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The heterointerface effect to boost the catalytic performance of single atom catalysts for sulfur conversion in lithium–sulfur batteries†

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Lithium–sulfur (Li–S) batteries are considered as one of the promising next-generation energy storage devices due to their characteristics of high energy density and low cost. However, the shuttle effect and sluggish conversion of lithium polysulfide (LiPs) have hindered their commercial applications. To address these issues, in our previous works, we have screened several highly efficient single atom catalysts (SACs) ($\text{MN}_4\text{@G}$, $\text{M} = \text{V}$, Mo and W) with atomically dispersed transition metal atoms supported by nitrogen doped graphene based on high throughput calculations. Nevertheless, they still suffer from low loading of metal centers and unsatisfactory capability for accelerating the reaction kinetics. To tackle such problems, based on first-principles calculations, we systematically investigated the heterointerface effect on the catalytic performance of such three $\text{MN}_4\text{@G}$ toward sulfur conversion upon forming heterostructures with 5 typical two-dimensional materials of TiS_2 , C_3N_4 , BN , graphene and reduced graphene oxide. Guided by efficient descriptors proposed in our previous work, we screened $\text{VN}_4\text{@G/TiS}_2$, $\text{MoN}_4\text{@G/TiS}_2$ and $\text{WN}_4\text{@G/TiS}_2$ possessing low Li_2S decomposition barriers of 0.54, 0.44 and 0.41 eV, respectively. They also possess enhanced capabilities for catalyzing the sulfur reduction reaction as well as stabilizing soluble LiPs. More interestingly, the heterointerface can enhance the capability of the carbon atoms far away from the metal centers for trapping LiPs. This work shows that introducing a heterointerface is a promising strategy to boost the performance of SACs in Li–S batteries.

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1. Introduction

To reduce the greenhouse gas emission caused by the consumption of fossil fuels stimulates great interest from researchers to develop high-performance energy storage devices. Among these state-of-the-art energy storage devices, lithium–sulfur (Li–S) batteries have garnered significant attention in recent years owing to their high theoretical specific capacity of 1675 mA h g^{-1} and high energy density of 2600 W h kg^{-1} .^{1–5} However, certain issues still exist, weakening the performance of Li–S batteries and thus impeding their commercial applications. The most significant issue among them is the occurrence of the ‘shuttle effect’. During the discharge process, lithium polysulfides (LiPs) formed on the cathode can dissolve into the electrolyte, diffuse through the separator, and accumulate on the lithium anode.

This phenomenon leads to a decrease in the Coulombic efficiency and capacity degradation of the batteries, thus hindering their cycle performance.^{6,7} Moreover, the intrinsic insulation properties of sulfur ($5 \times 10^{-30} \text{ S cm}^{-1}$) and Li_2S ($10^{-13} \text{ S cm}^{-1}$) hinder the efficient transfer of electrons, resulting in sluggish electrochemical reactions.⁸ Therefore, the rational design of catalysts exhibiting suitable adsorption capability for LiPs and superior catalytic performance for accelerating the reaction kinetics of sulfur redox in Li–S batteries has attracted increasing research attention in recent years.^{9–12}

Among the efficient catalysts, carbonaceous materials supported single atom catalysts (SACs) have been widely explored due to their superior catalytic performance for sulfur redox and LiP stabilization.^{10,13–15} Nevertheless, the performances of SACs for catalyzing sulfur redox, particularly the sulfur evolution reaction (SER), are still unsatisfactory. Therefore, to further enhance their catalytic performance toward the sulfur conversion is of importance, which might be realized by tailoring the electronic and structural properties of the central metals of SACs. In this regard, significant research efforts have been devoted to the design of SACs with transition metal atoms possessing various coordination environments, which involve

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graphene,^{13,14} C₂N¹⁰ and g-C₃N₄¹⁵ as the supports. In addition to doping strategies, the introduction of heterointerfaces has also been proved to be an efficient strategy to enhance the catalytic performance of electrochemical catalysts for energy storage and conversion, which can be realized by assembling two-dimensional (2D) materials into van der Waals heterostructures.¹⁶ These heterostructures are formed by chemical bonding or physical combination of two or more 2D materials. In recent years, this concept has also been adopted to design electrocatalysts for Li-S batteries, which will incorporate the merits of individual components to neutralize the shortcomings of each building block^{17–22} of the heterointerfaces. Nevertheless, there have been no reports on exploring the heterointerface effect on the catalytic performance of SACs for sulfur chemistry.

Up to now, various materials have been investigated for use as electrodes including 2D carbonaceous materials,^{23,24} metal sulfides,^{25,26} metal oxides^{27,28} and Mxenes.^{29,30} This implies that the combination of SACs with such materials will give rise to a huge number of heterostructures given the various metal centers of SACs. In this regard, to explore the catalytic performance particularly the SER performance of such heterostructures will be very time consuming, which accordingly requires an efficient descriptor guiding the systematic investigation. In our previous work, we have systematically investigated the descriptors of the Li₂S decomposition energy barrier on MN₄@G (typical configuration of SACs containing pyridine-N coordinated transition-metal atoms) and found that some properties could serve as universal descriptors for the rational design of SACs giving rise to a low Li₂S decomposition barrier, which could predict the activity of the catalyst quickly.¹⁴

Here, we investigated systematically the performance of heterostructures for sulfur chemistry, which are built by combining SACs with 5 typical 2D materials. For SACs, we utilized three MN₄@G (M = V, Mo and W) with the highest catalytic activity for Li₂S decomposition screened in our previous work.¹⁴ The other 5 types of 2D materials are TiS₂,³¹ C₃N₄,³² BN,³³ graphene (G)³⁴ and reduced graphene oxide (rGO).³⁵ After examining the extendibility, we selected ΔE (energy difference before and after the Li₂S decomposition) as the efficient descriptor for screening several heterostructures with enhanced catalytic performance for Li₂S decomposition, which were then further explored for their performance for catalyzing SRR and stabilizing LiPs. Our work will pave a new way for designing electrocatalysts for sulfur chemistry in alkaline metal sulfide batteries.

2. Computational details

The DFT simulations were carried out by using the Vienna Ab initio Simulation Package (VASP).^{36,37} Additionally, the Perdew–Burke–Ernzerhof functional^{38,39} within the generalized gradient approximation (GGA-PBE)⁴⁰ was employed to calculate the exchange–correlation energy and the projector augmented wave (PAW) method was used to describe the electron–ion

interactions.^{41,42} We employed the DFT-D2 scheme to take the van der Waals interactions into account.⁴³ To avoid the interaction between two neighboring surfaces, we set the vacuum space to be larger than 20 Å. In all of the calculations, the plane-wave cutoff energy was set to be 520 eV. All the calculations were carried out with the force and energy thresholds of 0.02 eV Å^{−1} and 10^{−4} eV, respectively. Self-consistent field (SCF) calculations were performed to obtain the energy of the optimized structure while non-self-consistent field (NSCF) calculations were used to gain the electronic density of states (DOS). Three different *k*-point meshes of 2 × 2 × 1, 3 × 3 × 1 and 7 × 7 × 1 were employed in the structural optimizations, and SCF and NSCF calculations. For the Li₂S decomposition, the minimum energy path (MEP) profiles are obtained by using the climbing image nudged elastic band (CI-NEB) method.^{44,45} The formulas for calculating binding energy of heterostructure materials, lattice mismatch of the heterostructure materials, adsorption energy, zero vibration energy, charge density difference and Gibbs free energy changes are labeled as eqn (1)–(10).

The binding energy of heterostructures were calculated according to

$$E_{\text{bin}} = \frac{E_{\text{total}} - E_{\text{ML1}} - E_{\text{ML2}}}{S} \quad (1)$$

where E_{total} represent the energies for heterostructures, E_{ML1} and E_{ML2} stand for the energy of two individual monolayers constituting the heterostructures, respectively, S is the cross-sectional area at the interface of two monolayers in the simulation box of the heterostructures. Additionally, the lattice mismatch of the heterostructures is calculated by

$$|a - a_h|/a_h \times 100\% \quad (2)$$

where a and a_h represent the lattice parameter of the supercell of one component and the double layer heterostructure material, respectively.

The adsorption energy (E_{ads}) is calculated based on the following formula:

$$E_{\text{ads}} = E_{\text{total}} - E_{\text{substrate}} - E_{\text{adsorbate}} \quad (3)$$

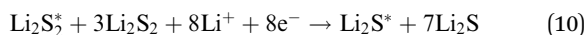
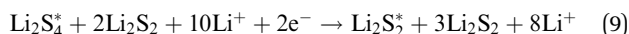
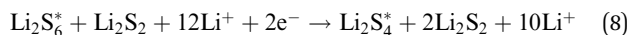
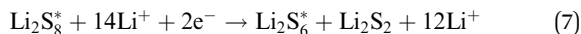
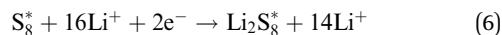
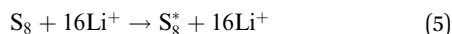
where E_{total} is the energy of adsorbed system, while $E_{\text{substrate}}$ and $E_{\text{adsorbate}}$ represent the energy of substrate and isolated adsorbate, respectively.

The Gibbs free energy of LiPs and S₈ on substrates are calculated by

$$G = E_{\text{DFT}} + E_{\text{zpe}} - TS \quad (4)$$

where E_{DFT} denotes the energy calculated by DFT simulations and E_{zpe} is the zero-point energy which is determined as $ZPE = \frac{1}{2} \sum_i h\nu_i$; here h and ν_i are the Planck constant and vibrational frequencies, respectively. S is the entropy, the entropies of molecules we utilized were acquired from experimental values in the NIST database,⁴⁶ while those of the absorbed intermediates were set to zero; T is the room temperature and is set at 298.15 K.

The elementary reaction steps for sulfur reduction in lithium-sulfur (Li-S) batteries are considered as



The reduction reaction process from Li_2S_8 to Li_2S is quite complex, which is accompanied with the formation of the by-product Li_2S_2 .⁴⁷ The energy of a single Li ion and an electron ($\text{Li}^+ + \text{e}^-$) pair was treated as the energy of a single crystalline Li atom. The adsorbents with an asterisk “*” refer to the state of being adsorbed, while the isolated state does not have that mark.

The linear correlations between E_b and three descriptors ΔE , $\Delta E(*\text{LiS})$ and ICOHP were identified in our previous work.¹⁴

$$E_b = 1.07 \times \Delta E + 0.16 \quad (11)$$

$$E_b = 0.87 \times \Delta E(*\text{LiS}) + 0.38 \quad (12)$$

$$E_b = -1.30 \times \text{ICOHP} - 3.49 \quad (13)$$

The difference between ΔE and $\Delta E(*\text{LiS})$ is shown below,

$$\Delta E = E(*\text{Li} + *\text{LiS}) - E(*\text{Li}_2\text{S}) \quad (14)$$

where $E(*\text{Li} + *\text{LiS})$ and $E(*\text{Li}_2\text{S})$ represent the energies of final and initial states of the Li_2S decomposition. The asterisk (*) means the adsorbed state of the adsorbents.

$$\Delta E(*\text{LiS}) = E(*\text{LiS}) + E(\text{Li})_{\text{bcc}} - E(*\text{Li}_2\text{S}) \quad (15)$$

where $E(*\text{LiS})$, $E(\text{Li})_{\text{bcc}}$, $E(*\text{Li}_2\text{S})$ refer to the total energy of the adsorbed LiS cluster, energy of single Li atom in the bcc bulk phase and total energy of adsorbed Li_2S , respectively.

3. Results and discussion

3.1 Structure and electronic properties of heterostructures

As shown in Fig. 1, five types of monolayers, which are TiS_2 , $\text{g-C}_3\text{N}_4$, BN, graphene, and rGO, are selected and combined with $\text{MN}_4@\text{G}$ to build heterostructures. Due to the different lattice parameters of those monolayers, various supercells are set up for TiS_2 , $\text{g-C}_3\text{N}_4$, BN, graphene and rGO to guarantee a small lattice mismatch in the heterostructure. The primitive cell parameters, corresponding supercells, lattice mismatches and the total number of atoms contained in the simulation box of the heterostructures are listed in Table S1 (ESI†). Regarding the model of rGO and $\text{MN}_4@\text{G}$, they are built using a $6 \times 6 \times 1$ supercell of graphene. rGO is then achieved by introducing two kinds of oxygen-containing defects in the graphene lattice. One type refers to the vacancy defects with hydroxyl saturating the dangling bonds of carbon atoms and the other type includes the epoxide functional groups adsorbed on the carbon atoms while the $\text{MN}_4@\text{G}$ are modeled by locating the TM atoms in the N doped graphene with the central metal atoms coordinated with four N atoms, which are accordingly labeled as $\text{MN}_4@\text{G}$. The largest lattice mismatch is 2.354% between TiS_2 and $\text{MN}_4@\text{G}$, and the others are lower than 2% when $\text{MN}_4@\text{G}$

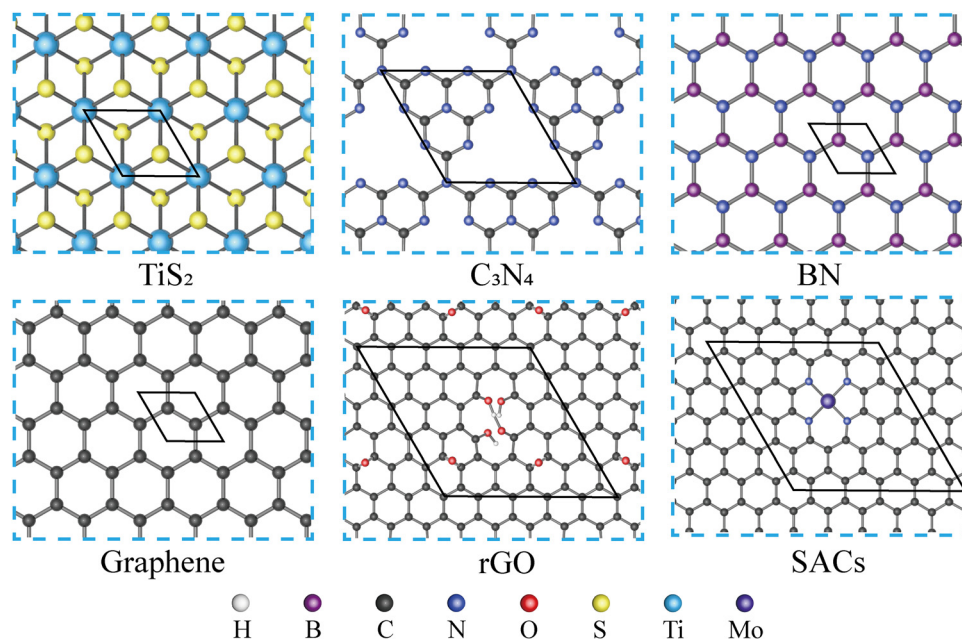


Fig. 1 Top view of TiS_2 , C_3N_4 , BN, graphene, rGO and SACs. The hexagonal line frames depict the primitive cells of various materials, while the elements represented by spheres of different colors are listed at the bottom of the figure. For SACs, $\text{MoN}_4@\text{G}$ is selected as an example.

forms heterostructures with g-C₃N₄(1.777%), BN(1.749%), graphene(0.000%) and rGO(1.211%). In order to distinguish those various heterostructures, we named them MN₄@G/ML (ML = TiS₂, C₃N₄, BN, G, rGO), as shown in Fig. S1 (ESI†). Moreover, MN₄@G/ML (ML = TiS₂, C₃N₄, G and rGO) and G/BN prefer AB stacking, while the configuration of MN₄@G/BN possesses a mixture of AB- and AA-stacking.

The interaction strength between the components of the heterostructures can be evaluated by the binding energy (E_{bin}), which is calculated by eqn (1) in the ESI.† As listed in Table S2 (ESI†), the E_{bin} values for different heterostructures are between −13 and −21 meV Å^{−2} and close to that for van der Waals interaction,⁴⁸ which can also be confirmed by the interlayer distance of 3.20–3.96 Å. Among them, the largest and smallest E_{bin} are −26.39 meV Å^{−2} (WN₄@G/BN) and −7.49 meV Å^{−2} (MoN₄@G/C₃N₄), respectively. Moreover, MN₄@G can bind more strongly with BN than with other monolayers, while the binding strength of MN₄@G with TiS₂ and C₃N₄ are relatively weak. Among MN₄@G/TiS₂ or MN₄@G/BN, the interaction strength of monolayers as M = V is stronger than that when M = Mo and W, due to the fact that V atom tends to sit between the two monolayers by forming chemical bond with two components of the heterostructures, as shown in Fig. S1 (ESI†). Note that heterostructures of MN₄@G/rGO have significantly larger interlayer distances than the others due to the presence of functional groups on the surface of rGO.

The formation of heterostructures also induces the charge redistribution in the components, *i.e.* MN₄@G loses charges to the adjacent layers leading to the metal centers more positively charged compared to that in the monolayer of MN₄@G. The diagram of charge density difference of various heterostructures are illustrated in Fig. S1 (ESI†). In general, the charge transfer occurs mainly around the MN₄ moiety and the specific values of charge transfer are listed in Table S2 (ESI†). However, for MN₄@G/TiS₂, there is a uniform charge redistribution throughout the interface. In general, the charge transfer between the monolayers in MN₄@G/TiS₂ and MN₄@G/C₃N₄ is more pronounced than that in MN₄@G/BN and MN₄@G/G as illustrated in Table S2 (ESI†). Moreover, for MN₄@G/TiS₂ and MN₄@G/C₃N₄, M = V gives rise to more charge transfer than M = Mo and W. Taking MN₄@G/TiS₂ as an example, the charge transfer in MN₄@G/TiS₂ is 1.48 e per cell, which is more than those in MoN₄@G/TiS₂ (1.11 e per cell) and WN₄@G/TiS₂ (1.11 e per cell). Although the total amount of charge transfer for MN₄@G/BN is less than that for MN₄@G/TiS₂, the interaction between the monolayers is still stronger in MN₄@G/BN than that in MN₄@G/TiS₂. This is attributed to the fact that the charge redistribution only occurs around the MN₄ in the former case while there is wider range of charge redistribution for the rest case.

3.2 Catalytic performance of MN₄@G/ML for SER

We next explored the catalytic performance of the heterostructures for SER. In the charging cycles of Li-S batteries, the decomposition of Li₂S is a crucial step for SER requiring efficient electrocatalysts to accelerate the reaction kinetics. This

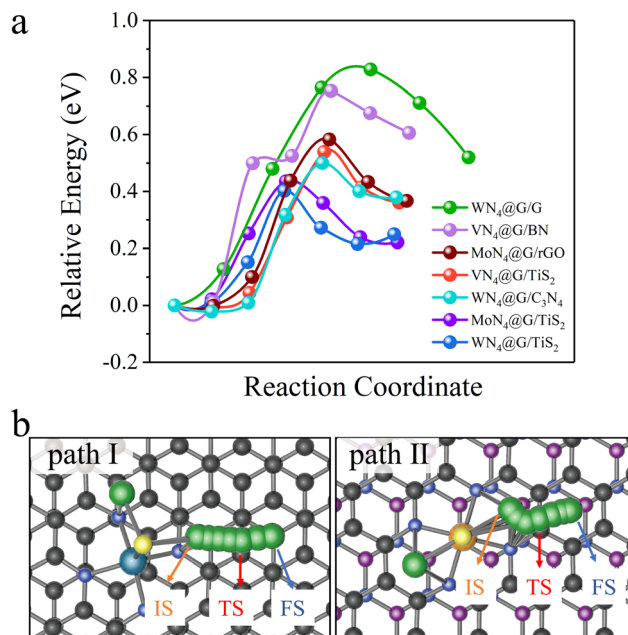


Fig. 2 (a) The energy profiles of Li₂S decomposition on selected heterostructures. (b) Two different energetically preferable Li₂S decomposition pathways. IS, TS, FS represent the initial, transitional, and final states of Li₂S decomposition on the heterointerfaces, respectively.

is usually evaluated by the energy barrier (E_b) of Li₂S decomposition, which can be achieved based on the nudged elastic band (NEB) method.¹⁴

We selected some heterostructures as representatives and explored the decomposition of Li₂S on them. The energy profiles of Li₂S decomposition on WN₄@G/G, VN₄@G/BN, MoN₄@G/rGO, WN₄@G/C₃N₄, MoN₄@G/TiS₂ and WN₄@G/TiS₂ with the energetically preferable decomposition pathways are illustrated in Fig. 2. It can be seen from Fig. 2a that the E_b of Li₂S decompositions on all heterostructures are lower than 1.0 eV. The lowest and the highest E_b are observed on WN₄@G/TiS₂ (0.41 eV) and WN₄@G/G (0.83 eV), respectively. The catalytic performances of the heterostructures for the Li₂S decomposition follow the order WN₄@G/TiS₂ > MoN₄@G/TiS₂ > WN₄@G/C₃N₄ > VN₄@G/TiS₂ > MoN₄@G/rGO > VN₄@G/BN > WN₄@G/G, and the corresponding E_b values are 0.41, 0.44, 0.50, 0.54, 0.58, 0.75 and 0.83 eV respectively. It should be noted that those heterostructures possess more enhanced capability for catalyzing SER than individual MN₄@G, such as VN₄@G (E_b = 0.70 eV), MoN₄@G (E_b = 0.58 eV), WN₄@G (E_b = 0.55 eV) and CoN₄@G (E_b = 1.37 eV).^{13,14} Overall, the catalytic performance of MN₄@G for the SER will be significantly improved when forming the heterostructures with C₃N₄, TiS₂ and rGO. Moreover, due to the different adsorption configurations of Li₂S, two different Li₂S decomposition pathways are identified as shown in Fig. 2b. And the cleavage of the Li–S bond on WN₄@G/G is along the path I, while for the rest cases it follows the relatively short path II.

It should be noted that the decomposition of Li₂S on VN₄@G/TiS₂ is a bit complex as reflected by the energy profiles of Li₂S decomposition (see Fig. 3a). This is due to the specific

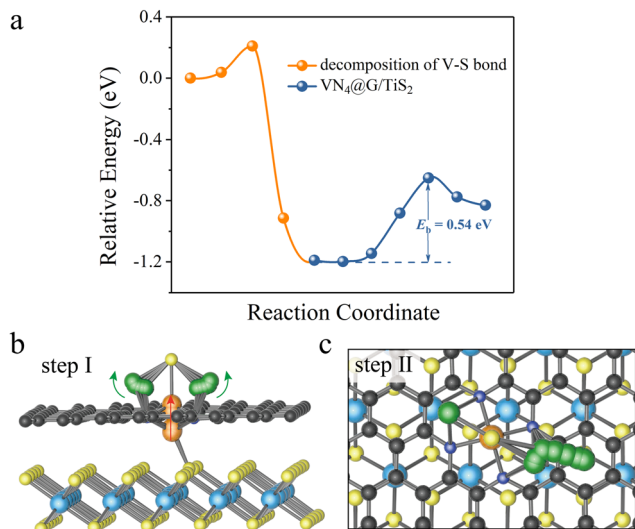


Fig. 3 (a) The energy profiles of Li₂S decomposition on VN₄@G/TiS₂. (b) The structural evolution before the Li₂S decomposition on VN₄@G/TiS₂. (c) The decomposition process of Li₂S on VN₄@G/TiS₂. The migration of V atom follows the direction of the red arrow while the change of angle of Li–S–Li is marked with green arrows.

structural configuration of VN₄@G/TiS₂, for which the V atom sits between the graphene layer and TiS₂ (see Fig. 3b). This further leads to the weak interaction between Li₂S and the V atom upon the adsorption of Li₂S on VN₄@G/TiS₂ since the S atom of Li₂S cannot form a chemical bond with the V atom with only the Li atoms binding to N/C atoms from the N doped graphene. Overall, the whole process of Li₂S decomposition on VN₄@G/TiS₂ can be divided into two subprocesses. Firstly, before the breakage of Li–S bonds in adsorbed Li₂S, the V atom moves back to the center of the N edged hole and binds to the S atom of adsorbed Li₂S, leaving the V–S (S from TiS₂) bond broken (see Fig. 3b). This process just requires overcoming a very small energy barrier of 0.21 eV as shown in Fig. 3a. Meanwhile, the angle of Li–S–Li bond gradually increases from 85.01° to 139.29° and the bond length of Li–S also expands from 2.25 Å to 2.39 Å. It is then followed by the second subprocess of Li₂S decomposition accompanied by the Li–S bond breakage as shown in Fig. 3c (consistent with the

decomposition pathway II in Fig. 2b), which necessitates surmounting an energy barrier of 0.54 eV.

It is time-consuming to calculate directly the E_b values for 15 heterostructures using the CI-NEB method. In our previous works, we have identified three descriptors ΔE , $\Delta E(*\text{LiS})$ and ICOHP correlating well with E_b for MN₄@G, where ΔE refers to the energy difference between the initial and final states of the Li₂S decomposition, $\Delta E(*\text{LiS})$ stands for the reaction energy of the Li₂S decomposition and ICOHP means the integral value of the crystal orbital Hamilton population for evaluating the binding strength of Li–S in adsorbed Li₂S.¹⁴ And the corresponding functions describing the linear correlations between E_b and ΔE , $\Delta E(*\text{LiS})$, ICOHP are shown in the computational details. Among them, ΔE performs the best in predicting E_b values. Based on the available data from the current study, we next explored the predictive capability of ΔE , $\Delta E(*\text{LiS})$, ICOHP for determining E_b and then to screen high performance MN₄@G/ML for Li₂S decomposition. As shown in Fig. 4a, all the data points of E_b fall near the line, implying the robustness of the functional of $E_b = 1.07 \times \Delta E + 0.16$ proposed in our previous work.¹⁴ The minimum percentage error of E_b between the ΔE – E_b prediction and the CI-NEB calculation occurs in VN₄@G/TiS₂, which is only 2.22%. The largest percentage error is observed in WN₄@G/C₃N₄, reaching 14%, but the specific difference is only 0.07 eV. The percentage errors of the predicted values with respect to those obtained from CI-NEB calculations for the remaining structures are all below 10%. In contrast, the $\Delta E(*\text{LiS})$ – E_b and ICOHP– E_b relationships from the current study do not follow the trend described by those linear functions obtained from previous works (see Fig. 4b and c). The corresponding data of predicted E_b values based on ΔE , $\Delta E(*\text{LiS})$ and ICOHP are listed in Table S3 (ESI†). Overall, these results show that ΔE can serve as the best descriptor and provide efficient theoretical guidance for fast screening of active MN₄@G/ML toward Li₂S decomposition based on the equation of $E_b = 1.07 \times \Delta E + 0.16$.

As listed Table S3 (ESI†), the E_b values are predicted based on the linear function $E_b = 1.07 \times \Delta E + 0.16$ for 15 heterostructures which are built by combining 3 MN₄@G with 5 monolayers. Among them, MoN₄@G/TiS₂ and WN₄@G/TiS₂ give rise to significantly low E_b values of 0.40 and 0.43 eV,

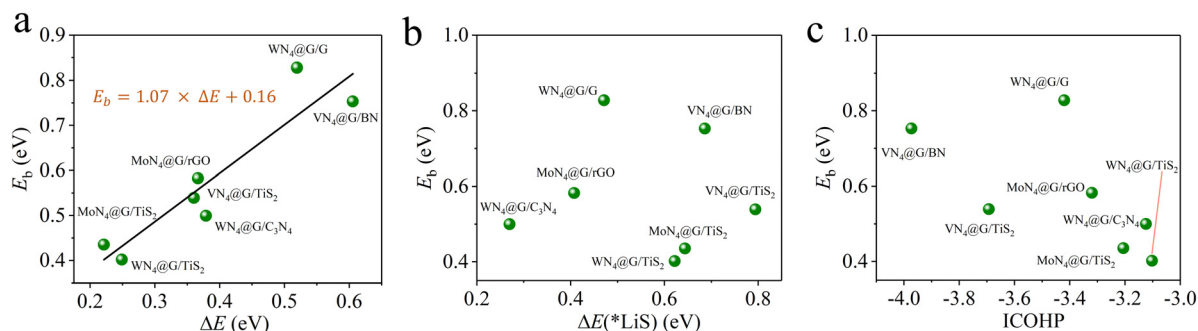


Fig. 4 Calculated values of E_b using the CI-NEB method (green balls) for representative heterostructures as a function of ΔE (a), $\Delta E(*\text{LiS})$ (b) and ICOHP (c). In (a), the linear relationship (black lines), obtained in our previous works for graphene supported SACs was included for comparison.¹⁴

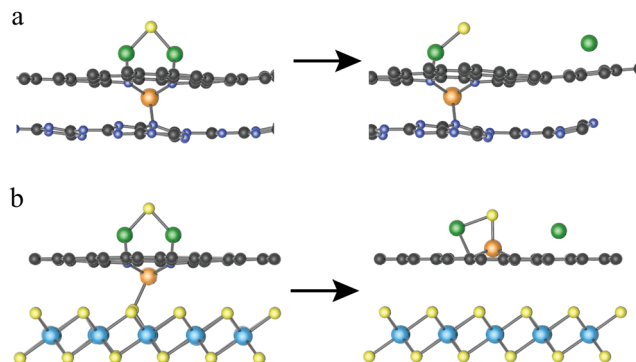


Fig. 5 Initial and final structures of Li₂S decomposition on VN₄@G/C₃N₄ (a) and VN₄@G/TiS₂ (b). The orange, yellow, green spheres represent the V, S and Li atoms.

which are accordingly highly efficient for catalyzing the SER. In contrast, the worst SER performance is found for VN₄@G/C₃N₄ with $E_b = 2.24$ eV since the V center does not participate in activating the Li–S bond. As shown in Fig. 5a, in VN₄@G/C₃N₄ the V atom tends to sit between the graphene and C₃N₄ monolayers leading to the absence of S–V bonds upon the Li₂S deposition indicating that there is no direct interaction between Li₂S and the V center. Moreover, this holds for the whole process of Li₂S decomposition. Therefore, the catalytic performance of VN₄@G/C₃N₄ for Li₂S decomposition is rather worse compared to the rest of the heterostructures. It should be noted that, in the VN₄@G/TiS₂ the V atom remains between graphene and TiS₂ monolayers after the Li₂S adsorption. However, during the Li₂S decomposition the V atom can move back the N-edged hole and form a chemical bond with S from Li₂S by overcoming a low energy barrier of 0.21 eV (see Fig. 2a). This S–V bond even remains when the Li–S bond is eventually broken as shown in Fig. 5b. Therefore, VN₄@G/TiS₂ still shows efficient SER performance by giving rise to a low E_b of 0.54 eV.

We next analyzed the heterointerface effect on the catalytic performance of MN₄@G for SER. To this end, three SACs of WN₄@G, MoN₄@G, and VN₄@G, screened by our previous work¹⁴ were considered to explore the changes of E_b before and after forming the heterointerfaces. Table 1 shows a comparison of E_b values between MN₄@G and MN₄@G/ML (M = V, Mo and W; ML = TiS₂, C₃N₄, BN, G and rGO). The energy barriers of Li₂S decomposition over MN₄@G are decreased when forming the heterostructures with TiS₂, C₃N₄ and rGO. Among them, TiS₂ provides the best effect on surface regulation leading to enhanced SER performance of MN₄@G by giving rise to E_b of 0.41, 0.44 and 0.54 for WN₄@G/ML, MoN₄@G/TiS₂ and VN₄@G/TiS₂, respectively, while the effect of C₃N₄ and rGO on enhancing the catalytic activity for SER was significantly weak. In contrast, BN and G actually increased the E_b on VN₄@G and WN₄@G, respectively, indicating decreased SER performances. Note that the VN₄@G/C₃N₄ gives rise to the E_b value of 2.24 eV significantly larger than that of 0.70 eV given by VN₄@G. This is due to the fact that the V atom does not participate in catalyzing the Li₂S decomposition. As shown in Fig. 5a, during the whole process of Li₂S decomposition, no chemical bond is formed

Table 1 Comparison of E_b (eV) between heterostructures and their corresponding MN₄@G

	Heterostructures	MN ₄ @G
WN ₄ @G/TiS ₂	0.41 ^a	0.55
MoN ₄ @G/TiS ₂	0.44 ^a	0.58
VN ₄ @G/TiS ₂	0.54 ^a	0.70
WN ₄ @G/C ₃ N ₄	0.50 ^a	0.55
MoN ₄ @G/C ₃ N ₄	0.57 ^b	0.58
VN ₄ @G/C ₃ N ₄	2.24 ^b	0.70
WN ₄ @G/BN	0.62 ^b	0.55
MoN ₄ @G/BN	0.63 ^b	0.58
VN ₄ @G/BN	0.75 ^a	0.70
WN ₄ @G/rGO	0.54 ^b	0.55
MoN ₄ @G/rGO	0.58 ^a	0.58
VN ₄ @G/rGO	0.79 ^b	0.70
MoN ₄ @G/G	0.74 ^b	0.55
WN ₄ @G/G	0.83 ^a	0.58
VN ₄ @G/G	0.79 ^b	0.70

^a E_b values obtained based on the NEB method. ^b E_b values predicted by the E_b – ΔE relationship.

between the Li₂S cluster and the atomically dispersed V atom sitting between VN₄@G and C₃N₄.

3.3 Heterointerface effect on the performance of MN₄@G for catalyzing SRR and stabilizing LiPs

Since the catalytic performance of SCAs for catalyzing Li₂S decomposition will be significantly enhanced when being combined with TiS₂, we next chose the heterostructures of MN₄@G/TiS₂ to further investigate their binding strengths to LiPs and S₈ as well as their SRR performance, which are also crucial for suppressing the shuttle effect as well. In this regard, both sides of the heterostructures were explored. To indicate the specific surface where the adsorbates locate, it is necessary to redefine the nomenclature for the heterostructures. The bilayer consisting of monolayers of ML1 and ML2 can be named ML1/ML2 or ML2/ML1, representing the adsorbate being adsorbed on the side of the ML1 or ML2. For example, MoN₄@G/TiS₂ means that MoN₄ provides the active sites for adsorbing the LiPs and S₈ while it means the opposite when it is represented by TiS₂/MoN₄@G.

As shown in Fig. 6a and Table S4 (ESI[†]), the adsorption energies of LiPs on MN₄@G/TiS₂ (M = Mo and W) are both below -3.00 eV, which are lower than those on the organic electrolyte molecules such as 1,3-dioxynaphthenes (DOL) and 1,2-dimethoxy ethane (DME) within the range of -1.00 to -0.80 eV.⁴⁹ This implies the advantages of such heterointerfaces in suppressing the shuttle effect because the host material exhibits stronger adsorption performance than the organic electrolyte molecules. Moreover, WN₄@G/TiS₂ possesses more enhanced capability in trapping LiPs than MoN₄@G/TiS₂. In detail, the adsorption energies of LiPs (Li₂S_x, x = 1, 2, 4, 6, 8) and S₈ on the WN₄@G/TiS₂ interface are -5.21 , -5.15 , -4.17 , -4.17 , -4.33 and -2.52 eV, respectively. They are lower than the corresponding values on MoN₄@G/TiS₂, which are -4.67 , -3.72 , -3.71 , -3.35 , -3.28 and -2.11 eV, respectively. Note that the adsorption energies on individual TiS₂ and MN₄@G are higher than those on the heterostructures as shown in

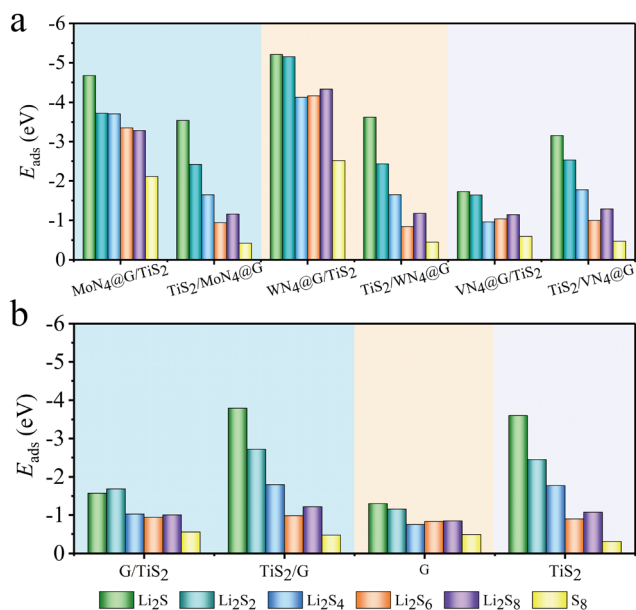


Fig. 6 The bar chart of adsorption energies of LiPs and S₈ on MN₄@G/TiS₂ (a), G/TiS₂, graphene (G) and TiS₂ (b). ML1/ML2 indicates the adsorption site is on ML1.

Table S4. Therefore, the capabilities of MoN₄@G and WN₄@G in stabilizing LiPs are generally enhanced when combined with TiS₂. In contrast, the adsorption strength of VN₄@G/TiS₂ to LiPs and S₈ are weaker than that for MN₄@G/TiS₂ (M = Mo and W). The lowest adsorption energy observed on VN₄@G/TiS₂ is merely −1.73 eV for Li₂S adsorption, which means that the adsorption strength of VN₄@G to LiPs is significantly weakened upon forming a heterointerface with TiS₂. This can be attributed to the formation of V–S bonds in the interlamination of VN₄@G/TiS₂. When the reaction intermediates are adsorbed on VN₄@G/TiS₂, the lack of V atoms on the surface of VN₄@G/TiS₂ leads to the absence of chemical bond between V atoms and LiPs/S₈, indicating a relatively weak interaction strength between the heterostructure and LiPs/S₈.

We also considered the binding strength of TiS₂ of three heterostructures to the adsorbates and found that the adsorption energies of various clusters on TiS₂/MN₄@G (M = V, Mo and W) are very similar. Furthermore, the values are comparable to the adsorption on pure TiS₂, suggesting that MN₄@G has a tiny impact on the adsorption performance of TiS₂ in heterostructures.

The application of MN₄@G is often constrained by the low loading density of metal atoms and heterogeneous distribution of doping sites. In the region without dopants, the local structure of MN₄@G retains the carbon lattice of pure graphene. Therefore, we set up a model of G/TiS₂ in order to further examine the regulatory role of TiS₂ on the performance of such carbon atoms far away from the metal centers. As shown in Fig. 6b and Table S4, G/TiS₂ possesses enhanced trapping capabilities for LiPs with respect to G. Moreover, the adsorption energies of Li₂S₄, Li₂S₆ and Li₂S₈ on G/TiS₂ are −1.03, −0.94 and −1.01 eV, respectively, which are lower than

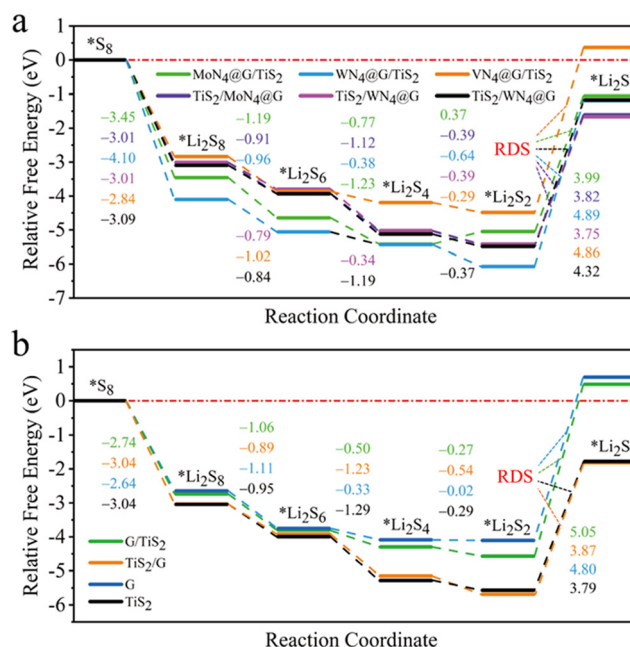


Fig. 7 Gibbs free energy profiles for SRR on MN₄@G/TiS₂ (a), G/TiS₂, graphene (G) and TiS₂ (b). Regarding heterostructures (ML1/ML2), ML1 represents the surface for adsorbing the adsorbates. The numbers with different colors are the Gibbs energy differences between the two adjacent states during SRR.

those for organic electrolyte (−1.00 to −0.80 eV). Therefore, combining with TiS₂ can enhance the adsorption performance of the entire region of MN₄@G monolayers for LiPs, which will help overcome the disadvantages of low loading of atomically dispersed atoms in MN₄@G.

We have also investigated the SRR performance of those heterostructures by calculating the Gibbs free energy changes (ΔG) profile as depicted in Fig. 7. For MoN₄@G/TiS₂ and WN₄@G/TiS₂ (see Fig. 7a), the ΔG values of overall SRR are −1.06 and −1.19 eV, respectively, which are lower than those of −0.41 and −0.33 eV for MoN₄@G and WN₄@G, respectively. Moreover, the ΔG of rate-determining step (ΔG_{RDS}) for the transition from Li₂S₂ to Li₂S are 3.99 and 4.89 eV, lower than the corresponding values of 4.25 and 4.36 eV for individual MoN₄@G and WN₄@G, respectively. These results imply the positive effect of heterointerface on enhancing the SRR performance of MN₄@G (M = Mo and W). In contrast, the overall ΔG of SRR on VN₄@G/TiS₂ is 0.37 eV, which is larger than −0.82 eV for VN₄@G. Such an increase of ΔG can be attributed to the structural feature of VN₄@G/TiS₂ with the V atom located between VN₄@G and TiS₂ and formation of the V–S bond. It means that the single V atom in VN₄@G/TiS₂ will not participate in forming chemical bonds with LiPs and S₈ during the SRR process leading to decreased SRR performance compared to individual VN₄@G. When it turns to TiS₂/MN₄@G (M = Mo, W and V), the overall ΔG of SRR are −1.61, −1.66, and −1.17 eV, respectively, while the related ΔG_{RDS} values are 3.82, 3.75 and 4.32 eV. These values are comparable to the corresponding values for individual TiS₂. This shows that the heterointerface

effect on the SRR performance of TiS_2 is relatively weak. Regarding G and G/ TiS_2 , they exhibit even worse performance for SRR, as reflected by the ΔG values of 0.69 and 0.48 eV for the overall SRR, respectively (see Fig. 7b). This also implies that the SRR performance of carbon atoms far away from the metal centers in $\text{MN}_4@\text{G}/\text{TiS}_2$ ($\text{M} = \text{Mo}, \text{W}$ and V) is relatively worse, which is still better than that for pristine graphene. Nevertheless, based on the above analysis, we believe that both sides of $\text{MN}_4@\text{G}/\text{TiS}_2$ possess promising performance for SRR. Overall, $\text{MN}_4@\text{G}/\text{TiS}_2$ ($\text{M} = \text{Mo}$ and W) show good performance in stabilizing LiPs and accelerating the kinetics of SER/SRR as confirmed by the low values of adsorption energies for LiPs/ S_8 , ΔG for overall SRR, ΔG_{RDS} and E_{b} for Li_2S decomposition, which demonstrate that they are promising candidates electrocatalysts for sulfur chemistry in Li-S batteries.

4. Conclusions

Using DFT calculations, we explored the heterointerface effect on the catalytic performance SACs toward sulfur conversion in Li-S batteries. To this end, 15 heterostructures were constructed by combining $\text{MN}_4@\text{G}$ ($\text{M} = \text{Mo}, \text{W}$ and V) with 5 different 2D materials of TiS_2 , C_3N_4 , BN, graphene and rGO. We then investigated their electronic properties, adsorption capabilities for LiPs/ S_8 and catalytic activities for sulfur redox. Using previously proposed descriptors of ΔE , we firstly screened three heterointerfaces $\text{MN}_4@\text{G}/\text{TiS}_2$ ($\text{M} = \text{Mo}, \text{W}$ and V) due to their low values of E_{b} of 0.54, 0.44, and 0.41 eV, respectively, indicating the enhanced SER performance of $\text{MN}_4@\text{G}$ caused by the interface effect. This effect also induces the increased binding strength to LiPs/ S_8 beneficial for suppressing the shuttle effect as reflected by the low adsorption energies. Moreover, our DFT calculations demonstrate that both sides of $\text{MN}_4@\text{G}/\text{TiS}_2$ ($\text{M} = \text{Mo}$ and W) possess enhanced SRR performance compared to the individual components of heterostructures. These can be confirmed by those competitive values of low values of adsorption energies for soluble LiPs ($< \sim -3$ eV), ΔG for the overall SRR (-1.66 to 0.37) and ΔG_{RDS} (3.82 to 4.89). Interestingly, the interface effect even strengthens the binding strength of the carbon atoms far away from the metal centers and soluble LiPs, which will probably address the issue of low loading rate of atomically dispersed metal atoms. This study paves a new way of designing novel electrocatalyst for sulfur chemistry for Li-S batteries and even other alkali-ion-chalcogen batteries.

Author contributions

H. Liang and Z. Zeng performed the calculations and the data analysis and H. Liang prepared the draft of the manuscript. Z. Qiao and Y. Li initialize the project and proposed the supervision. All authors have given approval to the final version of the manuscript.

Conflicts of interest

The authors declare no competing financial interest.

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