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A first-principles prediction of the structural, electronic, transport and photocatalytic properties of GaGeX₃ (X = S, Se, Te) monolayers

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The discovery of new 2D materials with superior properties motivates scientists to make breakthroughs in various applications. In this study, using calculations based on density functional theory (DFT), we have comprehensively investigated the geometrical characteristics and stability of GaGeX₃ monolayers (X = S, Se, or Te), determining their electronic and transport properties, and some essential optical and photocatalytic properties. AIMD simulations show that these materials are highly structurally and thermodynamically stable. Notably, the GaGeSe₃ monolayer is a semiconductor with a band gap of 1.9 eV and has a high photon absorption coefficient of up to $1.1 \times 10^5 \text{ cm}^{-1}$ in the visible region. The calculated solar-to-hydrogen conversion efficiency of the GaGeSe₃ monolayer is 11.33%, which is relatively high compared to some published 2D materials. Furthermore, the electronic conductivity of the GaGeSe₃ monolayer is $790.65 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Our findings suggest that the GaGeSe₃ monolayer is a new promising catalyst for the solar water-splitting reaction to give hydrogen and a potential new 2D material for electrical devices with high electron mobility.

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1 Introduction

Graphene, the first 2D material discovered, has shown a great combination of superior electronic, mechanical, and thermal properties compared to bulk materials, including the quantum Hall effect, high Young's modulus, high carrier mobility at room temperature, and high thermal conductivity.¹ Following the discovery of graphene, a large-scale search has been underway in materials science to discover new 2D materials. A series of new 2D materials have been discovered, such as silicene,^{2,3} germanene,⁴ phosphorene,^{5,6} hexagonal boron nitride (h-BN),⁷ and transition-metal chalcogenides.^{8–10} These 2D materials have a unique structure with a high surface-area-to-volume ratio, leading to superior chemical and physical properties compared to bulk materials.^{11–13} These characteristics offer the potential to achieve outstanding performances when applied in different fields, such as electronics,^{14–17} sensors,^{18–20} and catalysis.^{21–23}

2D chalcogenides have layered structures comprising elements of the chalcogenide group (S, Se, or Te) combined with transition-metal elements.^{24,25} These materials are atomically thick with many favorable electronic and mechanical properties, making them essential research subjects in nano-electronics, optoelectronics, sensors,^{18,26} and energy

conversion.²⁷ 2D chalcogenides are synthesized using the atomic layer deposition technique, allowing expansion of their industrial applications.^{24,28} Recently, chalcogenide two-dimensional materials with two transition-metal elements have attracted substantial attention due to the ability to tailor and enrich their structural and electronic properties, which should be due to the presence of a second transition-metal element in the structure.^{24,29–36}

Using first-principles calculations, Hao *et al.*²⁹ discovered 40 stable 2D materials of the MGeX₃ family (M = metallic elements, X = O, S, Se or Te), including eight ferromagnetic, 21 antiferromagnetic, and 11 ferroelectric semiconductors. The MnGeSe₃ and MnGeTe₃ monolayers are predicted to be ferromagnetic metals at room temperature. Naseri *et al.*³² demonstrated that 2D XSnS₃ (X = Ga, In) monolayers with the space group 162 *P* $\bar{3}1m$ have high energetic, kinetic, mechanical, and thermal stability. The results of Naseri *et al.* show that the 2D GaSnS₃ and InSnS₃ monolayers show moderate band gaps (1.34 eV and 1.68 eV, respectively), good absorption of visible light, and consistent band edge positions, indicating that the 2D GaSnS₃ and InSnS₃ materials are promising photocatalysts for water splitting reactions. Research by Jalil *et al.*³⁷ discovered that the CoGeSe₃ monolayer is a promising 2D photocatalyst due to its moderate band gap (1.508 eV), suitable band edge position, good visible light absorption, and high carrier mobility. Kishore *et al.*³¹ discovered new potential catalysts for the water-splitting reaction, including CdPSe₃ and ZnPSe₃ monolayers, which have low exciton binding energy (in the range of 100–600 meV), high optical absorption (up to 10^5 cm^{-1}

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in the visible region), high carrier mobility with mild anisotropy and moderate external potentials to promote water splitting reactions. The results of Kishore *et al.*³¹ and Jalil *et al.*³⁷ opened up a new solution to promote energy conversion applications by developing new two-dimensional catalytic materials based on elements with high reserves and low costs, to replace the currently used rare metals, such as ruthenium and iridium. However, the big challenge for this group of materials is the limited understanding of the structural characteristics, stability, and electronic, transport, and optical properties of new materials that have not yet been synthesized appropriately in practice.

In this study, *via* calculations and simulations based on density functional theory (DFT), we have comprehensively investigated the geometrical characteristics and stability of GaGeX₃ (X = S, Se, Te) monolayers, determining their electronic, transport, optical, and photocatalytic properties. Our results provide essential data on the fundamental properties of newly studied two-dimensional materials. In particular, in this study, we discovered the GaGeSe₃ monolayer as a new candidate for use as a catalyst in the solar water-to-hydrogen splitting reaction and a potential new material in electronic devices with high electron mobility.

2 Methodology

In this study, we performed DFT calculations using the open-source computer code Quantum Espresso.³⁸ The Perdew–Burke–Ernzerhof generalized gradient approximation (PBE–GGA) function has been used to describe the exchange–correlation potential.³⁹ In the optimization and density of states calculations, the k-point grid in the Brillouin zone was set to 15 × 15 × 1 according to the Monkhorst–Pack scheme. The Heyd–Scuseria–Ernzerhof hybrid functional (HSE06) was used to calibrate the electronic bands of the studied materials.⁴⁰ The van der Waals interaction was taken into account in the calculations using the DFT–D3 approach.⁴¹ Kinetic cutoff energies were set to 500 eV. A vacuum layer of 20 Å parallel to the monolayer surface was used to avoid unwanted interactions between periodic slabs in the simulations. The convergence thresholds for force and energy in the ionic and cell optimization calculations were set to 0.01 eV Å^{−1} and 10^{−6} eV, respectively. We apply density functional perturbation theory (DFPT) to calculate the phonon spectrum with the help of the PHONOPY package.⁴² Phonon spectrum calculations were performed with 4 × 4 × 1 supercells of the GaGeX₃ (X = S, Se, Te) monolayers. The thermal stability was investigated through *ab initio* molecular dynamics (AIMD) simulations⁴³ at room temperature.

3 Results and discussion

3.1 Structural properties

The optimized structure of the GaGeX₃ (X = S, Se, Te) monolayers is shown in Fig. 1a and b. The unit cell of these structures is rhombic in shape and contains two Ga atoms, two Ge atoms, and six chalcogen (S, Se, or Te) atoms. The main structural

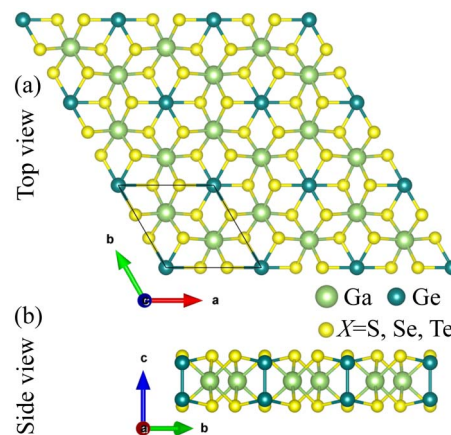


Fig. 1 The structural model of the GaGeX₃ (X = S, Se, Te) monolayers: (a) top view, (b) side view.

Table 1 The lattice parameters, *a* (Å), bond lengths, *d* (Å), thicknesses, *h* (Å), and cohesive energies, *E*_{coh} (eV per atom), of the GaGeX₃ (X = S, Se, Te) monolayers

	<i>a</i>	<i>d</i> _{Ga–X}	<i>d</i> _{Ge–X}	<i>d</i> _{Ge1–Ge2}	<i>h</i>	<i>E</i> _{coh}
GaGeS ₃	6.119	2.244	2.531	2.347	3.195	4.412
GaGeSe ₃	6.457	2.390	2.670	2.388	3.383	4.024
GaGeTe ₃	7	2.605	2.884	2.445	3.636	3.589

parameters of the GaGeX₃ monolayers were determined after optimization calculations with the PBE functional, and are shown in Table 1. The calculated lattice parameters of the GaGeX₃ monolayers are equal to 6.119, 6.457, and 7 Å, respectively, which increase from the top to the bottom of the chalcogen group in the periodic table for S, Se, and Te. In addition, the Ga–X and Ge–X bond distances (X = S, Se, Te) also increase from the top to the bottom of the chalcogen group in the periodic table for S, Se and Te (*d*_{Ga–S} < *d*_{Ga–Se} < *d*_{Ga–Te} and *d*_{Ge–S} < *d*_{Ge–Se} < *d*_{Ge–Te}) (see Table 1). The above fact is explained by the increase in the covalent radii of the chalcogen elements in the order *r*_S < *r*_{Se} < *r*_{Te} (by 1.05, 1.20, and 1.38 Å, respectively⁴⁴) and the decrease in their electronegativity according to order *μ*_S > *μ*_{Se} > *μ*_{Te} (corresponding to 2.58, 2.55 and 2.1, respectively).⁴⁵

Next, we investigated the structural stability of GaGeX₃ (X = S, Se, Te) monolayers by evaluating their energetic, mechanical, dynamical, and thermal stability. In particular, energetic stability is evaluated through the cohesive energy (*E*_{coh}) per atom, which is the average energy (over the number of atoms) to separate the structure into separate atoms:

$$E_{\text{coh}} = \frac{N_{\text{Ga}}E_{\text{Ga}} + N_{\text{Ge}}E_{\text{Ge}} + N_{\text{X}}E_{\text{X}} - E_{\text{tot}}}{N_{\text{Ga}} + N_{\text{Ge}} + N_{\text{X}}}, \quad (1)$$

where *E*_{tot} denotes the total energy of the GaGeX₃ (X = S, Se, Te) unit cell; *E*_{Ga}, *E*_{Ge} and *E*_X are the energies of isolated Ga, Ge, and chalcogen atoms, respectively; and *N*_{Ga}, *N*_{Ge} and *N*_X are the numbers of Ga, Ge, and X atoms in the GaGeX₃ unit cell, respectively.

The results of calculating the cohesive energies of the GaGeX₃ (X = S, Se, Te) monolayers are 4.412, 4.024, and 3.589 eV



per atom, respectively. These values are all positive, which allows the prediction that the GaGeX₃ (X = S, Se, Te) monolayer structures are energetically stable. Furthermore, it is known that E_{coh} is a quantity that characterizes the strength of the bonds between atoms in a material. The greater the cohesive energy, the stronger the bonding force between atoms in the material, which is the basis for the material's mechanical strength. In comparison with previously synthesized 2D materials, we find that the cohesive energies of the GaGeX₃ (X = S, Se, Te) monolayers are smaller than those of the MoS₂ monolayer (5.02 eV per atom), h-BN monolayer (7.07 eV per atom),⁴⁶ and graphene (7.85 eV per atom).⁴⁷ However, the cohesive energies of the GaGeX₃ (X = S, Se, Te) monolayers are significantly higher than those of germanene (3.26 eV per atom)⁴⁸ and phosphorene (3.47 eV per atom).⁶ These values demonstrate the relatively high motional stability of the studied 2D materials.

We calculated the phonon dispersions to evaluate the dynamical stability of the GaGeX₃ (X = S, Se, Te) monolayers, as shown in Fig. 2a. Negative frequencies are absent in the phonon curves of all three materials studied (Fig. 2a). This fact confirms the dynamical stability of the GaGeX₃ (X = S, Se, Te) monolayers.

The thermal stability of the GaGeX₃ (X = S, Se, Te) monolayers was evaluated through AIMD simulations. The variation in the total energy over time for the GaGeX₃ (X = S, Se, Te) monolayers at room temperature is shown in Fig. 2b. It can be seen that the fluctuation in the total energy of the GaGeX₃ (X = S, Se, Te) unit cells is negligible over the simulation period of 10 ps, indicating the high stability of the structure studied at room temperature.

To evaluate the mechanical stability, we use Born's stability criteria for various crystal systems, as clarified in the study of

Table 2 The calculated elastic constants (C_{11} , C_{12} and C_{66}), Young's moduli (Y^{2D} , in N m⁻¹), and Poisson's ratios (ν^{2D}) of the GaGeX₃ (X = S, Se, Te) monolayers

	C_{11}	C_{12}	C_{66}	Y^{2D}	ν^{2D}
GaGeS ₃	83.692	27.287	28.202	74.795	0.326
GaGeSe ₃	70.415	24.011	23.202	62.227	0.341
GaGeTe ₃	53.92	19.384	17.268	46.952	0.36

Mouhat *et al.*⁴⁹ Specifically, 2D hexagonal structures have mechanical stability when meeting the following conditions: $C_{11} > 0$ and $C_{11}^2 > C_{12}^2$.⁴⁹ The calculated elastic coefficients, as shown in Table 2, show complete satisfaction of the above conditions, confirming the mechanical stability of the GaGeX₃ (X = S, Se, Te) monolayers. In addition, the Poisson's ratios of the GaGeS₃, GaGeSe₃, and GaGeTe₃ monolayers are equal to 0.33, 0.34, and 0.36, respectively, indicating the structural flexibility of these materials under the influence of transverse deformation. These values are also significantly greater than those for graphene (0.19),⁵⁰ the MoS₂ monolayer (0.26), and the GaSe monolayer (0.25),⁵¹ indicating more flexibility than graphene and the MoS₂ and GaSe monolayers. Furthermore, with the same uniaxial strain (x or y) applied to the three materials studied, the most significant contraction was found in the structure of the GaGeTe₃ monolayer in the direction perpendicular to the applied strain. This fact shows that the GaGeTe₃ monolayer is more sensitive to horizontal uniaxial deformations than the other two materials.

To examine the mechanical properties of the monolayers, we calculated the Young's moduli and Poisson's ratios in different directions on their horizontal planes, as shown in Fig. 3a and b.

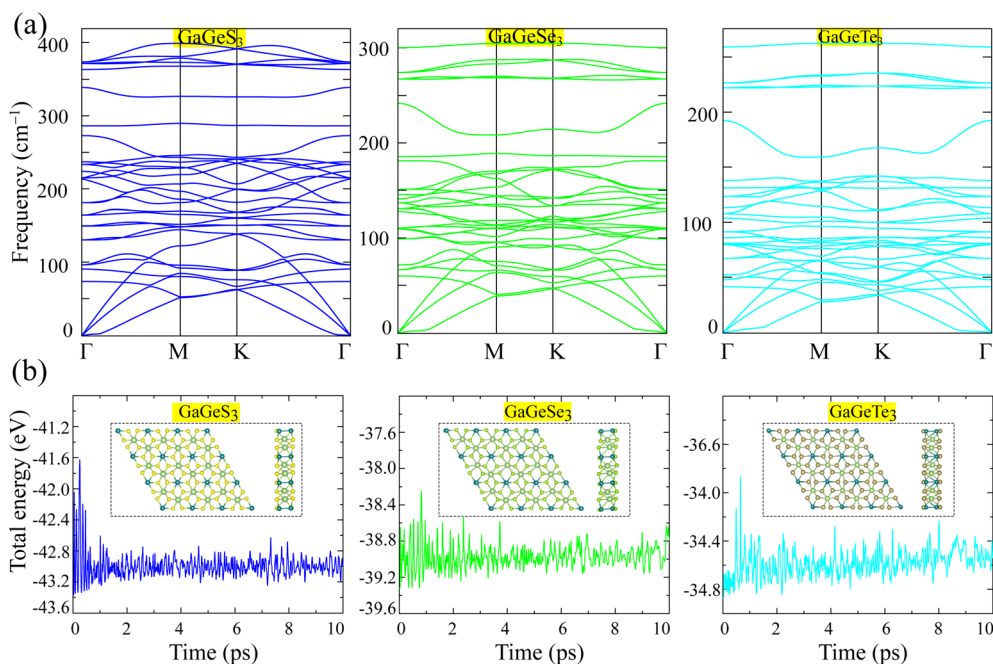


Fig. 2 (a) The phonon dispersions of the GaGeX₃ (X = S, Se, Te) monolayers and the energy fluctuations of the GaGeX₃ (X = S, Se, Te) unit cells during AIMD simulations at 300 K. (b) The energy fluctuations of the GaGeX₃ (X = S, Se, Te) unit cells during AIMD simulations at 300 K.

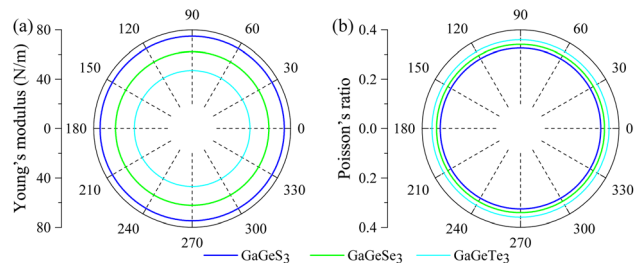


Fig. 3 The (a) Young's modulus and (b) Poisson's ratio in the xy -plane of the GaGeX_3 ($X = \text{S}, \text{Se}, \text{Te}$) monolayers.

It can be seen that the Young's modulus and Poisson's ratio do not change at all at different angles on the xy -horizontal plane, indicating isotropy in the xy -plane in terms of their mechanical properties.

3.2 Electronic properties

Examination of the band structures shows that the studied monolayers are all indirect semiconductors. The band gaps, calculated based on PBE, of GaGeS_3 , GaGeSe_3 , and GaGeTe_3 are 1.61, 1.124, and 0.549 eV, respectively. However, the PBE method often results in band-gap calculations that are significantly smaller than the experimental results.⁴¹ Meanwhile, the HSE06 functional⁴⁰ is known to provide band-gap results that are more similar to those from experiments than those from the PBE method are. Therefore, we have additionally calculated the band structures of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers using the HSE06 functional, as shown in Fig. 4 compared with the PBE functional results. The band gaps of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers from the HSE06 functional are 2.511, 1.908, and 1.109 eV, respectively. The projected bands of these monolayers (Fig. 5) show that the valence band maximum (VBM) of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers is mainly formed by the hybridization of the Ge-4s orbitals and the outermost orbital (p) of the chalcogen atoms (S, Se, and Te). The participation of the Ga-4p orbital is insignificant. Meanwhile, the conduction band minimum (CBM) of these 2D materials is formed by the hybridization of Ga-4s and Ge-4s orbitals, and s and p orbitals of the chalcogen atoms (S, Se, and Te) (Fig. 5).

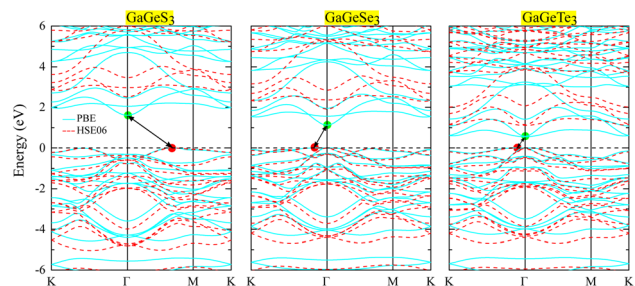


Fig. 4 Band structures of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers, calculated using PBE/HSE06 methods (cyan/red curves, respectively).

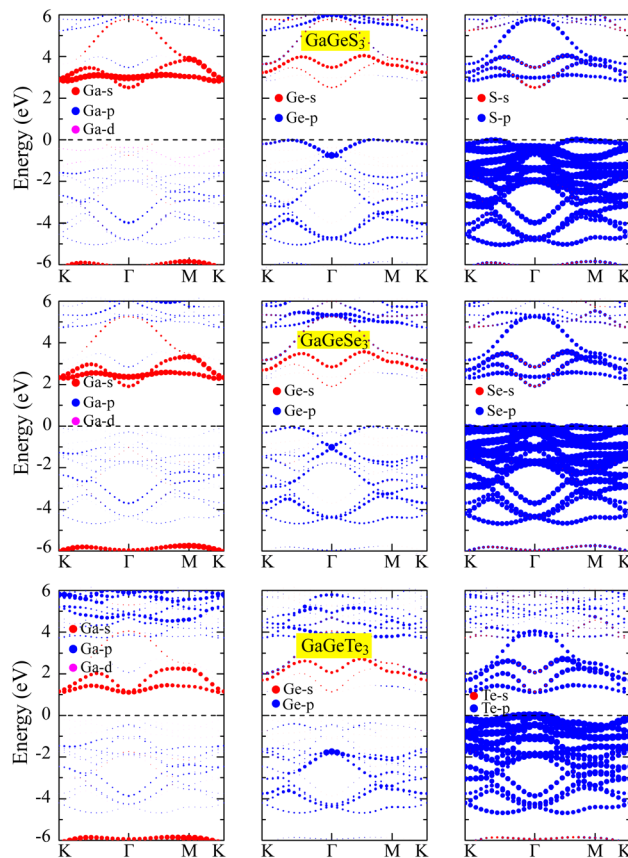


Fig. 5 Projected bands of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers using the HSE06 hybrid functional.

It can be seen that the PBE and HSE06 approximations both give similar results regarding the CBM and VBM positions of the GaGeS_3 , GaGeSe_3 , and GaGeTe_3 monolayers. The CBM of all three materials is set at the Γ -point, whereas their VBMs are different. Specifically, the VBM of GaGeS_3 is located on the line connecting the Γ -M points, while the VBMs of the other two materials are located on the line connecting K - Γ points in the Brillouin zone.

3.3 Transport properties

The carrier mobility was determined to consider the potential applications in electronic devices. The smaller mass of charged particles allows them to move faster depending on the exact value of the external electric field. High mobility of charge carriers in materials is essential for electronic applications.⁵² The carrier mobility is calculated with the DP method.⁵³ The carrier mobility of 2D materials is calculated according to the formula:

$$\mu_{2D} = \frac{e\hbar^3 C_{2D}}{k_B T m^* \bar{m}^* E_d^2}, \quad (2)$$

in which e , \hbar and C_{2D} denote the electron charge, reduced Planck's constant, and 2D elastic modulus, respectively; k_B , T , m^* , \bar{m}^* , and E_d denote the Boltzmann constant, temperature, carrier effective mass, average effective mass, and deformation



potential (DP) constant, respectively. The temperature is set to 300 K. The carrier effective mass m^* is calculated *via* parabolic fitting for the VBM and CBM according to the formula:

$$m^* = \left| \hbar^2 \left(\frac{\partial^2 E(k)}{\partial k^2} \right)^{-1} \right|, \quad (3)$$

where k and $E(k)$ are the wave vector and the energy dispersion, respectively.

The 2D elastic modulus (C_{2D}) and DP constant (E_d) are calculated according to the formulas:

$$C_{2D} = \frac{1}{\Omega_0} \frac{\partial^2 E_{\text{tot}}}{\partial \varepsilon_{\text{uni}}^2}, \quad (4)$$

$$E_d = \frac{\Delta E_{\text{edge}}}{\varepsilon_{\text{uni}}}, \quad (5)$$

where E_{tot} and ΔE_{edge} are the total energy and band-edge energy, respectively, of the supercell subjected to applied uniaxial strain ε_{uni} . Ω_0 is the optimized supercell area.

Here, we have calculated the effective mass (m^*), elastic modulus (C_{2D}), deformation potential (E_d), and carrier mobility (μ_{2D}) of the investigated 2D materials along the x - and y -axes, as presented in Table 3. The calculated data in Table 3 show that the carrier mobility of electrons in GaGeS₃ and GaGeSe₃ is much higher than that of holes. The carrier mobility of the holes of all three 2D structures is approximately equal along the x - and y -axis, indicating the directionally isotropic nature of the electron transport properties. However, for holes, the carrier mobilities of GaGeS₃, GaGeSe₃, and GaGeTe₃ along the x -axis are 1.8, 5.5, and 7.4 times larger than those along the y -axis, indicating high anisotropy of the hole transport. Notably, GaGeSe₃ has a high electron mobility of 790.65 cm² V⁻¹ s⁻¹, much higher than those of monolayer MoS₂ (200 cm² V⁻¹ s⁻¹),⁵⁴ MoSSe (52.7 cm² V⁻¹ s⁻¹),⁵⁵ and WSSe (125 cm² V⁻¹ s⁻¹).⁵⁶ These results demonstrate that the GaGeSe₃ monolayer is a potential material for application in electronic devices.

3.4 Photocatalytic properties

For this section, we have investigated some optical properties of the studied monolayer materials, thereby considering their applicability as photocatalysts. It should be noted that the necessary criteria for a photocatalyst in the reaction of splitting water into H₂ and O₂ include:^{57–59}

(1) The band gap needs to be greater than 1.23 eV. This lower limit of the band gap of a photocatalyst is equal to the difference

between the potential energy to produce H⁺ from H₂ (−4.44 eV) and the potential energy to produce oxygen from water (−5.67 eV).⁶⁰ However, a large band gap leads to loss of the ability to convert the energy of photons with energies less than the band gap into energy for stimulating the water-splitting reaction. Related to this issue, Ran *et al.*⁶¹ recommend that the optimal band gap for photocatalysts is about 2.0 eV to balance the requirements between chemical kinetics and light absorption to achieve an effective and high photocatalytic performance for the whole process.

(2) The CBM must be more positive than the water oxidation potential (to produce H₂ in the water oxidation reaction), and the VBM must be more negative than the H₂O reduction potential (to produce O₂ in the dehydration reaction).

(3) A proficient catalytic material should exhibit good absorption capabilities in either the visible or infrared regions, as these two regions collectively represent approximately 43%⁶² and 51%⁶³ of the solar energy reaching Earth, respectively.

From Fig. 6b, it can be seen that the CBM positions of both the GaGeS₃ and GaGeSe₃ monolayers are higher than the required reduction potential to produce hydrogen. Meanwhile, their VBM positions are lower than the oxidation potential necessary to generate oxygen. Therefore, it is expected that GaGeS₃ and GaGeSe₃ monolayers will be able to stimulate the generation of hydrogen and oxygen from water. For the GaGeTe₃ monolayer, only its CBM position is suitable to produce hydrogen gas. To clarify the fulfillment of the third criterion above, we calculated the optical absorption coefficients of all three materials according to the formula:

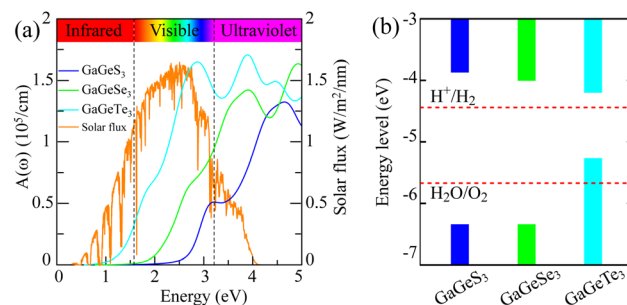


Fig. 6 (a) The optical absorption spectra of the GaGeS₃, GaGeSe₃, and GaGeTe₃ monolayers at the HSE06 level, compared with solar flux; (b) the band alignments of the studied monolayers in comparison with the oxidation and reduction potentials of water.

Table 3 The effective masses, m^* (m_0), elastic moduli, C_{2D} (N m⁻¹), deformation potentials, E_d (eV), and carrier mobilities, μ_{2D} (cm² V⁻¹ s⁻¹) along the x - and y -directions for the investigated 2D materials GaGeX₃ (X = S, Se, Te)

		m_x^*	m_y^*	C_{2D}^x	C_{2D}^y	E_d^x	E_d^y	μ_{2D}^x	μ_{2D}^y
Electrons	GaGeS ₃	0.19	0.19	54.97	54.96	−11.35	−11.36	246.02	254.84
	GaGeSe ₃	0.12	0.12	46.49	46.49	−9.70	−9.71	785.15	790.65
	GaGeTe ₃	0.55	0.49	37.06	37.04	−4.42	−4.42	142.27	158.39
Holes	GaGeS ₃	0.96	4.70	54.97	54.96	−6.66	−4.10	13.01	6.96
	GaGeSe ₃	0.27	1.76	46.49	46.49	−6.01	−5.55	146.69	26.55
	GaGeTe ₃	0.60	4.70	37.06	37.04	−6.45	−6.25	18.93	2.56



$$\alpha(\omega) = \frac{\sqrt{2}\omega}{c} \left(\sqrt{\varepsilon_1^2(\omega) + \varepsilon_2^2(\omega)} - \varepsilon_1(\omega) \right)^{1/2} \quad (6)$$

where ω , α , and c are used to demonstrate the angular frequency, absorption coefficient and speed of light in a vacuum, respectively; $\varepsilon_1(\omega)$ and $\varepsilon_2(\omega)$ are the real and imaginary parts of the dielectric constant, respectively.

Fig. 6a shows the absorption coefficient's dependence on the energy of the solar spectrum. From the optical absorption spectra in Fig. 6a, it can be seen that the GaGeTe₃ monolayer strongly adsorbs light in all visible light regions (E_{photon} in the range of 1.63–3.26 eV) with an adsorption coefficient in the range of $0.5 \times 10^5 \text{ cm}^{-1}$ to $1.5 \times 10^5 \text{ cm}^{-1}$. The adsorption coefficient of the GaGeTe₃ monolayer continues to be maintained at a high level above $1.5 \times 10^5 \text{ cm}^{-1}$ in the ultraviolet region ($E_{\text{photon}} > 3.26 \text{ eV}$). However, the position of the bands of the GaGeTe₃ monolayer (Fig. 6b) is not favorable for generating a reduction reaction that produces O₂ from H₂O, as analyzed above. The GaGeS₃ and GaGeSe₃ monolayers have lower adsorption coefficients than the GaGeTe₃ monolayer in the visible region. The adsorption coefficient of the GaGeSe₃ monolayer in the visible light region ranges from $0.1 \times 10^5 \text{ cm}^{-1}$ to $1.1 \times 10^5 \text{ cm}^{-1}$; this coefficient continues to increase strongly in the ultraviolet light region and reaches the maximum value of about $1.4 \times 10^5 \text{ cm}^{-1}$ (at a photon energy of 3.8 eV). This value of the GaGeSe₃ monolayer is lower than those of some other potential 2D photocatalysts, such as GeC ($2.6 \times 10^5 \text{ cm}^{-1}$),⁶² arsenene ($3.01 \times 10^5 \text{ cm}^{-1}$)⁶³ and MoTe₂ ($2.90 \times 10^5 \text{ cm}^{-1}$),⁶⁴ but is more significant than those of GaS ($0.71 \times 10^5 \text{ cm}^{-1}$),⁶³ GaSe ($0.92 \times 10^5 \text{ cm}^{-1}$)⁶³ and GaN ($0.59 \times 10^5 \text{ cm}^{-1}$).⁶⁵ This characteristic, combined with meeting the first and second criteria mentioned above, suggests that the GaGeSe₃ monolayer is a potential photocatalyst in the water-splitting reaction into hydrogen fuel.

To further clarify the applicability of the GaGeX₃ (X = S, Se, Te) monolayers in the water-splitting reaction, we have calculated the Gibbs free energy of hydrogen adsorption (ΔG_{H}) using the formula:^{66,67}

$$\Delta G_{\text{H}} = \Delta E_{\text{H}} + 0.24 \text{ eV}, \quad (7)$$

where ΔE_{H} is the differential hydrogen absorption energy and is determined using:

$$\Delta E_{\text{H}} = E_{\text{GaGeX}_3+\text{H}} - E_{\text{GaGeX}_3} - \frac{1}{2}E_{\text{H}_2} \quad (8)$$

where $E_{\text{GaGeX}_3+\text{H}}$ is the total energy of the GaGeX₃ (X = S, Se, Te) monolayer with one adsorbed H atom on the surface, and E_{GaGeX_3} and E_{H_2} are the total energies of the GaGeX₃ (X = S, Se, Te) monolayer and the energy of an H₂ molecule, respectively.

To facilitate the hydrogen evolution reaction (HER), hydrogen atoms' reversible adsorption and desorption must have small absolute values.^{68,69} The Gibbs free energies of hydrogen adsorption of the GaGeX₃ (X = S, Se or Te) monolayers are calculated to be lowest at site B (the top of the chalcogen atom, see Fig. 7), equal to -2.24 eV , -2.04 eV , and -1.95 eV , respectively. These high negative values represent strong interactions between hydrogen atoms and the catalytic surface,

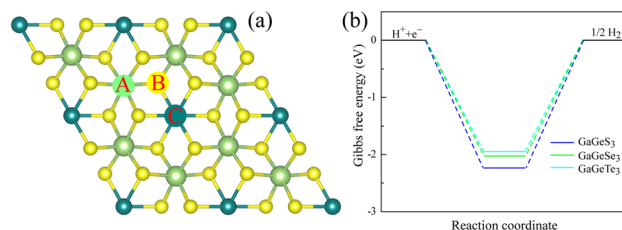


Fig. 7 (a) Different possible adsorption positions for the HER reaction on the GaGeX₃ (X = S, Se, Te) monolayers, (b) the calculated Gibbs free energy of the HER at the B position.

limiting the release of H atoms from the catalytic surface, so they predict low water-splitting catalytic performance of these monolayers compared to some other catalysts that have been reported, such as the β -PtSse monolayer (1.13 eV), WSe (1.51 eV)⁷⁰ and Zn₂SeTe (1.93 eV).⁷¹ However, the Gibbs free energy of hydrogen adsorption on 2D materials can be finely tuned by applying strain, an external electric field, or structural defects,^{72,73} or changing the pH of the water.⁷⁴

The solar-to-hydrogen (STH) conversion efficiency is known to be an important parameter for evaluating the efficiency of converting solar energy into hydrogen fuel in the water-splitting reaction. This efficiency is determined from the product of the light absorption efficiency and charge-carrier utilization:⁷⁵

$$\eta_{\text{STH}} = \eta_{\text{abs}} \times \eta_{\text{cu}}, \quad (9)$$

The light absorption efficiency is calculated according to the formula:

$$\eta_{\text{abs}} = \frac{\int_{E_g}^{\infty} P(h\omega) d(h\omega)}{\int_0^{\infty} P(h\omega) d(h\omega)} \quad (10)$$

where $P(h\omega)$ is the AM1.5 G solar energy flow at photon energy $h\omega$ and E_g is the photocatalyst band gap. The numerator indicates the light power density absorbed by the photocatalyst, while the denominator is the overall power density of the reference sunshine spectrum (AM1.5G). Charge-carrier utilization (η_{cu}) is calculated according to the formula:

$$\eta_{\text{cu}} = \frac{\Delta G_{\text{H}_2\text{O}} \int_E^{\infty} \frac{P(h\omega)}{h\omega} d(h\omega)}{\int_{E_g}^{\infty} P(h\omega) d(h\omega)} \quad (11)$$

where $\Delta G_{\text{H}_2\text{O}}$ represents the free energy of water splitting (1.23 eV) and the remainder of the numerator indicates the effective photocurrent density. Here, E denotes the photon energy that may be used in the water-splitting process.

$$E = \begin{cases} E_g, & (\chi(\text{H}_2) \geq 0.2, \chi(\text{O}_2) \geq 0.6) \\ E_g + 0.2 - \chi(\text{H}_2), & (\chi(\text{H}_2) < 0.2, \chi(\text{O}_2) \geq 0.6) \\ E_g + 0.6 - \chi(\text{O}_2), & (\chi(\text{H}_2) \geq 0.2, \chi(\text{O}_2) < 0.6) \\ E_g + 0.8 - \chi(\text{H}_2) - \chi(\text{O}_2), & (\chi(\text{H}_2) < 0.2, \chi(\text{O}_2) < 0.6) \end{cases} \quad (12)$$

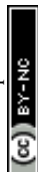


Table 4 The calculated band gap using the HSE06 method (E_g^{HSE06}), the overpotentials ($\chi(\text{H}_2)$ and $\chi(\text{O}_2)$), light absorption efficiency (η_{abs}), charge-carrier utilization (η_{Cu}) and STH conversion efficiency (η_{STH}) of the GaGeX₃ (X = S, Se, Te) monolayers

	E_g^{HSE06} (eV)	$\chi(\text{H}_2)$	$\chi(\text{O}_2)$	η_{abs} (%)	η_{Cu} (%)	η_{STH} (%)
GaGeS ₃	2.51	0.59	0.69	17.46	42.36	7.39
GaGeSe ₃	1.91	0.46	0.22	37.44	30.26	11.33
GaGeTe ₃	1.11	0.26	−0.38	81.09	19.4	15.73

The band gap of the 2D materials in eqn (12) is calculated at the HSE06 level, which is known to often yield computational values closely matching experimental values.⁴⁰ The solar-energy conversion efficiencies in the water splitting reaction for the studied 2D materials, calculated using formula eqn (9), are given in Table 4.

The calculation results in Table 4 show that the light absorption efficiency (η_{abs}) and charge-carrier utilization (η_{Cu}) of the studied 2D materials have a close relationship with their band gap. Comparatively, an increase in band gap is accompanied by a decrease in light absorption efficiency and an increase in charge-carrier utilization (Table 4). The GaGeS₃ monolayer, featuring the most significant band gap among the studied monolayers (2.51 eV), exhibits the lowest light absorption efficiency of 17.45%. In contrast, the GaGeTe₃ monolayer, with the smallest band gap (1.11 eV), possesses the most significant light absorption efficiency of 81.09% and the most minor charge-carrier utilization of 19.4%. Overall, the calculated STH efficiencies of the GaGeS₃, GaGeSe₃, and GaGeTe₃ monolayers are 7.39%, 11.33%, and 15.73%, respectively. The calculated STH efficiency of the GaGeTe₃ monolayer is the largest among the studied monolayers. However, the band gap of the GaGeTe₃ monolayer is 1.11 eV, which is smaller than the low band gap of traditional photocatalysts.⁶⁰ Therefore, the GaGeTe₃ monolayer is not suitable for application as a photocatalyst in the water-splitting reaction. The STH efficiency of the GaGeSe₃ monolayer, equal to 11.33%, is comparable to those of some previously reported 2D photocatalysts, such as the AgBiP₂Se₆ monolayer (10%),⁷⁶ Ge₂Se₂P₄ monolayer (12.33%),⁷³ heptazine-based frameworks (12%),⁷⁷ and Janus WS₂ monolayer (11.7%).⁵⁶ These results show that the monolayer GaGeSe₃ is a promising candidate as an photocatalyst in the water-splitting reaction.

4 Conclusion

In this study, we have systematically investigated the structural, electrical, transport, and notable optical and photocatalytic properties of GaGeX₃ (X = S, Se, Te) monolayers using DFT calculations. The AIMD simulations highlight the structural and thermodynamic stability of these 2D materials. Notably, the GaGeSe₃ monolayer is revealed to be a semiconductor with a band gap of 1.91 eV. In addition, it exhibits a significant photon absorption coefficient in the visible region, with a maximum value of $1.1 \times 10^5 \text{ cm}^{-1}$. The calculated solar-to-hydrogen conversion efficiency of the GaGeSe₃ monolayer is 11.33%. The GaGeSe₃ monolayer's electronic conductivity has

been calculated to be $790.65 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. These findings suggest that the monolayer GaGeSe₃ could be a promising catalyst for solar water-splitting reactions and could advance the field of electronic devices with high electron mobility.

Conflicts of interest

There are no conflicts of interest to declare.

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