottom of conduction band (green) are highlighted. Adapted with permission from ref. 68. Copyright 2011 by the American Physical Society.

electrical and optical application.⁷⁴⁻⁷⁷ For instance, Zhou *et al.* prepared TiO₂ NBs@MoS₂ NSs heterostructure *via* a hydrothermal reaction, and the heterostructure exhibits highly photocatalytic hydrogen production.⁷⁸ Herein, the synergistic effect of TiO₂ and MoS₂ resulting in the heterostructure provides efficient charge separation to suppress the electron-hole recombination, and further display an improved photocatalytic activity. In another case, Zhang *et al.* reported a hydrothermal method to fabricate a ZnO NRs/MoS₂ NSs heterostructure without a catalyst.⁷⁹ Due to the light antennae effect of ZnO NRs, enhanced Raman and PL emission are observed in this type of heterostructure.

According to the dimension of nanostructures, these heterostructures can be divided into 0D/2D and 1D/2D, as shown in Fig. 3. Generally, 0D nanostructures usually tiled on TMDs NSs, and 1D nanostructure usually served as an axis for TMDs NSs, which were loaded on their surface in form of 1D/2D.^{21,80-82} Every individual structure in these heterostructures plays an important role and contributes to tailored performance of the whole system. Layered TMDs have several crystal phases with different lattice structures and electronic character such as 1T and 2H, although integrated with the same LDNs, these heterostructures exhibit distinct performance.83,84 Bai et al. demonstrated that TiO₂-MoS₂ (1T) hybrid structure exhibited excellent performance as a co-catalyst to product hydrogen, which is in sharp contrast to TiO₂-MoS₂ (2H).85 This can be attributed to the active sites on the 1T-MoS₂ basal plane, which gives rise to a high charge diffusion rate and reduces the probability of charge recombination when integrated with TiO₂. On the contrary, 2H-MoS₂ does not provide reaction sites and may block the active sites on the TiO₂ nanocrystals surface. In addition, the layer numbers can affect the electrical and optical properties of TMDs. For example, monolayer MoS₂ has a large enhancement of the luminescence compared with the bulk material.13 Therefore, layer number and crystal phase of TMDs are indispensable considerations when integrated with LDNs. Besides, the morphology and distribution of LDNs have impact on the system performance.86,87 For instance, Wang et al. prepared various morphologies of spherical, triangle, clover-like and flower-like AuNPs (Fig. 4) by changing the ratio of MoS₂ and



Fig. 3 Schematic of integrated heterostructure (a) 0D/2D and (b) 1D/2D. SEM images of (c) 0D Au NPs/2D MoS₂ NSs and (d) 1D TiO₂ NBs/2D MoSe₂ NSs. Adapted from ref. 75 and 89 with permission of The Royal Society of Chemistry.

thionine (Thi), and demonstrated the clover-like Au NP/Thi- MoS_2 nanocomposites-based electrochemical immunosensor exhibit an excellent selectivity, which can detect carcino-embryonic antigen (CEA) as low as 0.52 pg mL⁻¹.⁸⁸

3. Synthesis methods

Preparation of high quality TMDs NSs is an important process in their heterostructures fabrication. Both physical and chemical methods can be considered to obtain layered TMDs, such as exfoliation and chemical vapor deposition (CVD).^{21,90-94} For the synthesis of integrated nanostructures, different approaches have already been developed, as concluded in Table 1, which can be classified into two main methods: self-assembly and hydrothermal/solvothermal.

3.1 Layer TMDs

To date, exfoliation of layered solid and CVD growth method are mainstream strategies to obtain layered TMDs. Typically, mechanical exfoliation use micromechanical force to separate bulk materials and obtain single or few layers NSs, but the yield is relatively low and the size is quite small.⁶⁰ In comparison, chemical exfoliation can conquer these problems and obtain large-scale TMDs NSs. Zheng *et al.* used metal naphthalenide as intercalating agents to exfoliate metal chalcogenides and obtained high quality sheets with large size up to 400 μ m².⁹⁵ The size distribution of the flakes is much better than the sheets obtained by using organolithium salts, and the prepared TMDs sheets could be directly jet-printed on substrate. Shear exfoliation can also prepare TMDs NSs by separating bulk materials.



Fig. 4 (A) Schematic of preparation process of shape-controlled Au NPs supported on Thi-MoS₂ NSs. TEM images of AuNP-Thi-MoS₂ nanocomposites with (B) spherical, (C) triangle, (D) clover-like and (E) flower-like AuNPs. Adapted from ref. 88 with permission of The Royal Society of Chemistry.

Table 1 Summary of synthesis methods for integrated nanostructure

Dimensionality	Synthesis methods	Integrated nanostructures	Applications	Ref.
0D/2D	Self-assembly	Ag NPs-WS ₂	Supercapacitor	102
	·	Au NPs-MoS ₂	Sensor	103
		TiO_2 NPs-MoS ₂	Hydrogen production	85
	Hydrothermal	TiO ₂ -RGO-MoS ₂	Hydrogen production	104
		ZnO-MoS ₂	Hydrogen production	105
		SnO_2-MoS_2	Sensor	106
	Solvothermal	GQDs-MoS ₂	LIBs	107
	Electrodeposition	Au NPs-MoS ₂	Sensor	108
	Thermal evaporation	Au NPs-MoS ₂	Sensor or detector	82
	Drop casting	Pd NPs- MoS_2	Sensor	109
	Successive ion layer adsorption and reaction method	CdS NPs-WS ₂	Water splitting	110
1D/2D	Self-assembly	Au NRs-MoS ₂	Hydrogen production	111
	Hydrothermal	C/TiO ₂ NBs-MoSe ₂	LIBs	89
	5	CoS ₂ NWs-MoS ₂	Hydrogen production	112
	Solvothermal	CNTs-MoS ₂	Hydrogen production	77
		SnO ₂ NTs-MoS ₂	Hydrogen production	113

Varrla et al. demonstrated the processing parameters for specific NSs concentration, length, and thickness and obtained large-scale shear-exfoliation of MoS_2 NSs (in the range $\sim 40-$ 220 nm for length and \sim 2–12 layers for thickness) in aqueous surfactant solution by using a kitchen blender.⁹⁶ CVD is a typical method to prepare high-quality TMDs layers with controllable thickness and scalable size.90 Lee et al. has utilized CVD approach to synthesis large-area MoS₂ NSs with six-fold symmetry hexagonal lattice and high crystallinity on SiO₂/Si substrates.97 In addition to preparing layered TMDs with certain thickness, CVD growth method provide a facile way to directly grow layered heterostructures, which eliminates interfacial contamination interfused during synthesis processes.98 Moreover, wet chemical approach is another available method to prepared layered TMDs, which can be directly obtained in solution with a high yield.99 However, improved purity and controllability over nanostructures are primary challenges

because of infancy.^{100,101} In general, chemical exfoliation is desirable method for mass production of TMDs NSs, because other methods usually have more or less limitations to some extent, such as low efficiency, long and complex process, requirement for expensive systems and severe synthetic conditions.¹¹⁴

3.2 LDNs/TMDs nanostructures

3.2.1 Self-assembly. Self-assembly approach offers a route for assembling various functional components and preserve lattice integrity.¹¹⁵ These discrete components spontaneously integrate to be a complete heterostructure *via* directly and/or indirectly specific interactions.¹¹⁶ The main synthesis process is immersing as-prepared NSs into nanostructure precursor solution and using available auxiliary technique to assist LDNs to be decorated on TMDs NSs. For instance, Shi and coworker

reported a simple method to decorate Au NPs on chemical exfoliation MoS₂ NSs and CVD-prepared MoS₂ NSs.⁸⁷ The CVD-MoS₂ NSs on sapphire substrates are directly immersed in AuCl₃ for 20 seconds, while the chemical exfoliation NSs need to disperse on water surface and then added several drops of AuCl₃. Au ions in the solution are reduced, leading to the anchoring of Au NPs on MoS₂ surface due to active nucleation sites of NSs.

Self-assembly is also available for metal oxide/TMDs heterostructure synthesis. Bai *et al.* prepared a TiO_2-MoS_2 (1T) hybrid structure *via* sonication.⁸⁵ The typical procedure is mixing the dispersion of MoS_2 NSs with aqueous dispersion of TiO_2 nanocrystals and then sonicated for 3 min. In another case, Sun *et al.* prepared a p-type semiconductor of Cu₂O decorated with MoS_2 NSs by using hexadecyl trimethylammonium bromide (CTAB) as the surfactant to control the morphology.¹¹⁷ Asprepared nanocomposite exhibits efficient solar hydrogen production under visible light.

Size distribution, morphology and density of metal NPs can be tuned by changing the defects density in TMDs layers.^{87,118} Lu *et al.* reported that a focused laser beam can achieve active surface domains in MoS₂ film, and the size of as-prepared Au NPs are controllable, which were preferentially decorated onto the modified regions.¹⁰³ The rough surface of laser-pruned MoS₂ could trap the precursor and provide initial nucleation sites for Au NP growth.

3.2.2 Hydrothermal/solvothermal. Hydrothermal and solvothermal methods are widely used to prepare the composite structures. The reaction is usually conducted in a heated solution beyond ambient temperature and pressure.¹¹⁹ Zhang *et al.* demonstrated a facile one-step hydrothermal synthesis to prepare Au NPs/MoS₂.¹²⁰ In an aqueous solution, hydrazine act as strong reductant reduced HAuCl₄ to Au NPs attached onto MoS₂ NSs with the S-Au bond. Su *et al.* reported a microwave-assisted hydrothermal method to prepare Au NPs/MoS₂ in a microwave reactor with a heated condition.¹²¹ In a typical synthesis process, MoS₂ NSs solution were first mixed with sodium citrate tribasic dehydrate, Tween and HAuCl₄·3H₂O, and then heated to 60 °C for 5 min in a microwave reactor. Finally, the target product of Au NPs/MoS₂ can be obtained with purification *via* a centrifugation step.

CNTs/TMDs heterostructure is widely studied in recent years due to their remarkable catalytic activity.77,122,123 Using in situ solid and hydrothermal reactions, Zhang et al. prepared Mo₂Cembedded N-doped CNTs/MoS2 nanostructure.124 In MoO2/ Mo_2C -NCNTs aqueous solution, O^{2-} ions are replaced with S^{2-} ions which resulted in the transformation of MoO₂ to MoS₂. Metal oxide/TMDs nanocomposites can be prepared through this method as well. Li et al. demonstrated that with the assistance of glucose, TiO₂ NWs can act as a backbone for the nucleation and growth of MoS2 NSs.125 As a binder, glucose suppressed the growth and stack of layered MoS₂, facilitating the growth of MoS₂ NSs with smaller sizes on the TiO₂ NWs surface.^{125,126} Liu et al. prepared a SnO₂@MoSe₂ nanostructure through facile electrospinning technique and solvothermal method.127 SnO2 NFs are first obtained via a simple electrospinning method, then mixed with Se solution and dispersed in

 Na_2Mo_4 solution, which is subsequently heated to 180 °C and maintained for 12 h. The black precipitates of $SnO_2@MoSe_2$ after natural cooling exhibit excellent electrochemical activity as catalyst.

Wu *et al.* reported a green technique to prepare the WS₂ and MoS₂ QDs/NSs composites by sonication and solvothermal treatment.¹¹⁴ Typically, bulk MoS₂/WS₂ powders were sonicated in *N*-dimethylformamide for 3 h, and then stirred the top 2/3 of the dispersion for 6 h at 140 °C. After settled the suspensions for several hours, the light yellow supernatant of MoS₂/WS₂ QDs and the centrifugate of composite of MoS₂/WS₂ QDs and NSs composites were separated. In addition, Li *et al.* prepared a new type of 1D/2D heterostructures: GeS NWs are grown as seeds followed by GeS NSs epitaxially growing at the pre-grown NWs.⁷³ The pre-grown NWs exposing to air caused a mild degree of oxidation at the NW surface, which could prompt the nucleation of the NSs. This strategy opens a novel avenue to synthesis NWs/NSs heterostructures.

4. Applications

4.1 Hydrogen production

Hydrogen is regarded as a potential fuel in the future to address the environmental crises and energy shortage issues.128,129 Utilizing electricity to split water is a green and effective approach to produce hydrogen. In general, it can be divided into two strategies: electrocatalytic and photoelectrocatalytic.^{130,131} Noble metals such as Pt, Pd, Ru and Au are widely known as effective electrochemical catalysts due to their excellent catalytic activity.132 Pt and its alloys have usually been the first choice of catalysts, however, scarcity and high cost severely hinder its practical application.133,134 TMDs are regarded as ideal candidates to replace Pt due to high chemical stability and excellent electrocatalytic properties.135 For instance, nanoscale MoS2 exhibits a good reduction capacity for protons due to the quantum confinement effect, and the marginal edges served as active sites can promote the decomposition of water.76 Xie et al. demonstrated defect-rich MoS2 NSs could present excellent hydrogen evolution reaction (HER) activity with a low onset overpotential of 120 mV and small Tafel slope of 50 mV dec⁻¹.¹³⁶ However, low conductivity of TMDs largely limited the charge transfer rate and affected the total efficiency.137 An efficient way to address this issue is integrating TMDs nanostructures with conductive substrates,124 such as graphene, carbon NTs or carbon NFs. Guo et al. prepared a N-doped CNFs/defect and Srich MoS₂ heterostructure for high efficiency HER with a small overpotential of 135 mV at 10 mA cm⁻² and a large cathodic current density of 65.6 mA cm⁻² at 200 mV (Fig. 5).¹²² Nitrogen doping promoted the conductivity of composites, and the embedded mode of MoS₂ NSs and CNFs greatly improved their stability and catalytic activity. CoS₂ NW/MoS₂ NSs supported on carbon cloth also exhibits excellent HER performance and prominent electrochemical durability.112 However, most of the conductive substrates are inert for the HER and will decrease the density of active sites of TMDs NSs, therefore, balancing the active sites and conductivity of electrochemical catalysts remains a knotty problem.124 On the other hand,



Fig. 5 Electrocatalytic performance of $MOS_2/NCNFs$. (a) Polarization curves, (b) Tafel plots, (c) electrochemical cyclic voltammogram of $MOS_2/NCNFs$ at different potential scanning rates, (d) the C_{dl} of different materials obtained at 0.15 V vs. RHE, (e) Nyquist plots and (f) stability of the $MOS_2/NCNFs$ with the initial polarization curve (black curve) and after 1000 cycles (red curve). (g) Polarization curves (g) and (h) the corresponding Tafel plots of $MOS_2/NCNFs$ prepared at different concentration of Mo precursor. Adapted from ref. 122 with permission of The Royal Society of Chemistry.

integrated with noble metal nanostructures, TMDs can achieve a high electrocatalytic performance toward HER.¹³⁸ For instance, Au NPs coated on TMDs NSs can largely improve the charge transport along interplanar directions and inhibited restacking, which improved the accessibility of protons to the catalytically active sites.¹¹⁸ Hou *et al.* reported the growth of Pt NPs/MoS₂ NSs on the surface of carbon fiber and demonstrated an overpotential of -5 mV and a corresponding Tafel slope of 53.6 mV dec⁻¹.¹³⁹ The large specific surface area of TMDs not only effectively collect and transport charges, but also provides plenty of nucleation sites for the growth of metal NPs.¹³⁸

In 1972, Fujishima *et al.* demonstrated a green approach to split water utilizing TiO₂ as a photochemical catalyst, which offers a promising way for clean and low-cost production of hydrogen *via* solar energy.^{140,141} However, the rapid recombination of the electron–hole pairs and low activation ability of the surface reduced the amount of charge, resulting in a low photocatalytic efficiency.⁸⁵ Introducing TMDs as co-catalysts which

serve as the reaction sites can promote the charge separation and transport.¹⁰⁵ Indeed, MoS₂ NSs coated on a TiO₂ surface significantly facilitated the separation of the photo-induced carriers, which resulted in a higher photocurrent and improved broad spectrum photocatalytic properties.142,143 Moreover, Zhou et al. demonstrated that nitrogen self-doped MoS₂ NSs integrated with MnO₂ NBs exhibited excellent performance with an onset potential of -156 mV (vs. RHE), a large current density, a small Tafel slope of 47.5 mV dec^{-1} and outstanding electrochemical durability.144 Nitrogen doping provides a localized state near the Fermi energy in MoS₂ band gap and thus leads to a high electronic conductivity of the heterostructure. Besides, electron-rich sites are beneficial to attract H⁺ to the catalyst surface and gains an enhanced HER activity. Plasmon-excited hot electrons injection mechanism is also an efficient and promising route for the improvement of catalyst activity.111 However, achieving a faster electrons injection from plasmonic metal to semiconductor than the recombination process is still a significant challenge.

4.2 Lithium battery

Rechargeable Li batteries with high energy density, good cycle life, and blameless power performance has become one of the most important energy storage devices in recent years.145 To date, silicon, metal alloys, metal oxides and TMDs have been widely explored as the replacement of graphite anodes in Li-ion batteries (LIB).146-148 The high surface-to-volume ratio and short diffusion path of TMD NSs render it as a brilliant electrode material for LIBs. For instance, Hwang et al. reported graphenelike MoS₂ nanoplates showing a reversible capacity of 912 mA h g⁻¹ at a rate of 1C and excellent cycling stability when fabricated in LIBs.149 To further improve the cycling stability and rate capability performance of TMDs, integrating LDNs such as Au NPs and TiO₂ NPs is an effective approach.^{120,150} Guo et al. demonstrated that GQDs/MoS2 exhibits excellent electrochemical lithium storage properties with a high reversible capacity (1099 mA h g^{-1} at 100 mA g^{-1}), good cyclic stability, as well as excellent rate performance (660 mA h g^{-1} at 5000 mA g^{-1}) as shown in Fig. 6.¹⁰⁷ GQDs acted as binder enhanced cyclic stability and facilitate the charge transfer within the electrode. Furthermore, it can enlarge the interlayer distance between MoS₂ layers which is beneficial for Li⁺ intercalation. Zhou et al. demonstrated that CNFs@MoS2 coaxial NFs showed an excellent Li storage properties, such as high specific capacity, good cycling stability, and superior high-rate capability.151 The synergistic effect of the two active components leads to a larger capacity and better cyclability.

TiO₂ with superior safety and rate capability exhibits excellent performance when employed as anodes materials.¹⁵² Li *et al.* demonstrated that TiO₂@MoS₂ heterostructure displayed a high initial discharge capacity of 862 mA h g⁻¹, and it maintained at 544 mA h g⁻¹ even after 100 cycles.¹²⁵ The synergistic effects of TiO₂ NW and ultrathin MoS₂ shorten the Li⁺ diffusion paths for rapid charge transfer, and improved cycling stability of the system at high rates. Xue *et al.* demonstrated a Fe₃O₄ NPs/ MoS₂ nanostructures as an anode for LIBs with a superior cyclic

Fig. 6 (a) Rate capabilities and (b) electrochemical impedance spectroscopy spectra of GQDs/MoS₂ and pristine MoS₂ electrodes. Adapted from ref. 107 with permission of The Royal Society of Chemistry.

and rate performances.¹⁵³ Fe₃O₄ NPs serving as spacers and effectively stabilize the integrated structure, facilitating the MoS₂ surfaces accessible to electrolyte during charge/discharge processes, thereby hindering the fast fading of reversible capacities. The heterostructure contribute a 1033 and 224 mA h g^{-1} at current densities of 2000 and 10 000 mA g^{-1} , respectively. The MoS₂ NSs provided a high reversible capacity and Fe₃O₄ NPs offered a high rate performance. In addition, MoS₂ has been reported as cathode material for lithium-oxygen (Li-O₂) batteries, which exhibits a 85% round-trip efficiency and good reversibility.159 Table 2 lists some typical examples comprised of different components for lithium storage performances.

TMDs anodes have been studied for many years, yet there are still many challenges. The large irreversible capacity was observed in the first cycle, indicating that a large portion of Li⁺ ions could not be utilized again in the following cycles, and the relatively high voltage behavior of the TMDs limited its applications.¹⁶⁰ Nevertheless, TMDs is a promising anodes material owing to superior capacity and rate capability.8

4.3 Sensor and detector

TMDs materials with a tuneable band gap applied in sensors and detectors usually exhibited high selectivity and rapid detection.¹⁶¹⁻¹⁶⁴ Using first-principles calculations, Yue et al. found that small gas molecules can be physically absorbed on monolayer MoS₂, and determined the most stable adsorption configuration and adsorption energy.¹⁶⁵ The band structure of monolayer MoS₂ will not significantly be altered though small gas molecules are absorbed. Many reports have demonstrated

0.1C

0.2C

 100 mA g^{-1}

 $100 \text{ mA} \text{ g}^{-1}$

TMDs-based sensors, when integrated with noble metal or metal oxide semiconductors, exhibiting an enhanced performance compared with individual component.166-168 For instance, He et al. demonstrated that Pt NPs deposited on MoS₂ NSs exhibits high sensitivity for NO2 detection.¹⁶⁹ Upon the adsorption of gas, the Schottky barrier between Pt NPs and MoS₂ channel is changed, which may help explain the increased sensitivity of MoS₂ thin film.^{170,171} In addition, Kuru *et al.* demonstrated Pd NPs/MoS₂ NS could show a highly sensitivity for H₂ detection at room temperature and the sensor exhibits a response of around 10 toward 50 000 ppm H₂ with a response and recovery time of 40 and 83 s, respectively.¹⁰⁹ TMDs-based biosensor can effectively and sensitively detect biomolecule.172,173 Using molecular dynamics and density functional theory simulation, Aluru et al. demonstrated that monolayer MoS₂ is an promising material for DNA sequencing technology.¹⁷⁴ Thiol modified monolayer MoS₂ integrated with Au NPs can largely enhance the DNA adsorption about 1 order of magnitude.¹⁷⁵ MoS₂ NSs exhibited different PL properties toward single-strained DNA versus double strained DNA when the concentration of DNA solution increased, which can be used for rapid and selective detection of DNA nucleoside chains. In another case, Su et al. reported a Au NPs/MoS₂ biosensor that could detect glucose in a concentration range from 10 to 300 µM with a detection limit of 2.8 µM.176 Furthermore, the sensor also displays good reproducibility and longterm stability, indicating its potential to be applied for determination of glucose concentration in human serum. In addition, Shao et al. reported an electrochemical dopamine (DA) sensor based on Au NPs@MoS2 nanocomposite, and the detection concentration of DA ranges from 0.1 to 200 mM, with a detection limit of 80 nM (S/N = 3),¹²¹ and the sensor can also detect DA in ascorbic acid existed environment.

Monolayer MoS₂ with a direct bandgap of 1.9 eV is extremely attractive for photodetector. Kis et al. reported a monolayer MoS_2 photodetector with a photoresponsivity of 880 A W^{-1} at a wavelength of 561 nm and a photoresponse in the 400–680 nm range.177 However, the slow responsivity is an important limiting factor for application. To address this situation, Kufer et al. demonstrated PbS QDs decorated MoS₂ for photodetector could achieve a high responsivity of 6 \times 10⁵ A W⁻¹, and the responsivity is higher than individual PbS QDs and MoS₂-based detectors.178 Owing to the effect of reverse electric induced by increasing separated charge carriers, the responsivity presents a decrease trend with increasing optical intensity. In addition,

805/100

 $\sim 953/50$

 $\sim 900/80$

Table 2 The lithium storage performances of TMDs based anode materials					
Anode materials	Current rate	Initial capacity (mA h g^{-1})	Capacity retention (mA h g ⁻¹)/(cycles)		
MoS ₂	1C	1062	907/50		
Graphene-MoS ₂	100 mA g^{-1}	1571	1187/100		
CNFs-MoS ₂	100 mA g^{-1}	1489	1264/50		
GQDs-MoS ₂	100 mA g^{-1}	1394	1031/80		
TiO ₂ -MoS ₂	0.10	588	350/100		

941.6

1063.9

1306

TiO₂-MoS₂

SnO₂-MoS₂

Carbon-TiO₂-MoS₂

Polyaniline-MoS₂

Ref.

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metal plasmon LDNs with near-field oscillation and scattering effect can effectively improve the photocurrent response and light absorption of TMDs, which can be applied to exploit plasmon resonance-based devices.¹⁷⁹ Although great progress has been made in this area, the mechanism and principles of electron transfer of TMDs is remain unclear.¹⁸⁰

5. Conclusion

In summary, the integration of LDNs and TMD exhibits a tailored performance due to synergistic effects. LDN materials with dissimilar properties that differ from their bulk counterparts effectively mitigate the genetic disadvantages of TMDs, while TMD NSs with controllable size and thickness provided suitable surface areas for LDNs to integrate. For LDN/TMD heterostructures, many synthesis methods such as self-assembly and hydrothermal methods have been developed for preparation via one step or multi-step approaches. The shape and distribution of LDNs can be controlled by changing the component ratio of precursor solution or modifying the surface of TMDs and have a large impact on the system performance. Through incorporating different types of LDNs, TMD heterostructures with unique properties have been applied in various areas. As a promising candidate to replace Pt catalyst for hydrogen production, TMDs integrated with LDNs solve the limitation of low conductivity, and shows a high chemical stability and excellent electrocatalytic activities. As electrode materials for LIBs, the heterostructure contributes a high reversible capacity and an excellent rate capability. Owing to the high surface-to-volume ratio and tuneable band gap of TMDs, the sensors combine with LDNs exhibit a high selectivity to detect biomolecules and gas molecules, and have great impacts in the field of photodetection.

Although extensive investigations have focused on LDNs/ TMDs heterostructures, several limitations still exist. Firstly, LDNs reported in most papers are noble metals, metal oxides, metal dichalcogenides and graphite derivatives, the fields may expand to organic materials in future. Secondly, a method to prepare TMD NSs with excellent morphology and desired properties is still necessary. Heteroatom doping can offer TMDs with various new or improved optical and structural properties,181 which may provide some inspiration for further development of LDNs/TMDs heterostructures. Finally, how the spatial organization and distribution affecting the system performances have not been fully investigated yet.182 Many reports are restricted to concern the component of the heterostructure, therefore more studies are still required to optimize the fabricated structures. Nonetheless, the study of TMDs is just in the infant stage and a greater potential is waiting for exploration.

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