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Large magnetic anisotropy and enhanced Curie temperature in two-dimensional MnTe₂ coupled with β -phase group-VA semiconductor monolayers

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Promoting the Curie temperature (T_C) and tuning the magnetocrystalline anisotropy energy (MAE) have been key issues with two-dimensional (2D) ferromagnetic (FM) materials. Here, the structural and magnetic properties of MnTe₂/X (X = As, Sb and Bi) heterostructures are investigated through first-principles calculations. We reveal that monolayer MnTe₂ weakly interacts with monolayer As or Sb through van der Waals (vdW) forces, but has strong covalent bonds with monolayer Bi, indicated by Bi–Te bond formation. The coupling of MnTe₂ with these β -phase group-VA semiconductor monolayers substantially modulates MAE, with MnTe₂/As showing a shift to in-plane easy magnetization, and MnTe₂/Sb exhibiting a large perpendicular MAE of 4.13 meV per cell. The formation of vdW heterostructures influence on Te spin–orbit coupling matrix elements markedly governs MAE. MnTe₂/Bi also has an in-plane MAE, contributed by both Te and Bi atoms. Additionally, coupling MnTe₂ with X significantly affects magnetic interactions. It is worth noting that the T_C of MnTe₂/Sb reaches 233.2 K, significantly larger than that of pure MnTe₂. A large perpendicular MAE and a heightened T_C makes MnTe₂/Sb desired candidates for next-generation spintronic applications. Our work provides a way to modulate the magnetic properties of 2D FM materials.

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1. Introduction

Ever since ferromagnetism has been observed in atomically thin Cr(Cl/Br/I)₃,^{1–3} Cr₂Ge₂Te₆ (CGT)⁴ and Fe₃GeTe₂ (FGT)^{5,6} nanosheets, magnetism in two-dimensional (2D) van der Waals (vdW) materials has emerged as a focal point of research, which could drive innovation in information storage and spintronics device applications. One of the most notable advantages of 2D magnetic materials compared to bulk materials is their easily modulated magnetic properties. Studies have demonstrated that the magnetic ordering temperature, magnetic anisotropy, coercivity force and magnetization can be tuned using various methods, including the use of an electric field, strain, electrostatic doping, adsorption, ion intercalation, *etc.*^{5,7–18} Additionally, owing to the absence of dangling bonds on the surfaces of 2D materials, it is feasible to stack two types of 2D materials to form vdW heterostructures.^{19–22}

It is widely recognized that constructing vdW heterostructure is an effective way to tune the magnetic properties and

raise Curie temperature (T_C) of 2D magnets,^{23–34} either through the proximity effect between ferromagnetic (FM) and antiferromagnetic (AFM) materials²³ or by interfacial exchange coupling between FM and nonmagnetic materials.²⁴ It was reported in the experiment that the T_C of FGT/FePS₃ and CGT/NiO heterostructures are approximately 150 K and 120 K, respectively.^{23,33} Theoretical predictions indicate that both the T_C and perpendicular magnetic anisotropy of the CGT/PtSe₂ heterostructure are considerably enhanced compared to pure CGT, owing primarily to the considerable influence of strain at the interface.³⁴ Moreover, the introduction of extra spin superexchange pathways in CrI₃/MoTe₂ and PtBr₃/WSe₂ heterostructures has resulted in a multiple-fold increase in the T_C of their FM parent material.^{24,25} VdW heterostructures significantly broaden the application of 2D magnets and are anticipated to serve as fundamental components in the development of next-generation spintronic devices.

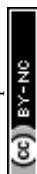
Layered transition-metal ditellurides have garnered significant attention due to their unique properties,^{35–42} including superconductivity,³⁵ charge density waves,³⁶ extremely large unsaturated magnetoresistance,³⁶ and the presence of Dirac and Weyl semi-metallic characteristics,^{37–39} particularly in relation to magnetism.^{40–42} First-principles calculations have revealed that monolayer MnTe₂ demonstrates FM ground states with adjustable band gaps, large magnetic moments, and high perpendicular magnetic anisotropy, making it a promising

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contender for the development of next-generation spintronic devices.^{42–45} However, the knowledge of the magnetism in MnTe₂-based heterostructure materials is yet to be revealed. On another note, 2D group-VA layered materials (*i.e.*, P, As, Sb, Bi) have shown a strong research interest and hold vast application prospects due to their semiconductor and stable environmental properties, positioning them as powerful contenders for future nano-devices.^{26,46} Monolayers of group-VA elements exhibit various allotropes, with the highly buckled graphene-like hexagonal crystal structure (β phase) being the most stable.⁴⁶ Theoretical predictions have suggested the possibility of first-to-second-order topological phase transitions in Bi monolayers grown on the (111) surface of EuO, induced by the proximity effect.⁴⁷ Moreover, when a heavy elemental (*i.e.*, As, Sb or Bi) atomic layer is placed onto monolayer CrI₃, it can result in the opening of a significant bulk energy gap, realization of the quantum anomalous Hall effect (QAHE), spin reorientation, and promotion of the Curie temperature.^{26,48} Motivated by these insights, we are intrigued by the potential influence of coupling the 2D MnTe₂ with the β -phase group-VA semiconductors (*i.e.*, As, Sb and Bi) on the magnetic properties of MnTe₂.

In this paper, we study the structure and the magnetic properties of the MnTe₂/X (X = As, Sb and Bi) heterostructures. Monolayer MnTe₂ weakly bonds with monolayer As or Sb by vdW interaction but strongly with monolayer Bi *via* Bi–Te covalent bonds. Coupling between the MnTe₂ and β -phase group-VA semiconductor monolayers notably alters the magnetic anisotropy energy (MAE) and affects magnetic interactions of MnTe₂. The MnTe₂/Sb heterostructure is noteworthy, showcasing a large perpendicular MAE of 4.13 meV, an enhanced FM coupling and a heightened Curie temperature of 233.2 K. Our finds may promote the development of novel vdW magnetic heterostructures between 2D β -phase group-VA semiconductor and magnetic materials.

II. Computational methods

Our first-principles calculations employ density functional theory (DFT)⁴⁹ within the Vienna *ab initio* simulation package (VASP). Ion-electron interaction is described using the projector augmented wave (PAW) method,⁵⁰ while the exchange–correlation energy is handled by the Perdew–Burke–Ernzerhof (PBE) form of the generalized gradient approximation (GGA).⁵¹ The on-site Coulomb interactions (U) for Mn-d orbitals are considered, with a value of 3.9 eV.^{44,52,53} We have also evaluated a range of U values from 2 to 5 eV and determined that our primary conclusions remain qualitatively unchanged. The energy cutoff for plane waves is set at 500 eV, with convergence criteria ensuring that the energy difference between electronic steps and the force on each atom are less than 10^{-6} eV and 10^{-4} eV Å⁻¹, respectively. The first Brillouin zone for MnTe₂/As(Sb) and MnTe₂/Bi heterostructures is sampled using Γ -centered $18 \times 18 \times 1$ and $9 \times 9 \times 1$ Monkhorst–Pack grids, respectively. Gamma-centered k -point meshes of $15 \times 15 \times 1$ are used to calculate the energy difference between FM and AFM states in a (2×2) supercell. The spin–orbit coupling (SOC) effect is considered in non-collinear calculations to obtain the magnetocrystalline

anisotropy energy (MAE). The energy cutoff for MAE calculations is set at 600 eV with a corresponding energy criterion of 10^{-7} eV. VdW correction (D3) is incorporated in all calculations to account for interactions between layers. Additionally, to prevent mirror interactions vertically, a vacuum layer of 20 Å is introduced along the z -direction. The magnetic transition temperature is calculated *via* Monte Carlo simulations, in which a (80×80) supercell is employed. The loops and the warm time are respectively set to 4×10^9 and 10^8 .

III. Results

To begin, we performed individual lattice structure optimization for each constituent material. First-principles calculations show that monolayer MnTe₂ presents an octahedral T-phase characterized by the $P\bar{3}m1$ space group, as depicted in Fig. 1(a). Among the H-, T-, and T'-phases, the total energy calculations indicate that the T-phase possesses the lowest energy. In the side view, the Mn atom layer is positioned between two Te atom layers. In the top view, each Mn atom is bonded to six Te atoms, forming an octahedral configuration. The optimized lattice constant a_0 of monolayer MnTe₂ is 3.87 Å, as listed in Table 1. Monolayers of group-VA elements X (X = As, Sb and Bi) display a graphene-like hexagonal crystal structure known as the β phase, which also adopts the $P\bar{3}m1$ space group. Notably, monolayer Bi exhibits significant buckling in contrast to the other two elements. The optimized lattice constant a_0 of monolayer As, Sb and Bi are 3.63, 4.10 and 4.31 Å, respectively.

The MnTe₂/X (X = As, Sb and Bi) heterostructure is constructed by vertically stacking the MnTe₂ and X monolayers. To minimize the artificial internal strain caused by lattice mismatch, the MnTe₂/As and MnTe₂/Sb heterostructures are used a unit cell of monolayer As and Sb to match the primary cell of monolayer MnTe₂, respectively, while the MnTe₂/Bi heterostructure is constructed by placing a (2×2) supercell of monolayer MnTe₂ on a $(\sqrt{3} \times \sqrt{3})$ supercell of monolayer Bi, as shown in Fig. 1(b)–(d). The calculation of lattice misfit is

accomplished by the formula $\varepsilon = \frac{|\alpha_1 - \alpha_2|}{\alpha_1 + \alpha_2}$, wherein α_1 and α_2

denote the lattice parameters of the two distinct monolayers subsequent to the process of relaxation. In the constructed MnTe₂/As, MnTe₂/Sb, and MnTe₂/Bi heterostructures, the lattice mismatch between monolayer As, Sb, and Bi and monolayer MnTe₂ is approximately 3.20%, 2.88%, and 1.92% respectively. The optimized structural data for the MnTe₂/X heterostructures are presented in Table 1. The optimized interlayer distances (d_0) for the MnTe₂/As and MnTe₂/Sb heterostructures are 3.76 Å and 3.61 Å, respectively, surpassing the sum of atomic radii at the interface, indicating the presence of vdW interaction between the two monolayers. The vdW heterostructure devices benefiting from the weak cleavage energy can be fabricated using an exfoliation-restacking technique in experiment. For MnTe₂/As, the As atoms are almost completely aligned with the Te atoms from the top view [see Fig. 1(b)]. In the case of MnTe₂/Sb, half of the Sb atoms align with Mn atoms, while the other half align with the bottom row of Te atoms in MnTe₂ [see Fig. 1(c)]. In contrast, the d_0 for the MnTe₂/Bi



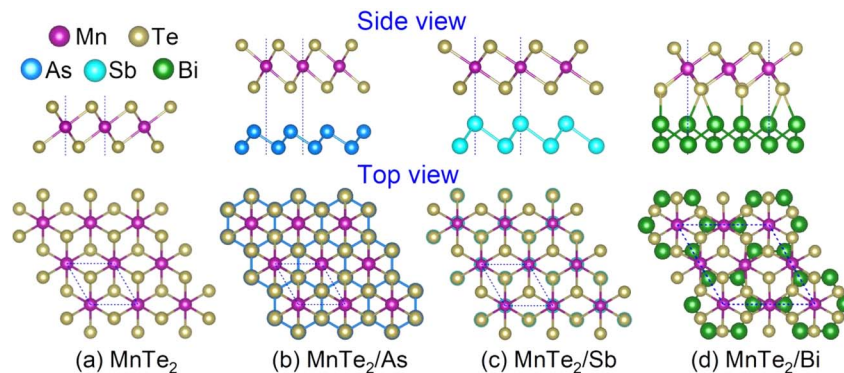


Fig. 1 Crystal structures of the (a) pure MnTe_2 monolayer, (b) MnTe_2/As , (c) MnTe_2/Sb and (d) MnTe_2/Bi heterostructures. The unit cell is denoted with dashed blue lines.

heterostructure is only about of 3.21 Å, which is less than the sum of atomic radii at the interface, suggesting a covalent bond formation between the Te and Bi atoms. To further confirm this, the Electron Localization Functions (ELF) are plotted, as shown in Fig. 2(a). For MnTe_2/Bi , the ELF reveals significant electron localization between Te and Bi atoms, a typical indicator of covalent bonding. On the contrary, MnTe_2/As and MnTe_2/Sb display low ELF values, indicative of weaker electron localization, consistent with vdW forces. We also take MnTe_2/Sb as an example and consider three different vertical stacking configurations. The energy differences between different stackings are minor, indicating their similar stability. In this context, this paper has selected the configuration with the lowest energy.

Comparing energies for four spin arrangements, one FM and three AFM arrangements (zigzag AFM (z-AFM), stripe AFM (s-AFM), and 120° noncollinear AFM (n-AFM)), as illustrated in Fig. 2(b). Our calculations reveal that the FM order exhibits enhanced energetic stability compared to the AFM configurations, and the following results are based on the FM MnTe_2/X heterostructure. The binding energy E_b of the constructed heterostructure is calculated as $E_b = E_{\text{MnTe}_2} + E_X - E_{\text{total}}$, where E_{MnTe_2} , E_X , and E_{total} are the total energies of the pure monolayer MnTe_2 , the monolayer of group-VA element X, and the MnTe_2/X heterostructure, respectively. The positive binding energy values signify that all the heterostructures exhibits favorable stability. Specifically, the binding energies computed are 0.18 eV, 0.41 eV, and 1.58 eV for MnTe_2/As , MnTe_2/Sb and MnTe_2/Bi , respectively (see Table 1), demonstrating that

monolayer MnTe_2 can maintain stability when interfaced with monolayer X.

Considering that MnTe_2/As and MnTe_2/Sb are vdW heterostructures, bound by weak vdW forces, in contrast to MnTe_2/Bi that is bonded through stronger covalent interactions, we will now discuss them separately. Compared to monolayer MnTe_2 , the magnetic moments of the MnTe_2/As and MnTe_2/Sb heterostructures are little larger, being $3.33 \mu_B$ and $3.35 \mu_B$, respectively, as listed in Table 1. Fig. 3 illustrates the total density of states (TDOS) and the partial densities of states (PDOS) for each atomic orbital in monolayer MnTe_2 and the MnTe_2/X (X = As or Sb) heterostructures. The results indicate that the spin-polarized bands around the Fermi level E_F primarily originate from the Mn-d local moments, whereas the contributions from the X-p and Te-p orbitals are significantly minor, meaning that the total spin moment (S_{tot}) is primarily contributed by the Mn atom (S_{Mn}). Examination of the PDOS reveals that the Mn-d states are hybridized with Te-p states, indicating some covalent character of the Mn-Te bond. If the transition metal (Mn atom in our case) is bonded to other ligands (Te atoms in our case), the five-degenerate d atomic orbitals will split in energy. Monolayer MnTe_2 and the MnTe_2/X (X = As or Sb) heterostructures all belong to the C_{3v} point group. According to the ligand field theory, the Mn-d atomic orbitals are split by the crystal field into three sets: a single degenerate state (d_{z^2}), and two twofold degenerate states ($d_{x^2-y^2}$, d_{xy}) and (d_{yz} , d_{xz}). The PDOS of Mn atom shows that the Mn-d atomic orbitals are strongly exchange splitting. The five-degenerate Mn-d atomic orbitals with different orientations are delocalized owing to

Table 1 Calculated lattice constants (a), interlayer distances (d), binding energy (E_b), total spin moment (S_{tot}), magnetic moment of Mn atom (S_{Mn}), atom-resolved MAE of Te atom, total MAE per cell, exchange energies (E_{ex}), exchange constant (J) and Curie temperature (T_C)

System	$a/\text{\AA}$	$d/\text{\AA}$	E_b/eV	S/μ_B		MAE/meV		E_{ex}/meV	J/meV	T_C/K
				S_{Mn}	S_{tot}	Te	Total			
MnTe_2	3.87	—	—	4.19	3.27	1.28	1.41	146.6	2.09	124.6
MnTe_2/As	3.79	3.76	0.18	4.12	3.33	−1.72	−1.76	49.8	0.73	40.2
MnTe_2/Sb	4.03	3.61	0.41	4.21	3.35	4.16	4.23	278.6	3.93	233.2
MnTe_2/Bi	7.72	—	1.58	4.20	13.89	−1.81	−12.72	160.6	2.28	136.7



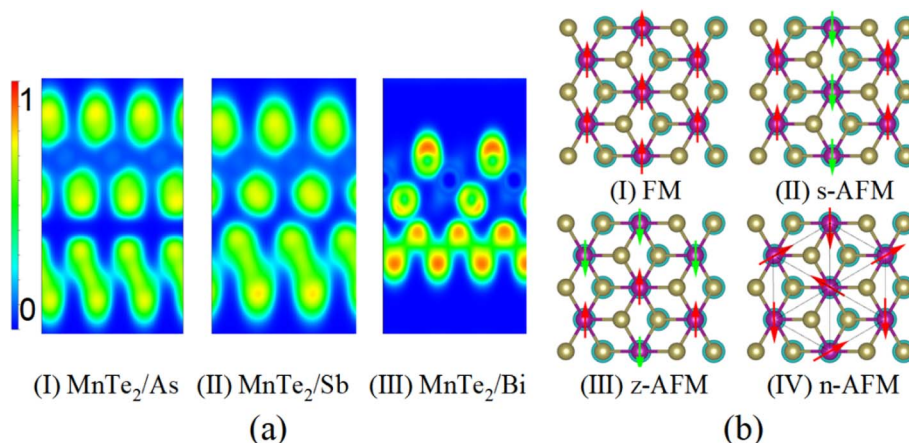


Fig. 2 (a) The Electron Localization Function (ELF) projection on the (110) plane of the MnTe_2/X ($\text{X} = \text{As}, \text{Sb}$ and Bi) heterostructures with the 0 and 1 being extremely low and highly localized regions, respectively. (b) Schematic diagram of ferromagnetic (FM) and three antiferromagnetic (AFM) configurations on honeycomb lattice: zigzag AFM (z-AFM), stripe AFM (s-AFM), and 120° noncollinear AFM (n-AFM).

overlap and hybridization between orbitals. According to Hund's rule and the Pauli exclusion principle, the spin-up (majority-spin) orbitals are almost totally occupied by the five unpaired Mn^{5+} d electrons, while the spin-down (minority-spin) states are partially occupied, causing S_{Mn} little smaller than the magnetic moment of an isolated Mn atom (the calculated value is $5 \mu_{\text{B}}$). The S_{Mn} in MnTe_2 and MnTe_2/X exceeding S_{tot} represent the local magnetic moment of an individual Mn atom within the Wigner-Seitz radius. For the chalcogen Te atom, the three p atomic orbitals are split into one non-degenerate (p_z) state and one double-degenerate (p_x, p_y) state under the influence of the crystal field. The sum of the spin-down occupied states slightly exceeds that of the spin-up occupied states, leading to a minor antiferromagnetic moment contribution from the Te atom. In the case of the As atom, a near-equal occupancy of spin-down and spin-up states is observed, which does not contribute to the S_{tot} of the MnTe_2/As heterostructure. In MnTe_2/Sb , Sb atom presents a higher occupancy in spin-down states compared to spin-up states, thus exhibiting a negative magnetic moment akin to that of Te. However, the consequent magnetic moment of the Sb atom is significantly lower than that of the Te atom, amounting to merely one-fourth of the magnetic moment of the later.

The MAE is calculated using GGA+U+SOC method. Self-consistent calculations are performed to obtain the total energies for in-plane and out-of-plane magnetization directions, respectively, and MAE is evaluated by the difference between the total energies for the two magnetization directions, defined as $\text{MAE} = E_{[100]} - E_{[001]}$, where $E_{[100]}$ and $E_{[001]}$ are the total energies when magnetization is in plane and normal to the plane, respectively. The negative MAE denotes the in-plane easy magnetization [100] axis and the positive one indicates their easily magnetized direction is the [001] axis. Table 1 shows the relevant data of monolayer MnTe_2 , the MnTe_2/X ($\text{X} = \text{As}$ or Sb) heterostructures, respectively. Interestingly, coupling monolayer MnTe_2 with a monolayer of As reorients the easy-magnetization axis from out-of-plane in monolayer MnTe_2 to

in-plane in MnTe_2/As . While coupling with a monolayer of Sb greatly enhances the perpendicular MAE, from 1.41 meV per cell in monolayer MnTe_2 to 4.18 meV per cell in MnTe_2/Sb . Crucially, as shown in Table 1, the MAE of monolayer MnTe_2 and the MnTe_2/X heterostructures mainly comes from Te atoms. Quantitatively, when monolayer MnTe_2 is coupled with monolayer As, the contribution of the Te atom to the MAE shifts from a positive 1.28 meV to a negative -1.72 meV, the negative contribution of the Mn atom to the MAE increases a little from -0.18 meV to -0.26 meV, and the contribution of the As atom to the MAE is negligible. When monolayer MnTe_2 is coupled with monolayer Sb, the positive contribution of the Te atom to the MAE greatly increases, reaching up to 4.16 meV, the contribution of the Mn atom to the MAE shifts from negative to a positive 0.32 meV, and the contribution of the Sb atom to the MAE is comparable to that of the Mn atom, at 0.47 meV. To investigate whether the reorientation of the easy-magnetization direction and the increased perpendicular MAE are caused by the strain induced by the monolayers of As and Sb, respectively, we further calculate the MAEs of the stressed MnTe_2 monolayers with the same lattice constants as those in MnTe_2/As and MnTe_2/Sb , yielding MAEs of -1.66 meV per cell and 2.71 meV per cell, respectively. This suggests that the MAE observed in MnTe_2/As mainly originates from strain exerted on the MnTe_2 layer. Conversely, in MnTe_2/Sb , the total MAE cannot be exclusively ascribed to the strain effects within the MnTe_2 layer, a contributing factor also stems from the Sb element.

In the single-ion model, MAE results from the combined effects of the SOC of magnetic atoms and the crystal field splitting of their orbital states. Notably, previous research indicates that the SOC of heavy elements also plays a crucial role in determining MAE, as observed in materials like CrI_3 and InCrTe_3 . To explore this further, we calculated the SOC contributions to MAE from each element. Fig. 4 presents the orbital-projected contributions to MAE from Mn, Te, and X atoms in monolayer MnTe_2 and the MnTe_2/X ($\text{X} = \text{As}$ or Sb) heterostructures. It is evident that the MAE primarily comes from the



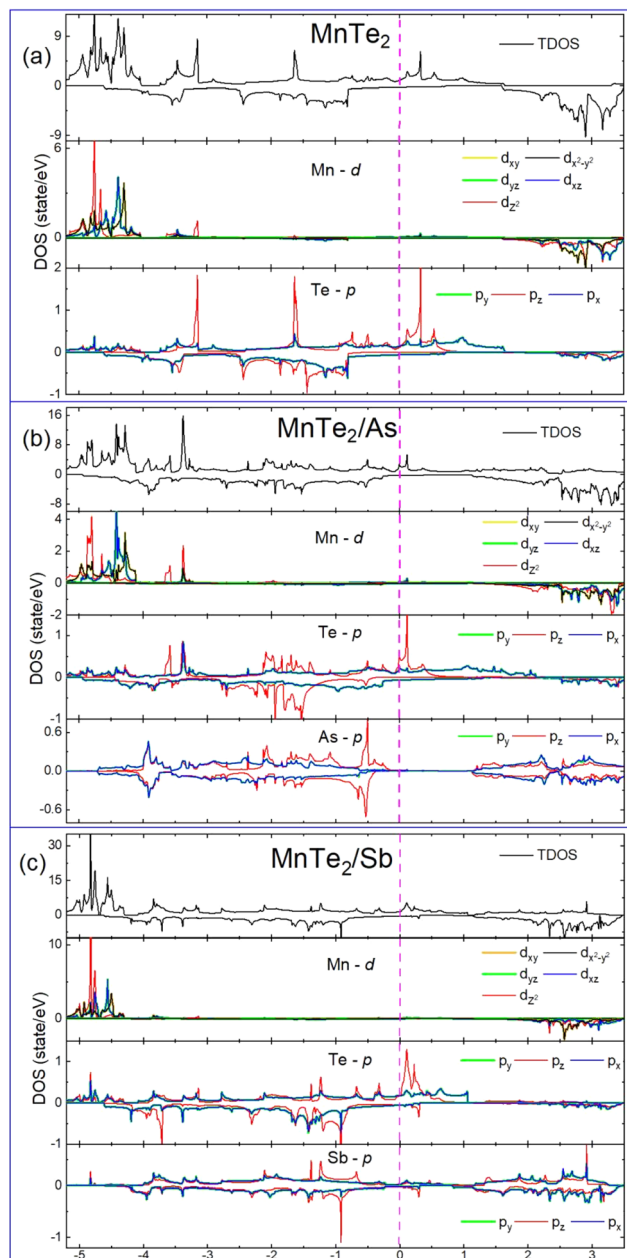


Fig. 3 Total DOS and corresponding PDOS of the (a) pure MnTe_2 monolayer, (b) MnTe_2/As and (c) MnTe_2/Sb heterostructures. The vertical dashed line represents the Fermi energy level which is set as zero.

contribution of the Te atom, despite its magnetic moment being much smaller than that of the Mn atom. In monolayer MnTe_2 , the positive contribution to the MAE arises from SOC through the Te atom's (p_z , p_y) orbitals, which outweighs the negative contributions from SOC between the (p_x , p_y), resulting in a net positive MAE [Fig. 4(a)]. When coupling monolayer MnTe_2 with a monolayer of As, the positive contribution from SOC through the Te atom's (p_z , p_y) orbitals significantly decreases, while the negative contribution from SOC between the (p_x , p_y) markedly increases [Fig. 4(b)]. Consequently, the easy magnetization direction changes from out-of-plane in

monolayer MnTe_2 to in-plane in MnTe_2/As . When coupling monolayer MnTe_2 with a monolayer of Sb, the contribution from SOC through the Te atom's (p_x , p_y) orbitals shifts from negative to positive, and SOC through the (p_z , p_y) also provides positive contributions [Fig. 4(c)]. As a result, MnTe_2/Sb exhibits a larger perpendicular MAE than monolayer MnTe_2 . Examining the contributions from the orbitals of the Mn and X atoms reveals nuanced impacts on the total MAE. The above results show that the formation of the heterostructure predominantly affects the SOC matrix element difference of Te atoms, which in turn regulates the magnetic anisotropy of the heterostructure.

By comparing the PDOS of monolayer MnTe_2 and the MnTe_2/X ($\text{X} = \text{As}$ or Sb) heterostructures in Fig. 3, we can qualitatively knowledge the reasons for the changes in the MAE contribution from Te atoms. Within the energy range of -1 to 0 eV around the Fermi level, the Te PDOS shows distinct characteristics. In MnTe_2/As , the spin-down (p_x , p_y) states of the Te atom are closer to the Fermi level compared to those in monolayer MnTe_2 , wherein these states are slightly further away. In contrast, for MnTe_2/Sb , the Te PDOS almost only displays the spin-up (p_x , p_y) states in the same energy span. Consequently, the contribution of the Te atom's (p_x , p_y) orbitals to the MAE is smaller in monolayer MnTe_2 than that in MnTe_2/As , shifting from a negative value in monolayer MnTe_2 to a positive value in MnTe_2/Sb . Further examining the p_z states of Te, both monolayer MnTe_2 and the MnTe_2/Sb heterostructure exhibit significant spin-down p_z states within the -1 to 0 eV range around the Fermi level, while the spin-down p_z states are absent in MnTe_2/As . Therefore, the MAE contribution from the Te atom's (p_z , p_y) orbitals in MnTe_2/As is further smaller than that in MnTe_2 and MnTe_2/Sb .

Next, we examine the magnetic properties of the MnTe_2/Bi heterostructure. Given that the SOC of heavy Bi atoms may significantly influence the MAE and exchange coupling, we conduct a detailed magnetic analysis. The calculated magnetic moment of MnTe_2/Bi is $13.87 \mu_B$, which is a little larger than that of a (2×2) MnTe_2 supercell. The TDOS and PDOS of MnTe_2/Bi [see Fig. 5(a)] show that the magnetic moment is mainly contributed by the Mn atoms. Specifically, each Mn atom contributes an average of about $4.20 \mu_B$, while each Te and Bi atom contributes an average magnetic moment of $-0.27 \mu_B$ and $-0.10 \mu_B$, respectively. The magnetic moments of the Te and Bi atoms changes oppositely to the Mn atoms, suggesting antiferromagnetic coupling between them. Examination of the PDOS reveals an evident hybridization between the Te-p and Bi-p states, indicating some covalent-like component of the Bi-Te bond, further suggesting that the layers of MnTe_2 and Bi are coupled through covalent bonds.

Fig. 5(b) presents the orbital-projected contributions to MAE from Mn, Te, and Bi atoms in MnTe_2/Bi . It is evident that the MAE primarily comes from the contribution of the heavy Te and Bi elements. Specifically, each Mn, Te, and Bi atom contribute -0.22 meV, -1.81 meV, and -1.39 meV to the negative MAE, respectively, resulting in a total MAE of -12.72 meV for MnTe_2/Bi . The Mn MAE in MnTe_2/Bi are almost equal to that in monolayer MnTe_2 , while the Te MAE shifts from positive to negative. This may be attributed to the formation of the Bi-Te covalent bonds when coupling monolayer MnTe_2 with



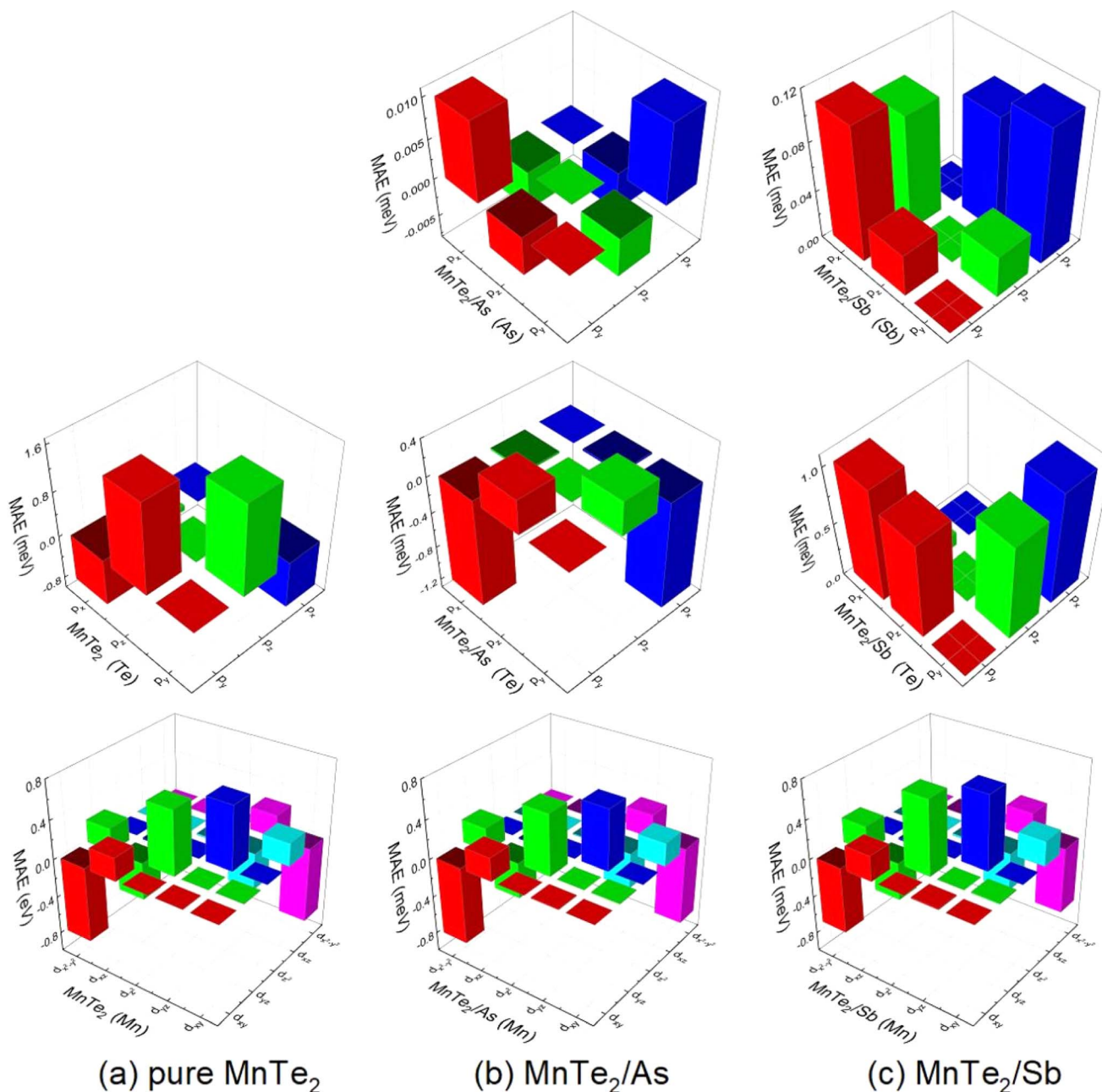


Fig. 4 Orbital-projected contribution to MAE from the SOC interaction for As and Sb (the upper row), Te (the middle row) and Mn (the bottom row) atoms in the pure MnTe_2 monolayer, the MnTe_2/As and MnTe_2/Sb heterostructures.

a monolayer of Bi, as shown in Fig. 1(d). Comparing Fig. 3(a) with Fig. 5(a) reveals that the PDOS of the Mn atoms in the pure MnTe_2 monolayer and the MnTe_2/Bi heterostructure remain largely unaffected, while the PDOS of the Te atoms exhibits significant changes. For example, within the -1 to 0 eV range near the Fermi level, the Te atoms in MnTe_2/Bi show a near-equal occupancy of the spin-down and spin-up (p_x , p_y) states, in contrast to the pure MnTe_2 monolayer. Additionally, the spin-down p_z states are nearly absent in MnTe_2/Bi , unlike in the pristine monolayer. As a result of forming the MnTe_2/Bi heterostructure, the orbital contribution to the MAE from the Mn remains almost unchanged, whereas there is a substantial

variation in the orbital contributions from the Te atoms to the MAE. Moreover, Fig. 5(b) shows that the Te MAE comes from the (p_z , p_y) orbitals, and the Bi MAE mainly arises from the (p_x , p_y) and (p_z , p_y) orbitals.

To elucidate the charge transfer between MnTe_2 and the substrates, we employed Bader charge analysis which provides insights into the bonding interaction between the two. Specifically, on average, each As atom in the MnTe_2/As heterostructure transfers a modest 0.00562 e to the MnTe_2 layer. The MnTe_2/Sb heterostructure is characterized by an average transfer of 0.03230 e per Sb atom, indicating a more substantial charge movement. In the MnTe_2/Bi heterostructure, each Bi atom



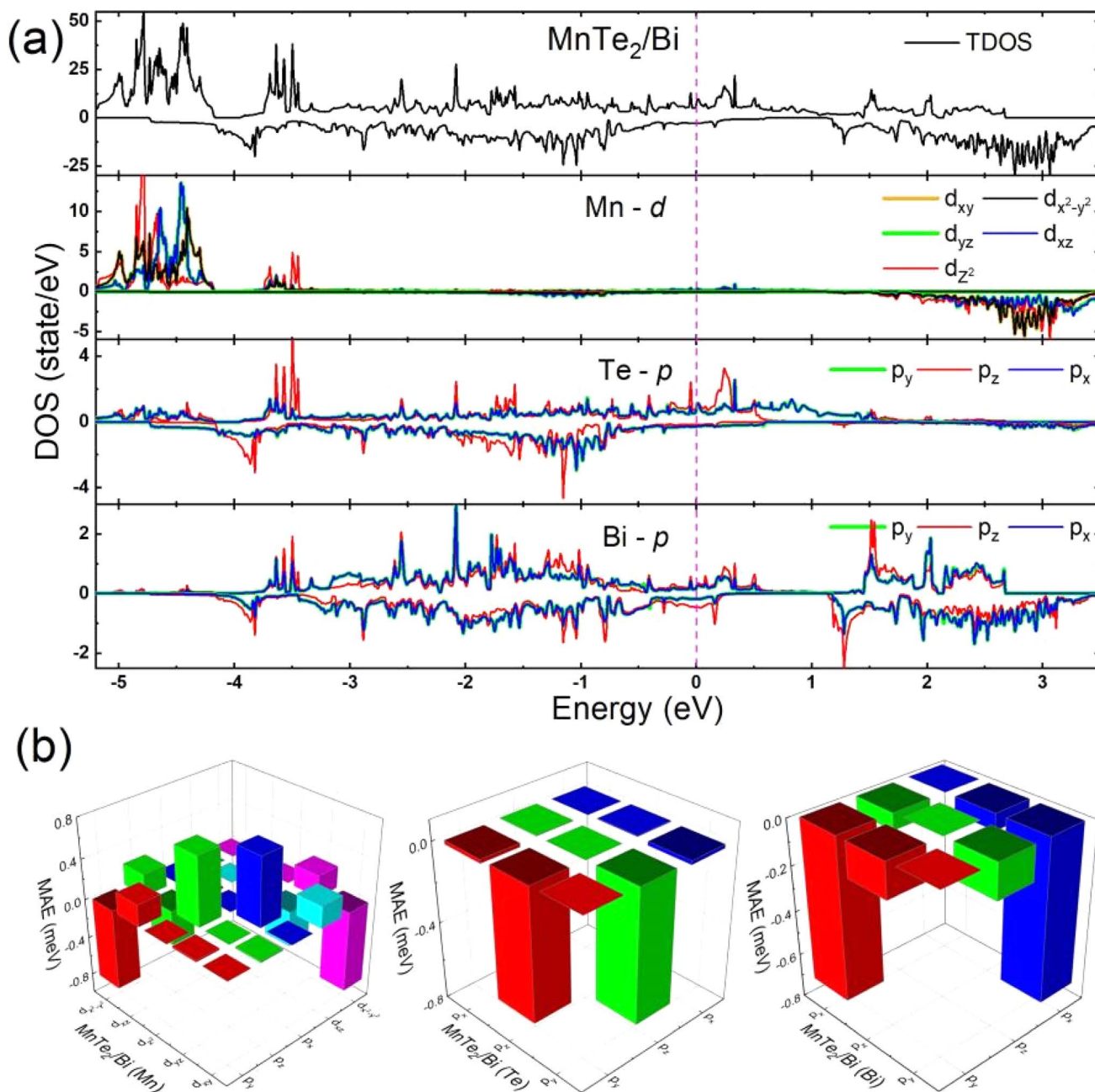


Fig. 5 (a) The TDOS and corresponding PDOS of the MnTe₂/Bi heterostructure. The vertical dashed line represents the Fermi energy level which is set as zero. (b) Orbital-projected contribution to MAE from the SOC interaction for Mn, Te and Bi atoms in the MnTe₂/Bi heterostructure.

contributes an average of 0.06956 e. This considerable charge transfer underscores the covalent Bi-Te bond formation.

The exchange interaction and the Curie temperature of the MnTe₂/X (X = As, Sb and Bi) heterostructures are further investigated. Based on the exchange energy, defined as the difference between the FM and AFM states in a (2 × 2) supercell with four Mn atoms, *i.e.*, $E_{\text{ex}} = E_{\text{AFM}} - E_{\text{FM}}$. As shown in Table 1, the results demonstrate that MnTe₂/Sb has an E_{ex} of 278.6 meV, which is significantly larger than the E_{ex} calculated for monolayer MnTe₂ at 146.6 meV, indicating that coupling monolayer MnTe₂ with a Sb monolayer not only enhances the

perpendicular magnetic anisotropy but also strengthens the FM coupling. The exchange energies (E_{ex}) of MnTe₂/As and MnTe₂/Bi are approximately 49.8 meV and 160.6 meV, respectively.

Using the Heisenberg model, perform Monte Carlo simulations to determine the Curie temperature and magnetic phase diagram of monolayer MnTe₂ and the MnTe₂/X heterostructures. Consider the classical spin Hamiltonian as^{25,54,55}

$$H = -\sum_{i<j} J_{ij} \mathbf{S}_i \times \mathbf{S}_j - \sum_i A (\mathbf{S}_i^z)^2. \quad (1)$$



where J_{ij} is the exchange coupling constant. S_i refers to the spin operator on i -th site, originating from the Mn magnetic moment. A is the single single-ion anisotropy parameter by means of $A = [E_{(100)} - E_{(001)}]/|S|^2$, and S_i^z is the spin component of i -th atom along the z -direction. Here, we calculate the J values of the nearest-neighbor (NN) Mn atoms. The exchange interactions concerning the Te and X atoms are considered negligible due to their magnetic moments being significantly smaller than that of the Mn atoms. Using the same procedure that only considering the NN interaction, the estimated T_C of the CrX_3 ($X = \text{Cl, Br, and I}$) monolayers are 11 K, 22 K and 43 K in sequence,⁵⁶ which agree with the experimental measurement of 17 K, 27 K and 45 K.^{16,57} The J values can be given by $E_{\text{ex}} = E_{\text{AFM}} - E_{\text{FM}} = 16JS_iS_j$, where $E_{\text{FM}} = 12JS_iS_j$, $E_{\text{AFM}} = -4JS_iS_j$. The estimated exchange parameters (J) and the magnetic transition temperatures (T_C) are shown in Table 1 and Fig. 6, respectively. The MnTe_2/Sb heterostructure has the largest T_C of 233.2 K. We have also considered three different magnetic configurations (FM, z -AFM, and s -AFM, as shown in Fig. 2) to calculate the exchange coupling constants J' for the next-nearest neighbor Mn atoms. The results reveal that J' is much smaller than J . For example, in the case of MnTe_2/Sb , the J and J' values are 4.06 meV and 0.32 meV, respectively. The magnetic behavior is predominantly controlled by the NN spin exchange interactions, with next-nearest neighbor effects playing a comparatively lesser role.

Compared with monolayer MnTe_2 , why do the magnetic coupling and the Curie temperature exhibit an increase in MnTe_2/Sb , whereas they experience a reduction in MnTe_2/As ? On the one hand, the variation can be attributed to strain effects. In MnTe_2/As , the MnTe_2 layer experiences compressive strain. Conversely, in MnTe_2/Sb , the MnTe_2 layer undergoes tensile strain. The strain-induced switch between FM and AFM exchange coupling can be qualitatively explained by the expression:^{44,54} $J = J_{\text{FM}} + J_{\text{AFM}} = J_{\text{FM}} - 2t^2/U$, which is widely used to describe the balance between FM and AFM exchange interactions. The exchange constant (J) comprises both FM and AFM components. The FM term (J_{FM}) signifies the direct exchange interaction and strengthens with the increase of exchange integral, which correlates with an augmentation in the overlap density. The AFM term (J_{AFM}) is inversely related to the on-site Coulomb repulsion (U) and is proportional to the square of the hopping integral (t). Increasing t typically associated with decreasing inter-atomic distances, reinforces the AFM exchange. As a crude rule, the AFM exchange coupling is more likely at small inter-atomic distances, while the FM coupling is favorable at intermediate distances. At very large inter-atomic distances, magnetic order tends to be absent. With this understanding, the compressive strain imposed on the MnTe_2 layer in MnTe_2/As shortens the inter-atomic distance between Mn atoms, enhancing the AFM coupling and thus lowering the overall magnetic exchange interaction (J), leading to a decreased

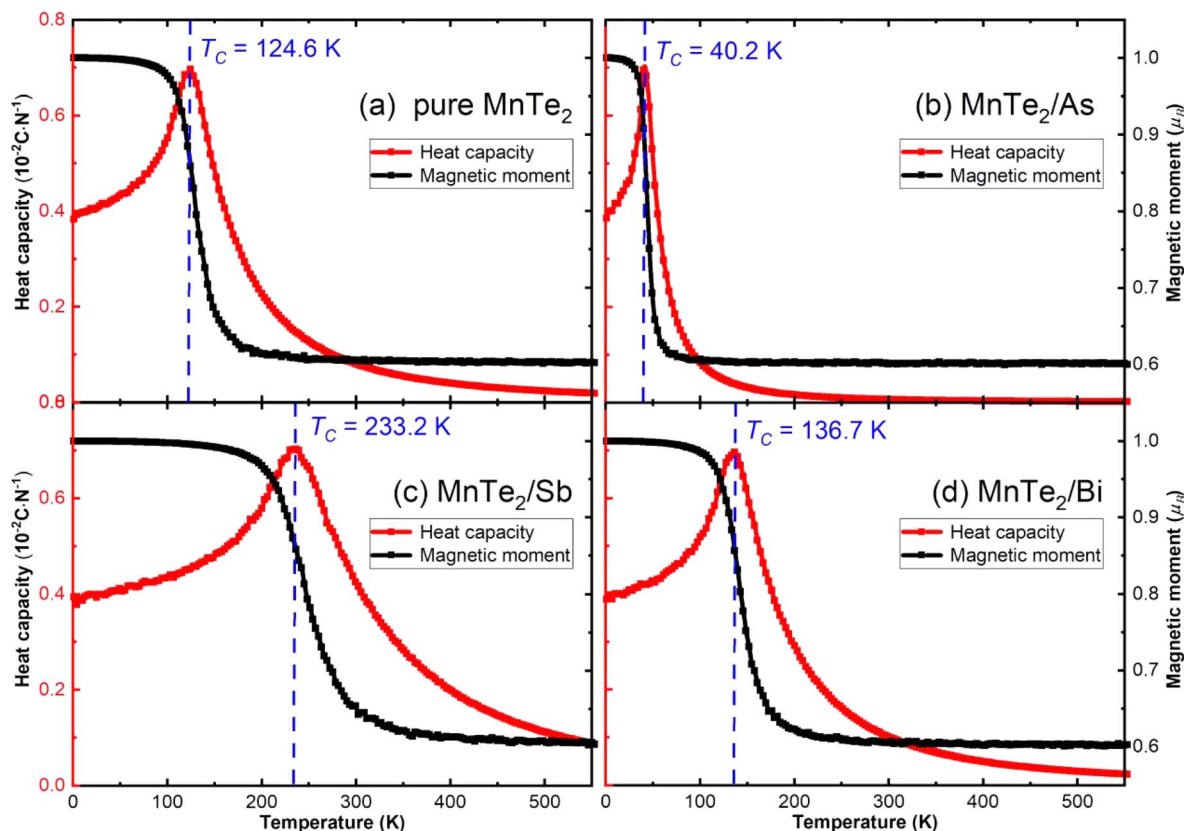


Fig. 6 Magnetic moment and specific heat capacity as a function of temperature for (a) pure MnTe_2 , (b) MnTe_2/As , (c) MnTe_2/Sb and (d) MnTe_2/Bi via Monte Carlo simulations.



T_C . In contrast, the MnTe_2 layer in MnTe_2/Sb subjected to tensile strain exhibit an increased Mn–Mn distance, favoring FM interactions due to more significant overlap of electronic orbitals at intermediate distances. It strengthens the direct exchange mechanism, leading to stronger magnetic coupling and a raised T_C . On the other hand, the interfacial coupling and the magnetic interaction pathways are crucially important. For MnTe_2/As , As atoms do not significantly contribute to magnetic interactions because they exhibit negligible magnetic moments, suggesting weak coupling with the Mn atoms, then they won't have a substantial impact on T_C . In contrast, in MnTe_2/Sb , the magnetic moment of the Sb atoms cannot be ignored. The exchange interaction exists not only between Te and Mn atoms but also between Sb and Mn atoms, indicating the existence of additional super-exchange pathways, which can further enhance the magnetic coupling and increase T_C . Thirdly, the impact of the SOC effect is an important consideration, as it can influence MAE, which in turn affects the stability of the magnetic moment orientations. Although MAE is not the determining factor for T_C , an increase in MAE could contribute to the thermal stability of the magnetization. It is essential to underline that these explanations are simplified models that capture some of the primary physical mechanisms involved. To fully understand these competing mechanisms, detailed computational modeling or experimental studies are necessary.

IV. Conclusions

In summary, we have investigated the structural and magnetic properties of MnTe_2/X ($\text{X} = \text{As}, \text{Sb}, \text{and Bi}$) heterostructures using first-principles calculations. Structural optimization reveals that monolayer MnTe_2 forms weak van der Waals interactions with the monolayer of As or Sb. In contrast, interaction with a Bi monolayer leans towards the creation of heterostructures with stronger covalent interactions, marked by the formation of Bi–Te covalent bonds. Notably, joining monolayer MnTe_2 with a monolayer of As, Sb, or Bi significantly tunes the MAE. Coupling with monolayer As reorients the easy-magnetization axis from out-of-plane in MnTe_2 to in-plane in MnTe_2/As , while coupling with monolayer Sb obtain a large perpendicular MAE, reaching as high as 4.13 meV per cell in MnTe_2/Sb . The configuration of the vdW heterostructures predominantly revises the SOC matrix element differential of the Te atoms, which in turn dictates the magnetic anisotropy. For MnTe_2/Bi , we also observed an in-plane MAE, which is significantly contributed by both Te and Bi atoms. This indicates the considerable role played by heavy element in steering magnetic anisotropy through SOC. Moreover, the coupling of the MnTe_2 and X monolayers notably impacts the magnetic interactions, attributable to strain in the MnTe_2 layer within the heterostructure and the magnetic proximity effects between the layers. The magnetic exchange energy and Curie temperature of MnTe_2/As are both diminished relative to monolayer MnTe_2 . In contrast, MnTe_2/Sb displays a significant enhanced FM coupling and an increased Curie temperature. Our studies provide a deep insight into the magnetic properties of $\text{MnTe}_2/\text{Group VA}$ semiconductor heterostructures.

Data availability

All relevant data are within the paper.

Conflicts of interest

The authors declare no competing financial interest.

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