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# Catalytic synergy effect of MoS<sub>2</sub>/reduced graphene oxide hybrids for a highly efficient hydrogen evolution reaction†

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Two-dimensional layered transition metal dichalcogenide (TMD) materials such as MoS<sub>2</sub> and WS<sub>2</sub> have received a great deal of attention as alternatives to Pt in hydrogen evolution reaction (HER) catalysts. Recently, confined synthesis of TMD nanoparticles on graphene exhibited great catalytic performance for HER, due to the presence of many active edge sites. However, the correlation of gradual electronic transition states of TMD/graphene hybrids to catalytic behavior has been rarely studied. By means of controlling only the graphene oxide (GO) content added during the solvothermal synthesis with MoS<sub>2</sub>, we have synthesized hybrids of MoS<sub>2</sub> and reduced graphene oxide (rGO) with tunable morphology; this tuning also brought about a gradual change in the electronic states of MoS<sub>2</sub> due to strain induced by van der Waals interaction between heterolayers. The GO content tuning gradually enhanced the HER catalytic performance of the MoS<sub>2</sub>/rGO hybrids, decreasing the Tafel slope from 82 to 48 mV per decade owing to synergistic effects of an increase of catalytically active areas, an electronic transition of MoS<sub>2</sub>, and conductivity of rGO substrates.

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## 1. Introduction

Hydrogen production using photoelectrochemical water splitting has received a great deal of attention as a sustainable and clean way to convert solar energy to hydrogen energy. The material requirements of photoelectrochemical cells (*i.e.*, high visible absorption, slow recombination, and fast carrier transport, *etc.*) have some analogues to those of solar cells, but photoelectrochemical water splitting is more challenging due to further redox reaction steps using photogenerated carriers. Accordingly, kinetically effective transfer of carriers from semiconductors to electrolyte is a critical step to achieve high

solar-to-hydrogen efficiency. To improve the reaction kinetics, the development of HER cocatalysts with low overpotential is a very important issue. Pt has been considered to be the most effective catalyst for the HER, but its large-scale application is limited due to its scarcity and high cost. Therefore, much effort has been devoted to developing cocatalysts made of earth-abundant materials with HER catalytic performance comparable to that of Pt. Moly-based catalysts such as MoP sheets<sup>1,2</sup> and Mo<sub>2</sub>C nanoparticles<sup>3</sup> have been demonstrated to be HER catalysts with good stability and performance. Mono transition metal dichalcogenides (TMD) sheets such as MoS<sub>2</sub>,<sup>4–8</sup> MoSe<sub>2</sub>,<sup>7,9</sup> and WS<sub>2</sub><sup>10,11</sup> have been considered to be promising candidates to replace Pt. For MoS<sub>2</sub>, the most studied TMD catalyst, most research has focused on increasing the number of unsaturated sulfide edges, based on the understanding that these are the primary catalytically active sites.<sup>12</sup> In contrast to this point of view, Voiry *et al.* reported that the conductivity of the basal plane is a critical factor in the catalytic performance of MoS<sub>2</sub>.<sup>13</sup> Based on this idea, graphene has been used as MoS<sub>2</sub> support to enhance charge transfer.<sup>14,15</sup> Recently, several groups have demonstrated that the conversion of electronic structures of TMD from 2H to 1T drastically improve their HER catalytic performance.<sup>13,16</sup> To understand the mechanism of the HER catalytic behavior of TMD, investigation of the correlation between catalytic performance and electronic structural changes will be very important. Very recently, Wang *et al.* demonstrated continuous tuning of the electronic structure of chemical vapour deposition (CVD)-grown vertically aligned

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MoS<sub>2</sub> by using electrochemical lithiation approaches.<sup>16</sup> However, synthetic approaches to gradually control the electronic states of MoS<sub>2</sub> by using reduced graphene oxide (rGO) supports without lithium intercalation have been rarely studied, and the effect on catalytic performance of such tunability in MoS<sub>2</sub>/rGO hybrids has been rarely reported so far.

In the present work, we developed facile routes to control the morphologies of MoS<sub>2</sub>/rGO hybrids, including continuous control over the electronic state of MoS<sub>2</sub> laid directly flat on rGO, by changing the ratio of MoS<sub>2</sub> and rGO during a solvothermal synthesis. MoS<sub>2</sub>/rGO hybrids synthesized by including an appropriate amount of rGO possessed many active sites because MoS<sub>2</sub> was well dispersed on the rGO sheets; these materials achieved good conductivity of carriers, leading to low overpotential.

## 2. Experimental section

### 2.1 Synthesis of MoS<sub>2</sub>/rGO composites

Graphene oxide (GO) was synthesized from natural graphite flakes (Alfa Aesar, -325 mesh, 99.8% metal basis flakes) by using a modified Hummers method.<sup>17</sup> Graphite flakes of 1 g and 0.5 g of sodium nitrate (NaNO<sub>3</sub>) were put into a 250 ml round-bottom flask and then kept in an ice bath while slowly adding 23 ml of sulfuric acid (H<sub>2</sub>SO<sub>4</sub>) with stirring. While maintaining mild agitation and keeping the reaction temperature below 20 °C, 3 g of potassium permanganate (KMnO<sub>4</sub>) was slowly added to the suspension. The ice bath was then removed and the suspension was heated in an oil bath to 35 °C; the suspension was maintained at this temperature for 1 h. As the reaction proceeded, the suspension gradually thickened and became paste-like. Then, 40 ml of DI water was added slowly with vigorous agitation while maintaining the oil bath condition. This reaction caused violent effervescence and increased the temperature of the suspension. When the temperature decreased to 40 °C, the suspension was diluted to 100 ml by addition of DI water and was then treated with 34.5% hydrogen peroxide until the suspension turned bright yellow. Next, the yellow suspension was vacuum-filtered, yielding a brown filter cake. The filter cake was washed with DI water and centrifuged at 4000 rpm for 10 min, and then was washed with 10% hydrochloric acid and centrifuged again at 4000 rpm for 10 min. Then, the material was rinsed four times by ultracentrifugation (30 000 rpm for 10 min) followed by resuspension in DI water. Then, the suspension was dialyzed by using a dialysis membrane (Spectra/Por) for 1 week, during which time the suspension reached approximately pH 7. Finally, the suspension was transferred to a plastic dish and dried in a convection oven at 60 °C for 12 h, yielding a free-standing GO film.

To synthesize MoS<sub>2</sub>/rGO hybrids, 22 mg of (NH<sub>4</sub>)<sub>2</sub>MoS<sub>4</sub> was added to various solutions of GO in DMF (2.5, 3.3, 5, and 10 mg of GO in 10 ml of DMF) and stirred at room temperature until the solutions were homogenous. Next, each solution was well dispersed by using an ultrasonic bath for 20 min, and was then transferred to a 40 ml Teflon-lined autoclave and kept in a convection oven at 200 °C for 10 h. The product was then centrifuged at 8000 rpm and washed with DI water. Next, the

solution was rinsed 5 times to completely remove DMF and organic residues. The final product was redispersed in 5 ml DI water. Pristine MoS<sub>2</sub> was prepared by using the same procedure but without the addition of GO.

### 2.2 Electrochemical measurements

Homogeneous catalyst solutions of MoS<sub>2</sub>/rGO hybrids and of pristine MoS<sub>2</sub> were prepared by mixing 4 mg of catalyst with 80 μl of 5 wt% Nafion solution, and then adding 0.2 ml of EtOH and 0.8 ml H<sub>2</sub>O and ultrasonically the resulting mixture for 20 min. Then, 10 μl portions of catalyst solution were deposited on glassy carbon working electrodes 3 mm in diameter and Pt working electrodes 2 mm in diameter with a PTFE body. All electrodes were dried at room temperature. Polarization curves were measured by using a three-electrode setup (using Pt mesh as a counter electrode, saturated calomel electrode (SCE) as a reference electrode, and the catalyst as a working electrode) in N<sub>2</sub>-bubbled 0.5 M H<sub>2</sub>SO<sub>4</sub> using a scan rate of 10 mV s<sup>-1</sup>. The potential in 0.5 M H<sub>2</sub>SO<sub>4</sub> was converted from SCE to RHE by using the equation  $E(\text{RHE}) = E(\text{SCE}) + 0.273 \text{ V}$ . All electrochemical data reported herein are given in terms of potential versus RHE. *iR*-drop by solution resistance and parasitic resistance is corrected by the following equation:  $E_{iR\text{-corrected}} = E_{\text{RHE}} - iR_{\Omega}$ , where *iR*<sub>Ω</sub> is *iR*-drop and *E*<sub>RHE</sub> is the potential vs. reversible hydrogen electrode. The Tafel slopes of all MoS<sub>2</sub>/rGO samples are calculated by compensating the *iR*-drop. EIS measurements were performed using the same experimental setup, at the overpotential  $\eta = 180 \text{ mV}$  (bias: -0.45 V vs. SCE from 100 000 to 0.01 Hz with amplitude 0.01 V).

### 2.3 Material characterization

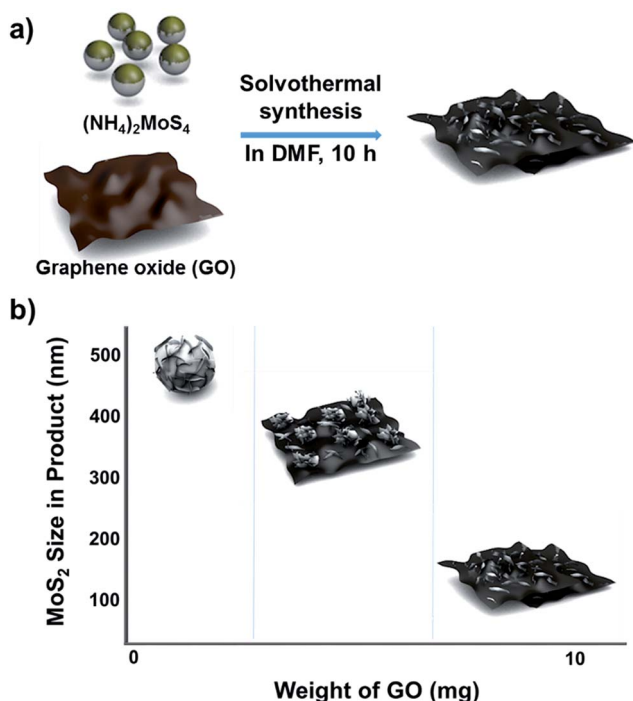
The synthesized materials were characterized by means of XPS (Thermo Electron K-Alpha), XRD (D8 Advance equipped with a Cu K<sub>α</sub> source), high-resolution TEM (HRTEM; JEOL JEM-2100 F, 200 kV), field emission scanning electron microscopy (FESEM; LEO SUPRA 55). Raman spectra were measured by using a custom-built micro-Raman setup detailed elsewhere;<sup>18</sup> briefly, an Ar ion laser operated at 514 nm with 1 mW output was focused to a diffraction-limited spot on the samples by using an objective lens (40×, numerical aperture 0.60). The Raman signal collected by the same lens was fed to a liquid nitrogen-cooled charge-coupled device detector (Princeton Instruments, SPEC-10) coupled with a spectrograph with a focal length of 30 cm (Princeton Instruments, SP-2300). The spectral resolution was determined to be 3 cm<sup>-1</sup> and the spectral accuracy was better than 1 cm<sup>-1</sup>.<sup>18</sup>

## 3. Results and discussion

### 3.1 Synthesis and characterization of MoS<sub>2</sub>/rGO hybrids

The method used to control the morphology of MoS<sub>2</sub> is summarized in Scheme 1. First, GO was synthesized by using a modified Hummer's method (see Experimental section).<sup>17</sup> The GO solution thus prepared was rinsed with deionized (DI) water and dried to make GO sheets. The desired amount of GO sheets was weighed, and then dispersed into a solution of MoS<sub>2</sub>



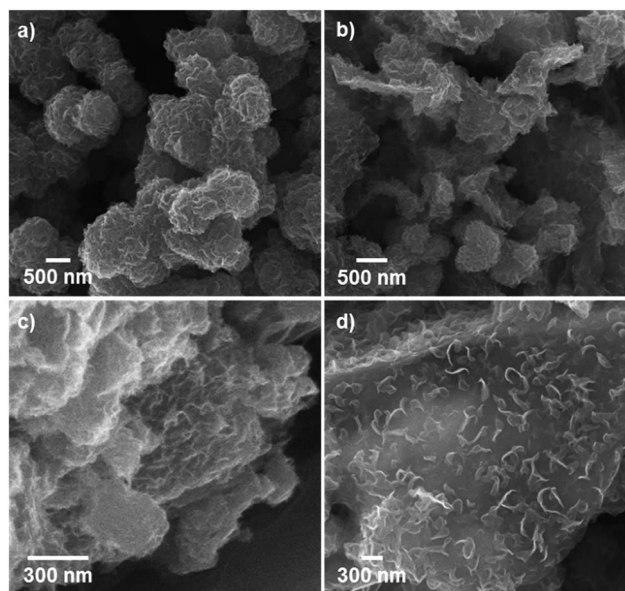


**Scheme 1** Schematic description of (a) the synthetic approach for  $\text{MoS}_2/\text{rGO}$  hybrids and (b) morphology and size changes depending on the GO content in the precursor solution.

precursors in dimethylformamide (DMF). Next, the solution of GO and  $\text{MoS}_2$  precursors was placed into a Teflon-lined autoclave and kept in a convection oven at 200 °C for 10 h. During this solvothermal process,  $\text{MoS}_2$  grew on the GO layers, and GO was simultaneously changed to reduced graphene oxide (rGO). Although  $\text{MoS}_2$  was grown on single layer rGO sheets, the final products look like intercalation of  $\text{MoS}_2$  between the rGO layers due to stacking of the rGO layers.

Pure  $\text{MoS}_2$  samples and  $\text{MoS}_2/\text{rGO}$  hybrids synthesized by means of the solvothermal process had different morphologies depending on the amount of GO included during the synthesis (Fig. 1). When  $\text{MoS}_2$  was synthesized without added GO, submicron-scale spherical particles consisting of highly packed corrugated  $\text{MoS}_2$  layers resulted (Fig. 1a). Pure  $\text{MoS}_2$  layers tend to stack onto each other by means of van der Waals interactions,<sup>12</sup> and tend to minimize surface energy by agglomerating to form spherical shapes. Accordingly, fewer catalytically active edge sites were available in this material compared to isolated nanoparticulate  $\text{MoS}_2$ .

When the solvothermal process was performed including  $\text{MoS}_2$  precursor solution (fixed at 22 mg) and various amounts of GO,  $\text{MoS}_2/\text{rGO}$  hybrids were synthesized (Fig. 1b–d). The interactions between  $\text{MoS}_2$  precursor and rGO were clearly reflected in the changes in  $\text{MoS}_2/\text{rGO}$  morphology observed as the amount of GO was increased. First, the amount of GO affected the amount of  $\text{MoS}_2$  sheets loaded on the GO, because GO oxygen functional groups such as carbonyls and other defect sites play an important role in nucleating  $\text{MoS}_2$  growth.<sup>15,19,20</sup> Second, the stacked GO sheets interfere with the growth of  $\text{MoS}_2$  in the (002) direction through the layer confinement effect;<sup>15,19</sup>



**Fig. 1** SEM images showing the different morphologies of (a) pristine  $\text{MoS}_2$  and (b–d)  $\text{MoS}_2/\text{rGO}$  hybrids prepared using various GO contents: (b) MS-GO<sub>1</sub>, (c) MS-GO<sub>3</sub>, and (d) MS-GO<sub>4</sub>.

thus, increasing the GO content decreases the number of stacked  $\text{MoS}_2$  layers. When the GO content was used as 2.5 mg (a composition denoted as MS-GO<sub>1</sub>), thick-layered  $\text{MoS}_2/\text{rGO}$  composites were synthesized (Fig. 1b). Also, spherical  $\text{MoS}_2$  particles were observed that had smaller diameters (200–500 nm) than those formed in the pure  $\text{MoS}_2$  sample (Fig. 1a). That is to say, the low GO content in MS-GO<sub>1</sub> provided relatively few nucleation sites, still allowing aggregation of  $\text{MoS}_2$  layers to occur, albeit to a lesser extent than in the reaction yielding pure  $\text{MoS}_2$ . When the GO content was increased to 3.3 mg (denoted as MS-GO<sub>2</sub>), small spherical  $\text{MoS}_2$  particles were observed that lay flat on rGO layers, and much less  $\text{MoS}_2$  aggregation was observed compared to that in MS-GO<sub>1</sub> (Fig. S1a†). However, both MS-GO<sub>1</sub> and MS-GO<sub>2</sub> had nanoparticulate rather than sheet morphology, and thus did not achieve the desired homogeneous distribution of  $\text{MoS}_2$  on rGO sheets. When the GO content was increased to 5 mg (denoted as MS-GO<sub>3</sub>), most rGO was well decorated with layered  $\text{MoS}_2$  and no spherical  $\text{MoS}_2$  particle was observed, indicating that the GO provided a sufficient number of nucleation sites to avoid aggregation (Fig. 1c). When the GO content of 10 mg was used (denoted as MS-GO<sub>4</sub>), well distributed  $\text{MoS}_2$  sheets were observed with lower loading density on the rGO compared to that observed for MS-GO<sub>3</sub> (Fig. 1d). Importantly, the amount of GO needs to be balanced: the GO content should provide sufficient nucleation sites to avoid aggregation of  $\text{MoS}_2$ , but should be low enough to maintain a high density of  $\text{MoS}_2$  in the resulting material. When the GO content was increased further while maintaining the  $\text{MoS}_2$  precursor content and the total synthetic volume, the greater GO content provided more nucleation sites, but lowered the density of  $\text{MoS}_2$  due to the excess of nucleation sites relative to the  $\text{MoS}_2$  content. This effect was clearly observed when the solvothermal synthesis was performed with excess amounts of



GO (over 10 mg); for example, when the GO content was 20 mg, the loading density of MoS<sub>2</sub> on the rGO sheets was drastically decreased (Fig. S1b†). This result indicates that the morphological changes of MoS<sub>2</sub>/rGO depend on the ratio of GO and MoS<sub>2</sub> precursor amounts.<sup>14,21</sup> In our study, the MoS<sub>2</sub>/rGO ratio is controlled by changing the amount of GO only, with a fixed amount of MoS<sub>2</sub> precursor. Decreased aggregation and size of MoS<sub>2</sub> can be achieved by increasing GO, but this is a trade-off with the low loading density of MoS<sub>2</sub>. Therefore, it is important to choose an appropriate amount of GO (10 mg of GO in our case) to obtain the optimum HER catalytic performance with a homogeneous distribution and appropriate loading density for MoS<sub>2</sub>. The reproducibility of the proposed morphology control and catalytic performance of each hybrid are confirmed in tens of experiments.

To verify the quality of MoS<sub>2</sub> hybridized on rGO, transmission electron microscope (TEM) images of MoS<sub>2</sub>/rGO hybrids were acquired. TEM images of aggregated spheres of pristine MoS<sub>2</sub> revealed the stacking of layers within these particles (tens of layers with approx. 0.67 nm interlayer distance; Fig. 2a–c). In a low-magnification TEM image of MoS<sub>2</sub>/rGO hybrids (MS-GO<sub>4</sub>), MoS<sub>2</sub> was observed throughout the surface of crumpled rGO layers (Fig. 2d), which were formed by self-assembly of the

flexible graphene layers during the solvothermal synthesis.<sup>21,22</sup> MoS<sub>2</sub> basal planes were clearly observed to sit parallel on the rGO (Fig. 2d–f). Unlike the structure of pristine MoS<sub>2</sub>, MoS<sub>2</sub> sheets grown on rGO had fewer (around three to five) stacked MoS<sub>2</sub> layers, with an interlayer distance of about 0.67 nm, as observed from a folded edge in the hybrid material (Fig. 2f). Energy-dispersive X-ray spectroscopy (EDS) mapping of selected areas of pure rGO and a MoS<sub>2</sub>/rGO hybrid confirmed that MoS<sub>2</sub> was well hybridized on rGO (Fig. S2†) and verified that Mo and S were distributed uniformly over the rGO sheets. SAED patterns indicated that the MoS<sub>2</sub> in the hybrids was polycrystalline (Fig. S3†); the MoS<sub>2</sub> was indexed as a hexagonal phase randomly oriented on the rGO.<sup>19,23</sup> Broad peaks in the X-ray diffraction (XRD) spectra of the hybrids confirmed the amorphous nature of MoS<sub>2</sub> in the hybrids (Fig. S4†). The poor crystallinity of MoS<sub>2</sub> was due to the incorporation of graphene, which interfered with the growth of MoS<sub>2</sub> crystals.<sup>21</sup>

Raman spectroscopy was used to further investigate the structure changes of MoS<sub>2</sub>/rGO. Raman spectra of all MoS<sub>2</sub>/rGO samples showed three distinct peaks corresponding to the graphene bands of D (1351 cm<sup>-1</sup>), G (1587 cm<sup>-1</sup>), and 2D (2691 cm<sup>-1</sup>; Fig. 3a). It is worth notice that the G band of GO

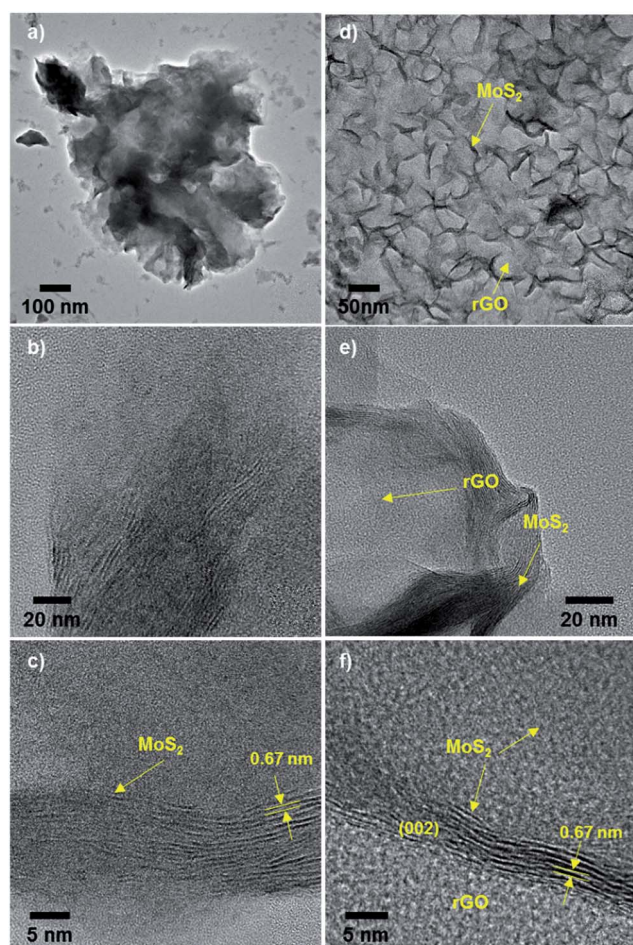


Fig. 2 TEM and HRTEM images of (a–c) pristine MoS<sub>2</sub> and (d–f) MoS<sub>2</sub>/rGO hybrids.

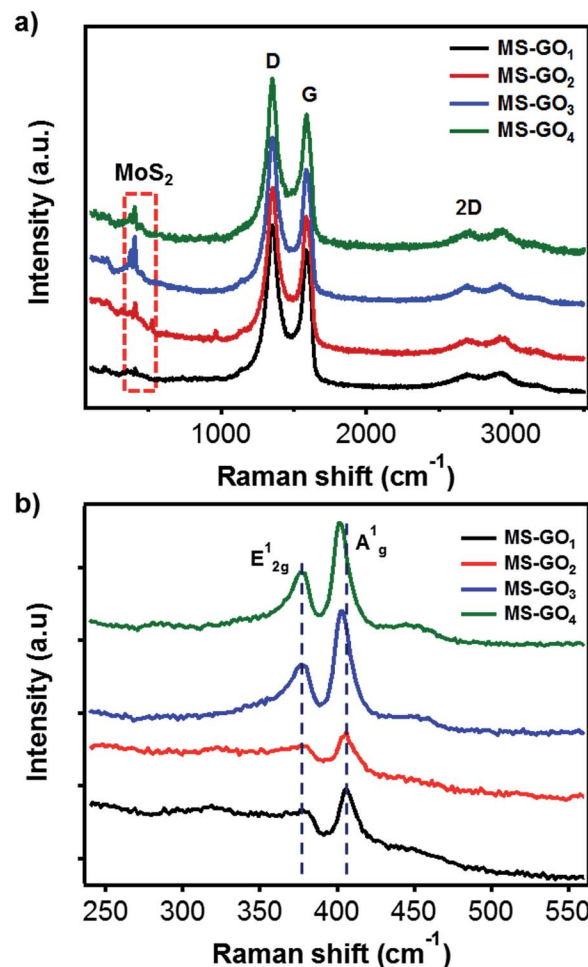


Fig. 3 Raman spectra of MoS<sub>2</sub>/rGO hybrids prepared using various GO contents: (a) rGO and (b) MoS<sub>2</sub> peak regions.



(1603  $\text{cm}^{-1}$ ) was downshifted for bare rGO (1595  $\text{cm}^{-1}$ ) due to the recovery of  $\text{sp}^2$  conjugation. The  $\text{MoS}_2/\text{rGO}$  hybrids exhibited further downshift of G bands (1588  $\text{cm}^{-1}$ ), which can be attributed to further reduction or addition of N atom possibly come from DMF or ammonium tetrathiomolybdate.<sup>24,25</sup> The downshift of G modes also might be caused by strain on rGO faced with  $\text{MoS}_2$  by lattice mismatching (Fig. S5†).<sup>26</sup> Basically, the D band corresponds to the  $A'_1$  vibration mode. In the case of perfect graphene, this mode cannot be observed by Raman scattering due to the perfect lattice symmetry. Thus, the D band responded to the vibrations of carbon atoms with in-plane terminations of disordered graphite dangling bonds. The G band, which is commonly found in graphite materials, responded to vibrations of carbon atoms in the opposite direction from each other with the adjacent atoms, and is due to the symmetry of  $E_{2g}$ . Measuring the ratio of D and G bands intensity ( $I_D/I_G$ ) is a useful indicator for estimating the quality of the graphite crystal structures. Crucially, in the case of rGO hybrid composites,  $I_D/I_G$  value can provide information on the unrepaired defects of rGO quantitatively. These defect sites on the rGO could play a critical role for the nucleation point during the synthesis of hybrid materials; therefore, we can estimate the amount of nucleation sites for  $\text{MoS}_2$  from the  $I_D/I_G$  value.<sup>27</sup> In our study  $I_D/I_G$  was 1.140, 1.141, 1.191, and 1.220 for MS-GO<sub>1</sub>, MS-GO<sub>2</sub>, MS-GO<sub>3</sub>, and MS-GO<sub>4</sub>, respectively; this trend indicates that an increase in total defect sites (*i.e.*, increase of nucleation sites for  $\text{MoS}_2$ ) results from increasing the GO amount. This shows why increasing the GO amounts inhibits the agglomerate of  $\text{MoS}_2$  gradually. Characteristic Raman peaks of  $\text{MoS}_2$  corresponding to the  $E_{2g}^1$  in-plane vibrational mode at 376  $\text{cm}^{-1}$  and the  $A_g^1$  out-of-plane vibrational modes at 403  $\text{cm}^{-1}$  were observed for all  $\text{MoS}_2/\text{rGO}$  hybrids (Fig. 3b). The  $A_g^1$  peaks of MS-GO<sub>3</sub> and MS-GO<sub>4</sub> were of lower frequency than those of MS-GO<sub>1</sub> and MS-GO<sub>2</sub>, indicating that MS-GO<sub>3</sub> and MS-GO<sub>4</sub> had fewer  $\text{MoS}_2$  layers because increased GO- $\text{MoS}_2$  interactions interfere the stacking of  $\text{MoS}_2$  attributed to van der Waals interaction between hetero interface of  $\text{MoS}_2$  and rGO.<sup>28,29</sup>

X-ray photoelectron spectroscopy (XPS) data gave clues regarding the electronic states of  $\text{MoS}_2/\text{rGO}$  hybrids (Fig. 4). C 1s peak analysis of  $\text{MoS}_2/\text{rGO}$  hybrids showed a decrease in the intensity of the C–O peak (286 eV) relative to that of the GO precursor, indicating the successful reduction of GO during the solvothermal process (Fig. S6†).<sup>30,31</sup> Five distinct peaks were observed in Mo 3d spectra of pristine  $\text{MoS}_2$  and of all  $\text{MoS}_2/\text{rGO}$  hybrids (Fig. 4a): pristine  $\text{MoS}_2$  showed peaks of  $3d_{5/2}$  (228.98 eV) and  $3d_{3/2}$  (232.08 eV), and these peaks gradually shifted to lower binding energy as the GO content was increased up to 10 mg ( $3d_{5/2}$  at 228.28 eV and  $3d_{3/2}$  at 231.48); the binding energy was very close to reported value of 1T- $\text{MoS}_2$ . The peak shifts indicated that the electron transfer might take place in between  $\text{MoS}_2$  sheets and rGO, and this transfer is more favourable for hybrids with high rGO contents. The transfer gives positive effect for catalytic performance with improved electronic and ionic conductance.<sup>25</sup> We carefully predict the electronic state changes by degree of van der Waals interaction depending on amount of rGO based on Raman and the XPS change. In addition to the Raman studies, the XPS peak shifts

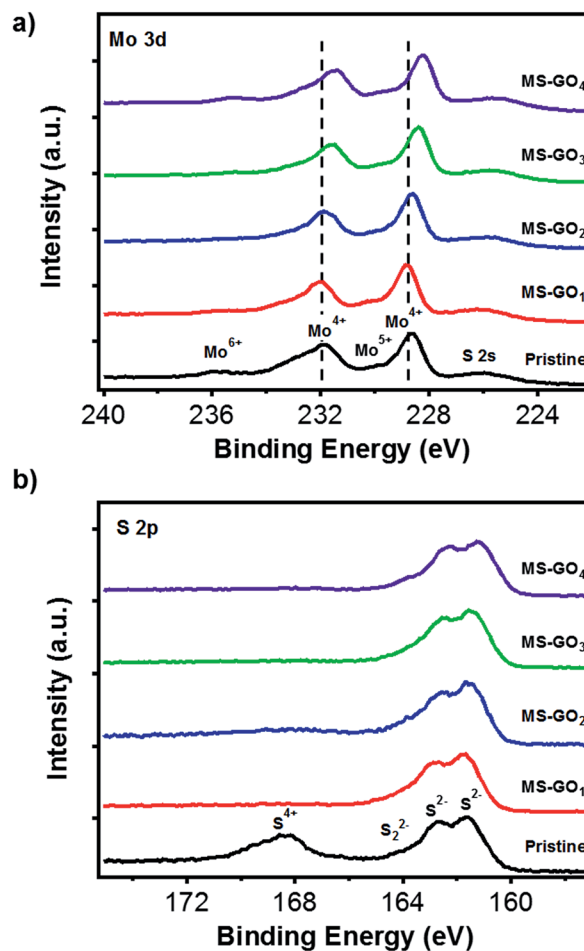


Fig. 4 (a) Mo 3d and (b) S 2p XPS spectra of pristine  $\text{MoS}_2$  and of  $\text{MoS}_2/\text{rGO}$  hybrids with various GO contents.

indicated that the GO content used during  $\text{MoS}_2/\text{rGO}$  synthesis not only changed the morphology of the  $\text{MoS}_2$ , but also induced a gradual change in the  $\text{MoS}_2$  electronic state due to van der Waals interaction between hetero 2D layers.<sup>13,29,32</sup> The peak observed at 236.0 eV was a residual peak from the +6 oxidation state, arising from slight oxidation during the experiment.<sup>33</sup> The small shoulder at 230 eV was evidence of a trace of conversion from  $\text{Mo}^{6+}$  to  $\text{Mo}^{5+}$ .<sup>34–36</sup> High-resolution XPS images of the S 2p doublet around 161 eV ( $S 2p_{3/2}$ ) and 162 eV ( $S 2p_{1/2}$ ) showed that the S 2p binding energies of MS-GO<sub>1</sub> and MS-GO<sub>2</sub> were similar to those of pristine  $\text{MoS}_2$  (161.58 and 162.68 eV), but these peaks were downshifted (161.28 and 162.18 eV) in MS-GO<sub>3</sub> and MS-GO<sub>4</sub>. The shoulder around 164 eV indicated that bridged  $S_2^{2-}$  or apical  $S^{2-}$  were present; these are considered to be active HER species (Fig. 4b).<sup>15,34–36</sup>

### 3.2 Electrochemical properties of $\text{MoS}_2/\text{rGO}$ hybrids

To test the electrocatalytic HER performance of  $\text{MoS}_2/\text{rGO}$  hybrids, electrochemical analyses were carried out using  $\text{MoS}_2/\text{rGO}$  coated on glassy carbon working electrodes. The polarization curves of pristine  $\text{MoS}_2$  exhibited the onset potential—defined here as the potential at  $j = -3 \text{ mA cm}^{-2}$ —of  $-0.347 \text{ V}$



(Fig. 5a). Compared to the pristine MoS<sub>2</sub>, MS-GO<sub>1</sub> had a large positive shift of the onset potential, to  $-0.207$  V. The polarization curves of MS-GO<sub>2</sub>, MS-GO<sub>3</sub>, and MS-GO<sub>4</sub> hybrids showed the onset potentials of  $-0.157$ ,  $-0.147$ , and  $-0.152$  V, respectively; the onset potential of MS-GO<sub>3</sub> was shifted positively by about 200 mV compared to that of pristine MoS<sub>2</sub>. The measured current densities of MoS<sub>2</sub>/rGO hybrid electrodes at  $-200$  mV were  $-24.6$ ,  $-24.4$ ,  $-16.1$ , and  $-3.0$  mA cm<sup>-2</sup> for MS-GO<sub>4</sub>, MS-GO<sub>3</sub>, MS-GO<sub>2</sub>, and MS-GO<sub>1</sub> hybrids, respectively. Compared to MoS<sub>2</sub>/rGO hybrids, pure MoS<sub>2</sub> exhibited the much lower current density of  $-0.8$  mA cm<sup>-2</sup>.

Tafel plots were prepared using the polarization curve data after correction of the potential by the ohmic potential drop ( $iR$ ) losses induced by the resistance between the electrolytes and the electrode. Tafel slopes were calculated by using the Tafel equation (Fig. 5b).<sup>37</sup> Pristine MoS<sub>2</sub> showed the highest Tafel slope (178 mV dec.<sup>-1</sup>) among the samples studied; MS-GO<sub>1</sub> had a much lower Tafel slope (82 mV dec.<sup>-1</sup>), and MS-GO<sub>2</sub> had the Tafel slope of 60 mV per decade. The Tafel slope of MS-GO<sub>4</sub> was the lowest (48 mV dec.<sup>-1</sup>) among all the MoS<sub>2</sub>/rGO hybrids studied. MS-GO<sub>3</sub> had a similar Tafel slope (50 mV dec.<sup>-1</sup>) to that of MS-GO<sub>4</sub>, which was expected because of these materials' similar morphologies and electronic states. Pt, a well-known HER catalyst, was compared to estimate catalytic performance of MoS<sub>2</sub>/rGO hybrids, and it shows 18 mV per decade lower Tafel slope (30 mV dec.<sup>-1</sup>) than MS-GO<sub>4</sub>. The Tafel slopes of the MoS<sub>2</sub>/rGO hybrids could be used to estimate the kinetics of the HER on these materials based on the Heyrovsky reaction, which

is the rate-determining step in the electrochemical desorption.<sup>14,38</sup> Contrastingly, MoS<sub>2</sub>/rGO hybrids with excess GO content had worse onset potential and higher Tafel slope than those with lower GO content. For example, the onset potential of MoS<sub>2</sub>/rGO synthesized with 20 mg of GO was more negative than that synthesized with 10 mg of GO (MS-GO<sub>4</sub>), and the corresponding Tafel slope (53 mV dec.<sup>-1</sup>) was higher than that of both MS-GO<sub>3</sub> and MS-GO<sub>4</sub> (Fig. S7a and b†). These data show that the use of excessive GO decreases the MoS<sub>2</sub> loading density (and thus the density of catalytically active sites) in the resulting hybrid (Fig. S1b†). This effect deteriorates the overall catalytic performance. That is to say, the GO content used can not only control the MoS<sub>2</sub>/rGO hybrids' morphology, but can also affect their catalytic performance in terms of conductivity and the number of active edge sites. All electrochemical characterizations are summarized in ESI Table S1.†

Electrochemical impedance spectroscopy (EIS) was conducted to compare the hybrids' electrical transport and electrode kinetics characteristics. Nyquist plots were prepared for each hybrid based on a Randles equivalent circuit model (Fig. 5c); all MoS<sub>2</sub>/rGO hybrids showed series resistances ( $R_s$ ) of about 10  $\Omega$ , suggesting good conductivity of the electrolytes. Importantly, charge transfer resistance ( $R_{CT}$ ) at the interfaces between the glassy carbon and the MS-GO hybrids and between MS-GO and electrolytes increased in the following order: MS-GO<sub>3</sub> (25.59  $\Omega$ ) < MS-GO<sub>4</sub> (31.56  $\Omega$ ) < MS-GO<sub>2</sub> (104.6  $\Omega$ ) < MS-GO<sub>1</sub> (242.0  $\Omega$ ). This observed trend supports the explanation that charge transfer is enhanced because of a transition of MoS<sub>2</sub>

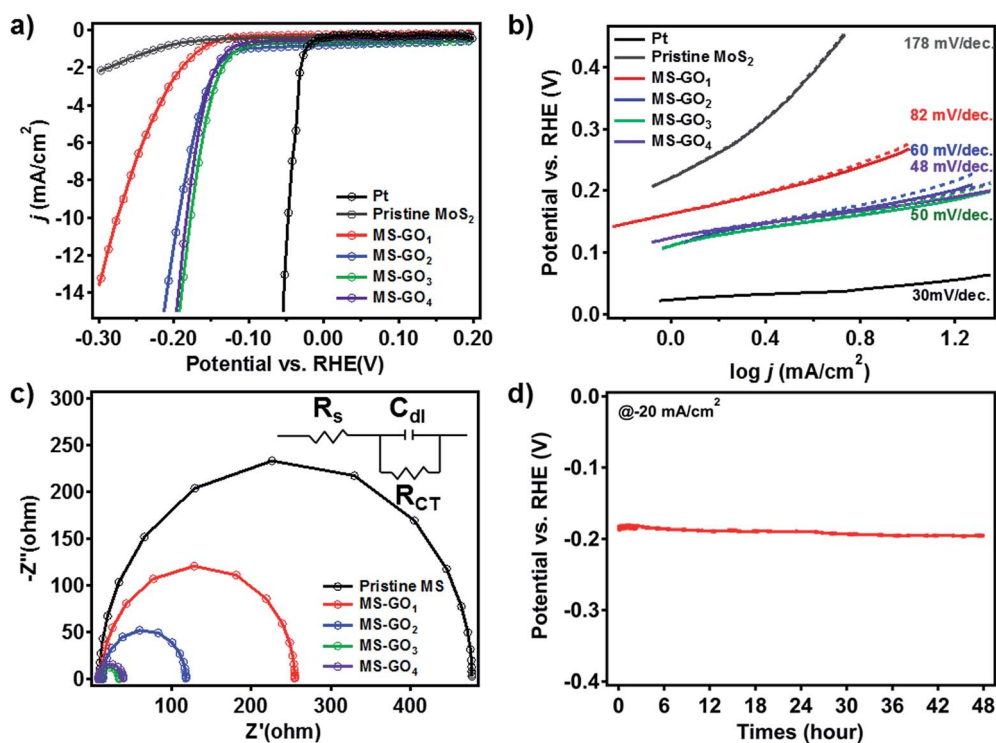


Fig. 5 Electrochemical characterizations of pristine MoS<sub>2</sub> and MoS<sub>2</sub>/rGO hybrids. (a) Polarization curves of MoS<sub>2</sub> and MoS<sub>2</sub>/rGO hybrids. (b) Tafel plots obtained from the polarization curve data in (a), (dashed lines) before and (solid lines) after  $iR$  correction. (c) Nyquist plots of pristine MoS<sub>2</sub> and of MoS<sub>2</sub>/rGO hybrids. (d) Long-term stability test for the MS-GO<sub>4</sub> HER catalyst.



crystals to a more conductive electronic phase (Fig. 5c). Also, the higher amount of rGO in good contact with MoS<sub>2</sub> of high density can improve the conductivity of a MoS<sub>2</sub>/rGO hybrid, thereby enhancing the charge transfer. The low  $R_{CT}$  observed for MS-GO<sub>3</sub> and MS-GO<sub>4</sub> is strong evidence of these hybrids' fast electrode kinetics (*i.e.*, good catalytic performance). Furthermore, the double-layer capacitance ( $C_{DL}$ ) of the MS-GO hybrids was extracted based on the equivalent circuit model to provide information on the active surface area. MS-GO<sub>3</sub> and MS-GO<sub>4</sub> showed the highest  $C_{DL}$  (3.9 and 4.2 mF) among the samples studied (Table S2<sup>†</sup>), indicating that these hybrids have a large active surface area of the electrode.<sup>39</sup> The high  $C_{DL}$  values of MS-GO<sub>3</sub> and MS-GO<sub>4</sub> originated from the density of the MoS<sub>2</sub> sheet's distribution on the rGO, which depended on the relative contents of MoS<sub>2</sub> and rGO. Therefore, to achieve both good charge transfer and high active surface area, precise control is required over the ratio of MoS<sub>2</sub> to rGO content used during the synthesis of the hybrids.

To evaluate the stability of the MoS<sub>2</sub>/rGO hybrid as a HER catalyst, we performed durability test over 48 h by chronopotentiometry (Fig. 5d). Overpotential drift at the static current of  $-20 \text{ mA cm}^{-2}$  was less than 10 mV after the test, showing good long-term stability of the catalyst toward HER. Besides, we carried out 1000 consecutive cycles of cyclic voltammetry for MS-GO<sub>4</sub> under potential between 0 and  $-0.3 \text{ V}$  versus a reversible hydrogen electrode (RHE); negligible current density change was observed during the test, suggesting superior long-term stability as a HER catalyst (Fig. S8<sup>†</sup>).

## 4. Conclusion

In conclusion, we have demonstrated the morphology-dependent HER catalytic performance of MoS<sub>2</sub>/rGO hybrids. The morphology of MoS<sub>2</sub>/rGO hybrids was well controlled by simply changing the content of rGO used during solvothermal synthesis, relative to the MoS<sub>2</sub> content. When an appropriate amount of GO was used, the resulting MoS<sub>2</sub>/rGO hybrids had a high density of homogeneously distributed MoS<sub>2</sub> sheets on the rGO, yielding many catalytically active edge sites; also, using the appropriate GO content yielded good contact between the MoS<sub>2</sub> and rGO and caused the electronic states of MoS<sub>2</sub> to transition to a more conductive phase, increasing the hybrids' conductivity. The synthetic approach discussed herein can be applied to other TMD/rGO hybrids as well as other layered materials.

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