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## First-principles study of the oxidation susceptibility of WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers†

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The environmental stability of two-dimensional (2D) transition metal dichalcogenide monolayers is of great importance for their applications in electronic, photonic, and energy storage devices. In this study, we focus on understanding the susceptibility of WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers to oxygen exposure in the form of atomic oxygen and O<sub>2</sub> and O<sub>3</sub> molecules, respectively. Calculations based on the van der Waals-corrected density functional theory predicted that O<sub>2</sub> and O<sub>3</sub> molecules are weakly adsorbed on these monolayers, although atomic oxygen prefers chemisorption accompanied by a significant charge transfer from the surface to oxygen. In the physisorbed molecular configurations consisting of O<sub>2</sub> and O<sub>3</sub>, the partially oxidized monolayers retain their geometrical and electronic structures. The calculated transition path as the oxygen approaches the surface shows a high-energy barrier for all cases, thus explaining the photo-induced formation of the oxidized configurations in the experiments. Furthermore, oxidizing the WS<sub>2</sub> monolayer is predicted to modify its electronic structure, reducing the band gap with increasing oxygen coverage on the surface. Overall, the calculated results predict the resilience of WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers against oxygen exposure, thus ensuring stability for devices fabricated with these monolayers.

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### 1. Introduction

Two-dimensional (2D) semiconductors, especially transition metal dichalcogenides (TMDs), such as WX<sub>2</sub> and MoX<sub>2</sub> (X: S, Se, Te), have emerged as an attractive class of materials for a wide range of applications in electronics and optoelectronics devices because of their unique electronic properties, such as high carrier mobility, tunable band gap, and anisotropic electron transport.<sup>1–11</sup> However, their device applications also encounter challenges due to their enhanced susceptibility to oxidation under ambient conditions. This rather undesirable chemical property has drawn considerable attention in understanding the stability and oxidation behavior of TMDCs, especially WS<sub>2</sub> and MoS<sub>2</sub>.<sup>12–15</sup> In a recent study of thermal stability, Rahman *et al.*<sup>16</sup> found that the monolayer MoS<sub>2</sub> is

quite stable up to a temperature of 1300 K against oxidation. However, at 1400 K, oxidation initiation begins, and by 1500 K, MoS<sub>2</sub> readily reacts with O<sub>2</sub>. Another study by Zhao *et al.* delved into O<sub>2</sub> adsorption on both pristine and defective TMD monolayers. The research highlighted the inert nature of defect-free TMDs to O<sub>2</sub>, while oxidation, an exothermic process, primarily occurred at chalcogen vacancies with adsorption energies ranging from 1.8 to 3.9 eV.<sup>17</sup> Investigations on bilayer MoS<sub>2</sub> demonstrated a substantial reduction in the “ON” state current under ambient conditions. The reduced current was attributed to additional scattering centers from chemisorption on defect sites, indicating the sensitivity of TMDs to ambient conditions and the impact on electronic properties.<sup>18</sup> For the case of WS<sub>2</sub>, a recent experimental study has demonstrated its oxidation under exposure to UV light, but this photo-oxidation of WS<sub>2</sub> is not fully understood.<sup>19</sup> These studies collectively provide an enhanced understanding of the susceptibility of TMDs toward oxidation and its implications on device performance. However, this understanding also raises the following questions: (1) What is the mechanism of oxidation of TMDs? (2) What kind of oxidative species are more effective in oxidizing TMDs, thereby affecting the electronic band structure and other electronic properties? To address these questions, we have systematically studied the reaction of three oxidizing species, namely free O atoms and

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O<sub>2</sub> and O<sub>3</sub> molecules with WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> within the framework of density functional theory (DFT) and climbing image nudged elastic band (CINEB) methods. Our emphasis will be on understanding the effects on geometrical and electronic structures and trying to develop a detailed understanding of the oxidation process in terms of chemical bonding, dissociation energy, and density of states in the current study.

## 2. Computational method

DFT-based calculations using the projected augmented wave (PAW) pseudopotential<sup>20</sup> were performed as implemented in the Vienna *ab initio* simulation package (VASP).<sup>21–24</sup> The Perdew–Burke–Ernzerhof form of the generalized gradient approximation (PBE-GGA)<sup>25</sup> was used, along with the van der Waals (vdW) correction term (D3) proposed by Grimme.<sup>26</sup> The convergence criteria for energy and the Hellmann–Feynman force acting on each atom were set to 10<sup>−6</sup> eV and 0.01 eV Å<sup>−1</sup>, respectively. The Brillouin zone was sampled using a centered *k*-point grid of size (12 × 12 × 1). A (2 × 2 × 1) periodic supercell was constructed for the monolayers, and periodic image interactions were minimized by using a vacuum of 15 Å along the *z*-axis direction. The dynamic stability of the system was determined by calculating the phonon frequencies using the PHONOPY package,<sup>27,28</sup> for which the force constants were obtained using density functional perturbation theory.<sup>29</sup>

The oxygen adsorption energy ( $E_{\text{adsorption}}$ ) was calculated using the following expression.<sup>30–34</sup>

$$E_{\text{adsorption}} = E_{(\text{oxygen}+\text{WX}_2)} - (E_{(\text{WX}_2)} + E_{(\text{oxygen})}) \quad (1)$$

where  $E_{(\text{oxygen}+\text{WX}_2)}$  is the total energy of the adsorbed configuration,  $E_{(\text{WX}_2)}$  is the total energy of the pristine monolayer, and  $E_{(\text{oxygen})}$  is the total energy of an oxygen (atomic oxygen or O<sub>2</sub> or O<sub>3</sub> molecule).

The CINEB method,<sup>35</sup> as implemented in VASP, was employed to calculate the minimum energy paths describing the interaction between an oxygenous species, atomic oxygen, and O<sub>2</sub> and O<sub>3</sub> molecules, respectively, and a TMD monolayer. The CINEB method generates a set of six intermediate configurations (*i.e.*, images) from the predetermined initial and final configurations. The initial (non-interacting) configuration consists of a molecule about 4.5 Å above the surface for these calculations. The final configuration consists of dissociated oxygens (atomic oxygen or O<sub>2</sub> or O<sub>3</sub> molecule) adsorbed on the monolayer.<sup>36</sup>

## 3. Results and discussion

Fig. 1 shows the hexagonal (2 × 2) supercell considered for the calculations. For the pristine WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers, the calculated lattice constants and band gaps are presented in Table 1 and the band structures are provided in Fig. S1, (ESI<sup>†</sup>) which are in good agreement with the previously reported DFT values. Table S1 (ESI<sup>†</sup>) lists the structural pro-

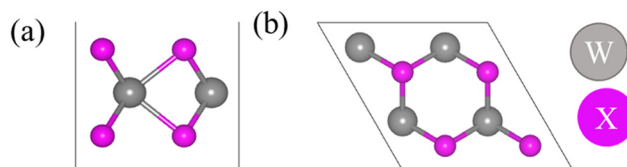


Fig. 1 (a) Side and (b) top views of the pristine WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers. Color codes: gray: W and pink: chalcogen (S/Se/Te).

Table 1 Lattice parameters and band gaps for WX<sub>2</sub> monolayers calculated at the PBE-DFT level of theory

Monolayers	$a = b$ (Å)	Band gap (eV)
WS <sub>2</sub>	3.18 (3.18 <sup>37,38</sup> )	1.86 (1.81 <sup>37,38</sup> )
WSe <sub>2</sub>	3.31 (3.31 <sup>37</sup> , 3.32 <sup>39,40</sup> )	1.57 (1.55 <sup>37</sup> , 1.53 <sup>40</sup> )
WTe <sub>2</sub>	3.56 (3.56 <sup>37</sup> )	1.08 (1.02 <sup>37</sup> )

perties of O<sub>2</sub> and O<sub>3</sub> molecules calculated at the DFT (GGA) level of theory and are reasonably in good agreement with reported theoretical and experimental values: O<sub>2</sub>: 1.24 Å (DFT)<sup>41</sup> and 1.21 Å (experiment)<sup>42</sup> and O<sub>3</sub>: 1.28 Å (DFT)<sup>43</sup> and experiment<sup>44</sup>, 116.49° (experiment)<sup>43</sup> and 117.90° (DFT).<sup>44</sup>

The equilibrium configurations of the oxygen adsorbed on WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers are shown in Fig. 2. Three different surface sites were considered for adsorption calculations: (chalcogen)<sub>top</sub>, W<sub>top</sub>, and hollow. Interestingly, the energetically preferred sites, shown in Fig. 2, consist of an O atom forming a bond with the chalcogen atom (*i.e.*, the (chalcogen)<sub>top</sub> site). The remaining O atoms in O<sub>2</sub> and O<sub>3</sub> are slightly elongated parallel to the surface approaching the neighboring chalcogen atom. Table 2 lists the adsorption energy ( $E_{\text{adsorb}}$ ), dissociation energy ( $E_{\text{diss}}$ ), molecule–surface distance ( $R_{\text{X-O}}$ ), charge transferred from the surface to molecule ( $Q_{\text{O}}$ ), and activation barrier height ( $E_{\text{barrier}}$ ), describing the interaction of O, O<sub>2</sub>, and O<sub>3</sub> with the WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers. Note that the dissociation energy ( $E_{\text{diss}}$ ) was calculated as the difference between the total energy of the dissociated configuration (*i.e.*, O<sub>2</sub> → O + O or O<sub>3</sub> → O + O + O) and the non-interacting configuration consisting of a molecule of about 4.5 Å above the surface.<sup>36</sup>

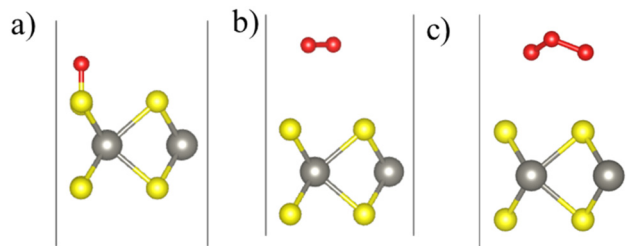


Fig. 2 Calculated equilibrium configurations of (a) O, (b) O<sub>2</sub>, and (c) O<sub>3</sub> molecules adsorbed on the WS<sub>2</sub> monolayer. Color code: S (yellow), W (gray), and O (red).

**Table 2** WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers interacting with O, O<sub>2</sub>, and O<sub>3</sub>: the calculated adsorption energy per oxygen atom ( $E_{\text{adsorb}}$ ), dissociation energy ( $E_{\text{diss}}$ ), molecule–surface distance ( $R_{\text{X-O}}$ ), charge transferred from the surface to molecule ( $Q_{\text{o}}$ ), and the energy barrier height for dissociation ( $E_{\text{barrier}}$ )

Monolayer			WS <sub>2</sub>	WSe <sub>2</sub>	WTe <sub>2</sub>
O	Chemisorption	$E_{\text{adsorb}}$ , eV per atom	−3.92	−3.00	−3.44
		$R_{\text{X-O}}$ , Å	1.48	1.65	1.85
		$Q_{\text{o/O}}$ atom	1.91e	0.86e	0.98e
O <sub>2</sub>	Physisorption	$E_{\text{adsorb}}$ , eV per atom	−0.05	−0.03	−0.16
		$R_{\text{X-O}}$ , Å	3.39	3.59	3.67
		$Q_{\text{o/O}}$ atom	≈0.0e	0.03e	0.08e
	Dissociation	$E_{\text{diss}}$ , eV	−0.96	1.23	0.28
		$R_{\text{X-O}}$ , Å	1.48	1.65	1.82
O <sub>3</sub>	Physisorption	$E_{\text{adsorb}}$ , eV per atom	−0.07	−0.08	−0.14
		$R_{\text{X-O}}$ , Å	3.05	2.95	2.93
		$Q_{\text{o/O}}$ atom	0.06e	0.15e	0.22e
	Dissociation	$E_{\text{diss}}$ , eV	−1.43	1.04	≈0
		$R_{\text{X-O}}$ (Å)	1.48	1.65	1.82
		$Q_{\text{o/O}}$ atom	1.88e	0.58e	0.77e
		$E_{\text{barrier}}$ , eV	6.03	7.30	6.85

Atomic oxygen interacting with the WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers tends to chemisorb itself onto the top of the chalcogen atom (*i.e.*, S or Se or Te) with an equilibrium bond distance,  $R_{\text{X-O}}$ , of 1.48, 1.65, and 1.85 Å for WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>, respectively. The calculated  $E_{\text{adsorb}}$  is −3.92, −3.0, and −3.44 eV for WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>, respectively. We note that atomic oxygen forms an ionic-covalent bond with an S atom of WS<sub>2</sub> as in the SO molecule for which  $R_{\text{S-O}}$  is 1.48 Å.<sup>45</sup> The bonding follows a relatively large charge transfer (1.91e) from the monolayer (S) to atomic O, thereby resulting in chemisorption on the surface. A lesser degree of ionicity is predicted for the Se–O and Te–O bonds for the chemisorbed complexes on the WSe<sub>2</sub> and WTe<sub>2</sub> monolayers. In the context of monolayers composed of WX<sub>2</sub>, the interaction between tungsten (W) and chalcogen (X) atoms is characterized by a reduction in the charge transfer from W to X, *i.e.*  $\Delta Q = 1.31e$ ,  $0.56e$ , and  $0.11e$  for WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub>, respectively.<sup>46</sup> Hence the affinity of oxygen for forming a bond with S is much higher than those for Se and Te since S has more charge than Se/Te. Furthermore, an inspection of the partial density of states (Fig. S2, ESI†) shows that chemisorption of atomic oxygen does not induce gap states in the band gaps of the WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers.

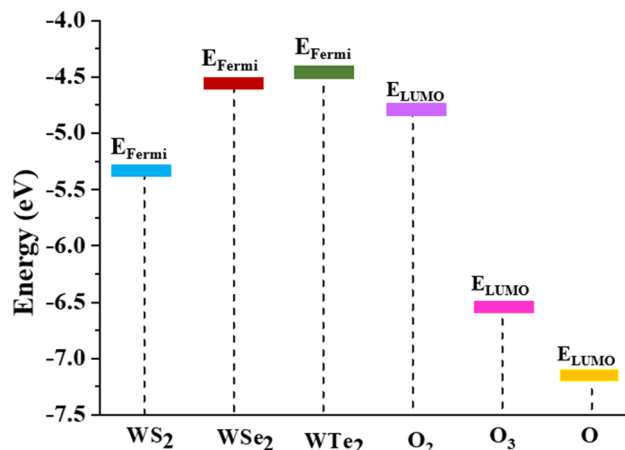
In contrast to the atomic oxygen chalcogenide interaction, the O<sub>2</sub> and O<sub>3</sub> molecules prefer a weakly physisorbed configuration on top of the WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers with much lower  $E_{\text{adsorb}}$  in the range of 0.03–0.16 eV with the corresponding bond distance,  $R_{\text{X-O}}$ , of about ≈3 Å or greater in their equilibrium configurations (Table 2).

This contrasting nature of adsorption can be attributed to the strong O–O bond(s) with bond dissociation energies of 5.11 and 6.27 eV in O<sub>2</sub> and O<sub>3</sub> molecules, respectively,<sup>47</sup> which prevents a strong interaction with surface chalcogen atoms of the WS<sub>2</sub>, WSe<sub>2</sub>, and WTe<sub>2</sub> monolayers. To assess the feasibility

of charge transfer from the surface to the molecules, we have compared the relative positions of the Fermi levels of the monolayers with the lowest unoccupied molecular levels (LUMO) of the O/O<sub>2</sub>/O<sub>3</sub> molecules.<sup>36,48</sup> From Fig. 3, we note that for the WSe<sub>2</sub> and WTe<sub>2</sub> monolayers, the Fermi levels lie above the O, O<sub>2</sub>, and O<sub>3</sub> levels, whereas for WS<sub>2</sub>, the Fermi level straddles only the O and O<sub>3</sub> levels. We can, thus, expect finite charge transfer in all the adsorption cases except for the O<sub>2</sub> on the WS<sub>2</sub> monolayer. We quantified this charge transfer using Bader charge analysis as presented in Table 2, which confirms that there is almost no charge transfer in the case of O<sub>2</sub> physisorbed on the WS<sub>2</sub> monolayer, as displayed in Fig. 3. It is worth noting that in the weakly physisorbed configurations, both O<sub>2</sub> and O<sub>3</sub> retain their structural identity in terms of the bond length and bond angles:  $R(\text{O–O})$  is 1.24 Å for the O<sub>2</sub> complexes, and ( $R(\text{O–O})$ ,  $A(\text{O–O–O})$ ) are (1.29 Å, 117.5°), (1.30 Å, 117.0°), and (1.31 Å, 116.3°) for the O<sub>3</sub>–WS<sub>2</sub>, O<sub>3</sub>–WSe<sub>2</sub>, and O<sub>3</sub>–WTe<sub>2</sub> complexes, respectively. The calculated  $R(\text{O–O})$  values for isolated O<sub>2</sub> and O<sub>3</sub> molecules are 1.24 Å and 1.28 Å, respectively. Note that the adsorption energy of the O<sub>2</sub> molecule for the pristine MoS<sub>2</sub> was reported to be 58 meV.<sup>49</sup>

Next, we calculated the transition path taken by both O<sub>2</sub> and O<sub>3</sub> molecules approaching the surface using the CINEB method, as displayed in Fig. 4. Here, the initial (non-interacting) configuration consisted of a molecule placed at ≈4.5 Å above the monolayer, and the final configuration consisted of the dissociated atomic oxygen, forming bonds with the surface atoms (*i.e.*, S or Se or Te) of the monolayers.

The calculated molecular transition path exhibits a relatively high energy barrier for either O<sub>2</sub> or O<sub>3</sub> dissociation on these monolayers. The energy barrier for O<sub>2</sub> dissociation to atomic oxygens is calculated to be ≈5 eV, whereas that for O<sub>3</sub> dissociation to atomic oxygens is predicted to be ≥6 eV (Table 2). Notably, among the investigated monolayers, only the WS<sub>2</sub> monolayer preferred the oxidized configurations with an  $E_{\text{dissociation}} \approx -0.96$  eV for O<sub>2</sub> and −1.43 eV for O<sub>3</sub> relative to



**Fig. 3** Schematic diagram displaying the monolayer's Fermi level ( $E_{\text{Fermi}}$ ) and the lowest unoccupied molecular orbital ( $E_{\text{LUMO}}$ ) of atomic O and molecular O<sub>2</sub> and O<sub>3</sub>.

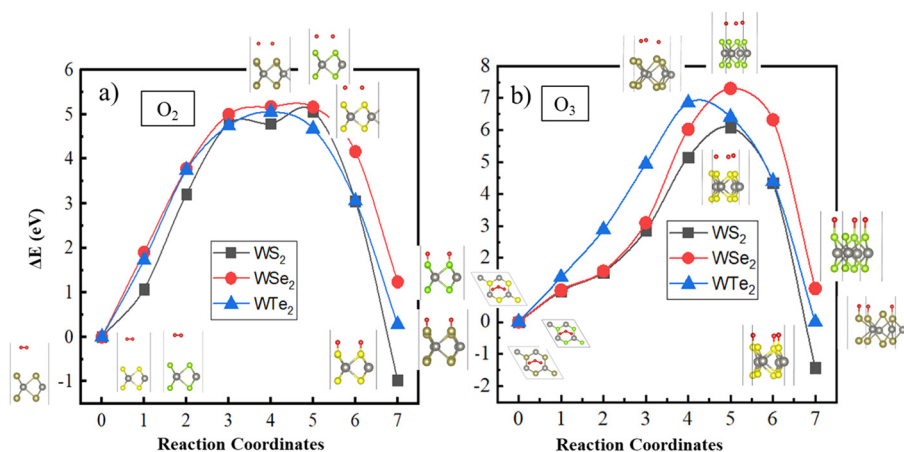


Fig. 4 Molecular transition path on the  $\text{WS}_2$ ,  $\text{WSe}_2$ , and  $\text{WTe}_2$  monolayers for (a)  $\text{O}_2$  and (b)  $\text{O}_3$  molecules calculated using the CINEB method.

the non-interacting configurations. This can be attributed to the ease with which S–O bonds can form on the  $\text{WS}_2$  monolayer relative to the Se–O or Te–O surface bonds for the other monolayers. The oxidized  $\text{WSe}_2$  or  $\text{WTe}_2$  monolayers are not predicted to be energetically preferred (Table 2). It should be noted that experiments have been performed on the diatomic molecules SO, SeO, and TeO, reporting their vibrational properties.<sup>50</sup>

After recognizing that a partially oxidized  $\text{WS}_2$  monolayer (with 25% surface coverage) can be stable, we now examine the electronic properties and the stability of the fully oxidized  $\text{WS}_2$  monolayer (with 100% surface coverage).

In the equilibrium configuration of the oxidized  $\text{WS}_2$  monolayer, the calculated S–O bond length is 1.48 Å, similar to that predicted for a partially oxidized  $\text{WS}_2$  surface (Table 2). Another striking feature appears in the calculated total density of states at the Fermi level for the oxidized  $\text{WS}_2$  monolayer, as shown in Fig. 5. By comparing the pristine  $\text{WS}_2$  (Fig. 5a) with the partially oxidized one (Fig. 5b), we observed that the band gap reduces by 0.36 eV, and as we move away from the Fermi level in the valence states, new hybridized S–O states appear due to the formation of S–O bonds. A similar observation has been made for SnS/SnSe/GeS/GeSe monolayers where oxygen chemisorption leads to band gap reduction with the activation barrier  $\text{O}_2$  in the range from 1.26 to 1.60 eV.<sup>51</sup> Notably, these studies did not address the oxidation of the monolayers by atomic O and  $\text{O}_3$  molecules.

Further comparison with the fully oxidized monolayer (Fig. 5a) shows that the band gap reduces from 1.86 eV (pristine) to 1.50 eV (Fig. 5b) for the partially oxidized and to 0.30 eV for the fully oxidized  $\text{WS}_2$  monolayer and the hybridized states appear near the Fermi level due to the increase in the S–O bonds. In the case of a partially oxidized  $\text{WS}_2$  monolayer (Fig. 5b), the upper valence band (width of 6 eV) consists of the dominating S–O bonds with small contributions from W–O bonds. In the fully oxidized monolayer, however, the upper valence band splits into two parts; the S–O band has moved down to about 4 eV relative to the Fermi level as can be seen in Fig. 5c. The reduction in the band gap in TMDs with oxidation has also been previously reported by DFT calculations.<sup>52</sup>

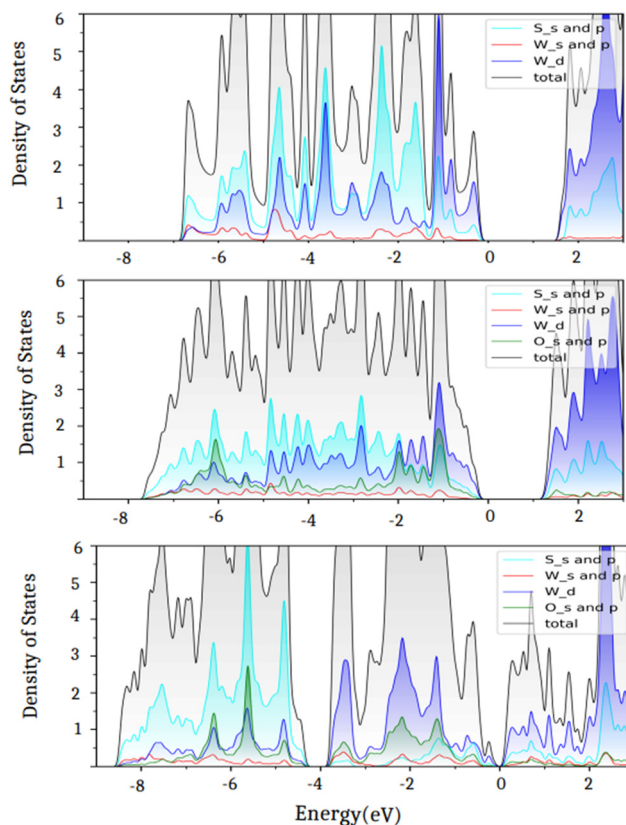


Fig. 5 Projected densities of states for the (a) pristine, (b) partially oxidized, and (c) fully oxidized  $\text{WS}_2$  monolayers.

To assess the dynamic stability of the fully oxidized  $\text{WS}_2$ , phonon dispersion calculations were performed using the PHONOPY package. Fig. 6b displays the calculated phonon dispersion relationship, in which a small pocket of negative frequencies (<0.25 THz) near  $\Gamma$  along the  $\Gamma$ – $M$  direction in the Brillouin zone is noticed. We believe that this small pocket of negative frequencies is an artifact of the technical details such as the supercell size and functional used<sup>53</sup> in the present

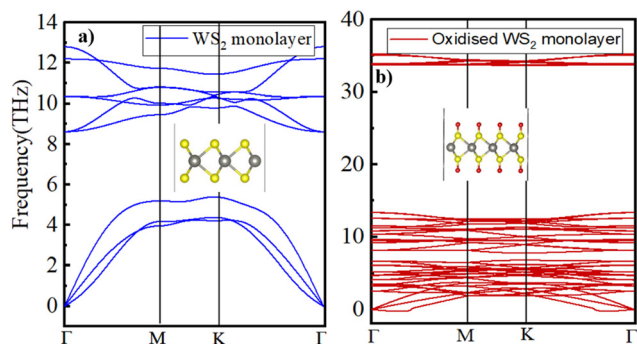


Fig. 6 Calculated phonon dispersion curves for the (a) pristine and (b) oxidized  $WS_2$  monolayers.

study. Otherwise, the calculated phonon band structure for the pristine  $WS_2$  monolayer (displayed in Fig. 6a) is in good accordance with the earlier published reports.<sup>54</sup> A comparison of the phonon band structures of the oxidized  $WS_2$  monolayer with the pristine one clearly shows a distinct phonon branch appearing at approximately 33 THz, which typically corresponds to the S–O bond stretching frequency.<sup>55</sup>

## 4. Summary

The oxidation susceptibility/resistance of  $WS_2$ ,  $WSe_2$ , and  $WTe_2$  monolayers was investigated from their interaction with atomic oxygen and  $O_2$  and  $O_3$  molecules, respectively. Calculations using van der Waals-corrected density functional theory (DFT) predicted the strongly chemisorbed O in the case of interaction with atomic oxygen, but weakly physisorbed  $O_2$  and  $O_3$  on the monolayer surface. These results are in accordance with a significant charge transfer from the surface to atomic oxygen for all the cases. The weakly physisorbed  $O_2$  and  $O_3$  molecules retain their molecular configurations at about 3.0 Å or more above the surface. The CINEB calculations predicted a large energy barrier for either  $O_2$  or  $O_3$  to dissociate into atomic oxygens on the surface. Interestingly, the oxidized  $WS_2$  is energetically preferred over the pristine  $WS_2$ , although the energy barrier is about 5.5 eV, which explains the experimental observation of the high resistance of  $WS_2$  to ambient oxidation for up to ten months but is susceptible to photo-induced oxidation.

## Conflicts of interest

There are no conflicts to declare.

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