

Cite this: *J. Mater. Chem. C*,
2024, 12, 4682

Novel valleytronic and piezoelectric properties coexisting in Janus MoAZ₃H (A = Si, or Ge; Z = N, P, or As) monolayers†

Xiaolin Cai,^a Guoxing Chen,^a Rui Li,^a Zhixiang Pan^a and Yu Jia^{b,c}

In this paper, for the newly proposed two-dimensional (2D) Janus MoAZ₃H (A = Si, or Ge; Z = N, P, or As) monolayer (ML) materials, we theoretically explore the valleytronic and piezoelectric properties using first-principles calculations. The calculated results show that Janus MoAZ₃H MLs have obvious valleytronic properties due to the broken inversion symmetry and strong spin-orbit coupling (SOC) effects, and the spin-valley coupling of MoAZ₃H MLs can be enhanced from 173 to 283 meV by changing the A or Z element, comparable to the corresponding MoA₂Z₄ MLs. The non-zero Berry curvatures with opposite signs at the *K* and *K'* points can induce the valley Hall effect. Furthermore, Janus MoAZ₃H MLs exhibit obvious in-plane and out-of-plane piezoelectric responses, and their independent *d*₁₁ and *d*₃₁ piezoelectric coefficients range from 1.62 to 8.60 pm V⁻¹ and from 0.058 to 0.325 pm V⁻¹, respectively. This piezoelectricity is much stronger than those of the corresponding MoA₂Z₄ and MoSiGeN₄ MLs, attributed to the unique Janus structure of the MoAZ₃H MLs. More importantly, strain can tailor both the spin-valley coupling and piezoelectricity of the MoAZ₃H MLs. Our findings not only enrich the excellent properties of the MoAZ₃H MLs, but also indicate a direction for their application in valleytronics and energy conversion devices.

Received 14th January 2024,
Accepted 1st March 2024

DOI: 10.1039/d4tc00188e

rsc.li/materials-c

1. Introduction

The extreme values of electronic energy in momentum space are referred to as energy valleys in crystals,¹ which gives electrons an additional degree of freedom except for charge and spin, the valley degree of freedom.^{2,3} Valleytronic devices based on the valley degree of freedom as information carriers have unique advantages, such as high integration, fast processing speed, low energy consumption, and nonvolatile nature, and have been considered as the development direction of future electronic devices.^{4–8} The booming two-dimensional (2D) materials provide an ideal platform for the study of valleytronics. The newly discovered MA₂Z₄ (M = Mo, W, V, Nb,

Ta, Ti, Zr, Hf or Cr; A = Si or Ge; Z = N, P or As) monolayer (ML) family,⁹ with a septuple-layer structure, is another intriguing family of 2D valleytronic materials^{10,11} after the transition metal dichalcogenides (TMDCs) represented by MoS₂,^{12,13} which is attributed to their broken inversion symmetry and strong spin-orbital coupling (SOC) effect. Among them, one class of members has a twofold valley degeneracy related by time-reversal symmetry at the *K* and *K'* points of the hexagonal Brillouin zone, which exhibits extraordinary spin valley-coupling in the two nonequivalent valleys, leading to valley transport characteristics and spin-valley coupling optical selection rules,^{14–16} including MoSi₂Z₄ (Z = N, P, or As), MSi₂N₄ (M = Hf, Ti, or Zr), WA₂Z₄ (A = Si, or Ge; Z = P, or As), *etc.* In addition, when the magnetic moments are out-of-plane, the spontaneous valley polarization can be driven by both the inversion and time-reversal symmetries breaking in magnetic VSi₂N₄ and VSi₂P₄ MLs.^{17,18}

2D Janus materials have garnered increasing attention owing to their unique physical properties arising from the dissimilar types of atoms on each side.¹⁹ The larger thickness makes the MA₂Z₄ MLs have an advantage over the other ML materials in constructing Janus structures. Substituting the Ge element for the Si element in the MSi₂N₄ (M = V, Mo, W, Zr, or Hf) ML can form stable Janus MSiGeN₄ MLs, which induces tunable electronic properties,²⁰ efficient photocatalytic

^a School of Physics and Electronic Information Engineering,
Henan Polytechnic University, Jiaozuo 454000, China.
E-mail: caixiaolin@hpu.edu.cn

^b Key Laboratory for Special Functional Materials of Ministry of Education,
Collaborative Innovation Center of Nano Functional Materials and Applications,
School of Material Science and Engineering, Henan University, Kaifeng 475004,
China. E-mail: jiaoyu@henu.edu.cn

^c International Laboratory for Quantum Functional Materials of Henan, and
School of Physics and Microelectronics, Zhengzhou University, Zhengzhou 450001,
China

† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d4tc00188e>

properties,^{21,22} Rashba splitting,^{23,24} and valley and spin properties.^{25–27} The Janus ML XYSiN_2 ($\text{X} = \text{S}, \text{Se}, \text{or Te}$; $\text{Y} = \text{Mo}, \text{or Cr}$) materials have good stability, high mechanical strength and excellent electronic properties,^{28,29} and can be constructed by substituting chalcogen X atoms for the SiN_2 layer on either side of the central Mo atoms in the MoSi_2N_4 MLs. Forming Janus structures breaks the vertical symmetry of the ML materials and thus causes out-of-plane piezoelectric properties, which is exactly required for energy conversion devices. For instance, Guo *et al.* found both in-plane and out-of-plane piezoelectric polarizations in MSiGeN_4 ($\text{M} = \text{Mo}, \text{or W}$) MLs.²⁴

Our group theoretically proposed the Janus MoAZ_3H ($\text{A} = \text{Si}, \text{or Ge}$; $\text{Z} = \text{N}, \text{P}, \text{or As}$) ML materials by substituting H atoms for one AZ atomic layer of MoA_2Z_4 MLs, exhibiting semiconducting nature with high carrier mobility, and excellent photovoltaic and catalytic performances.³⁰ However, for such a system including both a strong SOC effect and broken inversion symmetry, the valleytronic and piezoelectric characteristics are not uncovered, which is crucial for their application in valleytronics and energy conversion devices. Consequently, this work aims to systematically explore the valleytronic and piezoelectric properties of MoAZ_3H MLs using first-principles calculations. The calculated results show that the Janus MoAZ_3H MLs have obvious valleytronic properties, and comparable spin-valley coupling to that of the corresponding MoA_2Z_4 MLs, in which the valley Hall effects are observed attributed to the non-zero Berry curvatures with opposite signs at the K and K' points. Also, Janus MoAZ_3H MLs not only exhibit stronger in-plane piezoelectric response than the corresponding MoA_2Z_4 MLs, but also have obvious out-of-plane piezoelectric responses induced by the unique Janus structures. Furthermore, strain can tailor both the spin-valley coupling and piezoelectricity of MoAZ_3H MLs. Our results show that the MoAZ_3H MLs with the valleytronic and piezoelectric properties coexisting are promising for valleytronic and energy conversion devices in future.

2. Computational details

All calculations are performed in the Vienna *ab initio* simulation package (VASP)³¹ based on density functional theory (DFT).³² The exchange correlation potential is described by the generalized gradient approximation (GGA)³³ with the Perdew–Burke–Ernzerhof (PBE) functional. The cut off energy of

the plane wave is set to 500 eV, and the convergence criteria are 10^{-5} eV and 0.01 eV \AA^{-1} for the energy and the force, respectively. The vacuum space is set to 30 Å to avoid adjacent interactions. The $21 \times 21 \times 1$ Monkhorst–Pack k -point mesh is used to sample the Brillouin zone. The Heyd–Scuseria–Ernzerhof (HSE)³⁴ hybrid functional method is used to obtain a more precise band structure. The maximum-localized Wannier function (MLWF) calculated by the WANNIER90³⁵ package is used to obtain the high-symmetry point Berry curvature, and the Berry curvature of the 2D section is plotted by the VASP-BERRY code.³⁶ Meanwhile, the spin texture is calculated using VAVSPKIT.³⁷

3. Results and discussion

Fig. 1 presents the crystal structures of Janus MoAZ_3H MLs and corresponding high-symmetric path in the Brillouin zone. It is clearly found that the Janus MoAZ_3H MLs can be obtained by replacing one AZ layer with H atoms in the MoA_2Z_4 ML, which still maintains the hexagonal lattice structure, with six atomic layers in a queue of H–Z–Mo–Z–A–Z. As the atomic number of the A or Z element increases, both the lattice constants and the thicknesses of the MoAZ_3H MLs also gradually increase.

3.1 Valleytronic properties

In order to unveil the valleytronic properties of the MoAZ_3H MLs, we firstly plot the projected band structure of atomic contributions using the PBE scheme, as shown in Fig. S1 (ESI†). Distinctly, the conduction band minima (CBMs) of all the six MoAZ_3H MLs are at the K point. Meanwhile, the K point is either the valence band maximum (VBM) or the extreme point of the energy for the highest valence band. All the electronic states of the CBMs and the highest valence bands at the K points are mainly determined by the Mo atom of the MoAZ_3H MLs. Further calculated results in Fig. 2 show that the Mo orbital-resolved band structure shows that the CBM is mainly from the Mo- d_{z^2} orbital, while the highest valence band at the K point is contributed by the Mo- $d_{x^2-y^2}$ and $-d_{xy}$ orbitals. As a result of the C_{3h} group at K/K' , the basis functions are chosen as $|\varphi_c^\tau\rangle = |d_{z^2}\rangle$ and $|\varphi_v^\tau\rangle = \sqrt{\frac{1}{2}}(|d_{x^2-y^2}\rangle + i\tau|d_{xy}\rangle)$, where the subscript $c(v)$ indicates conduction (valence) band, and $\tau = \pm 1$ is the valley index corresponding to the K/K' point. When we approximate the SOC term as an intra-atomic contribution and



Fig. 1 (a) and (b) are the top and side views of the crystal structures, and (c) the high symmetry path in the Brillouin zone for the MoAZ_3H MLs, respectively. In panel (a), black rhombi and blue rectangles represent the unit cells and rectangular supercells of the MoAZ_3H MLs, respectively.



Fig. 2 Orbital-resolved band structures of the d-orbitals of Mo atoms in MoAZ₃H MLs.

only keep the leading-order term, the k - p effective model is obtained as

$$\hat{H}^{\tau} = \alpha(\tau k_x \hat{\sigma}_x + k_y \hat{\sigma}_y) + \frac{A}{2} \hat{\sigma}_z - \frac{\lambda}{2} \tau (\hat{\sigma}_z - 1) \hat{s}_z. \quad (1)$$

Here, k refers to the wave vectors of the K and K' points, $\hat{\sigma}$ refers to the Pauli matrices for the two basis functions, and α and A are real-valued model parameters. The third term on the right side of the above equation is the SOC effect term, where \hat{s}_z is the Pauli matrix for spin and λ is the effective SOC strength. The energies of the VBM and CBM at the K/K' point are $E_v^{\tau} = \langle \varphi_v^{\tau} | \hat{H}^{\tau} | \varphi_v^{\tau} \rangle$ and $E_c^{\tau} = \langle \varphi_c^{\tau} | \hat{H}^{\tau} | \varphi_c^{\tau} \rangle$. Based on the above analysis, we can obtain the spin splitting of the VBM and CBM at the K/K' point:

$$\Delta E_v = E_v^{-} - E_v^{+} = i \langle d_{xy} | \hat{H}^{\tau} | d_{x^2-y^2} \rangle - i \langle d_{x^2-y^2} | \hat{H}^{\tau} | d_{xy} \rangle = 2\lambda, \quad (2)$$

$$\Delta E_c = E_c^{-} - E_c^{+} = 0. \quad (3)$$

This result means the significant and negligible spin splittings of the VBM and CBM at the K/K' point, respectively, which can also be verified by the d-orbital-resolved band structure from the PBE+SOC scheme, as shown in Fig. 2.

Fig. 3 shows the spin-resolved band structures of MoAZ₃H MLs along the path of $M-K-\Gamma-K'-M-\Gamma$ using the PBE+SOC method. Firstly, as discussed above, there exists obvious spin

splitting in the band structures of MoAZ₃H MLs resulting from the strong SOC effect. In particular, due to the broken inversion symmetry as well as the preserved time-reversal symmetry, the highest valence bands at the K' and K points have spin polarization in the opposite direction, proving that the Janus MoAZ₃H MLs have valleytronic properties. These valleytronic properties can also be illustrated by the spin texture for the two highest spin-split valence bands at the K/K' point over the entire Brillouin zone, and for simplicity, we only calculate the spin texture for MoSiP₃H and MoGeAs₃H MLs, as shown in Fig. 4. It is clearly revealed that the out-of-plane components of the spin polarization at the K and K' points are opposite at the same band (Fig. 4(a) and (b)); meanwhile, the in-plane components of the spin polarization at the K or K' points are also opposite at different bands (Fig. 4(a) and (b)). This fully illustrates the opposite spin polarizations of the highest valence band at the K and K' points caused by the strong SOC under the spatial inversion symmetry breaking in Janus MoAZ₃H MLs.

Table 1 lists the spin-valley coupling (ΔV) and band gap (E_g) of MoAZ₃H MLs both from the PBE+SOC and HSE+SOC schemes. Compared to the PBE+SOC method, although the HSE+SOC method significantly enhances the band gap and spin-valley coupling of the MoAZ₃H ML (Fig. S2, ESI[†]), they both predict the same variation trends of the band gap and the

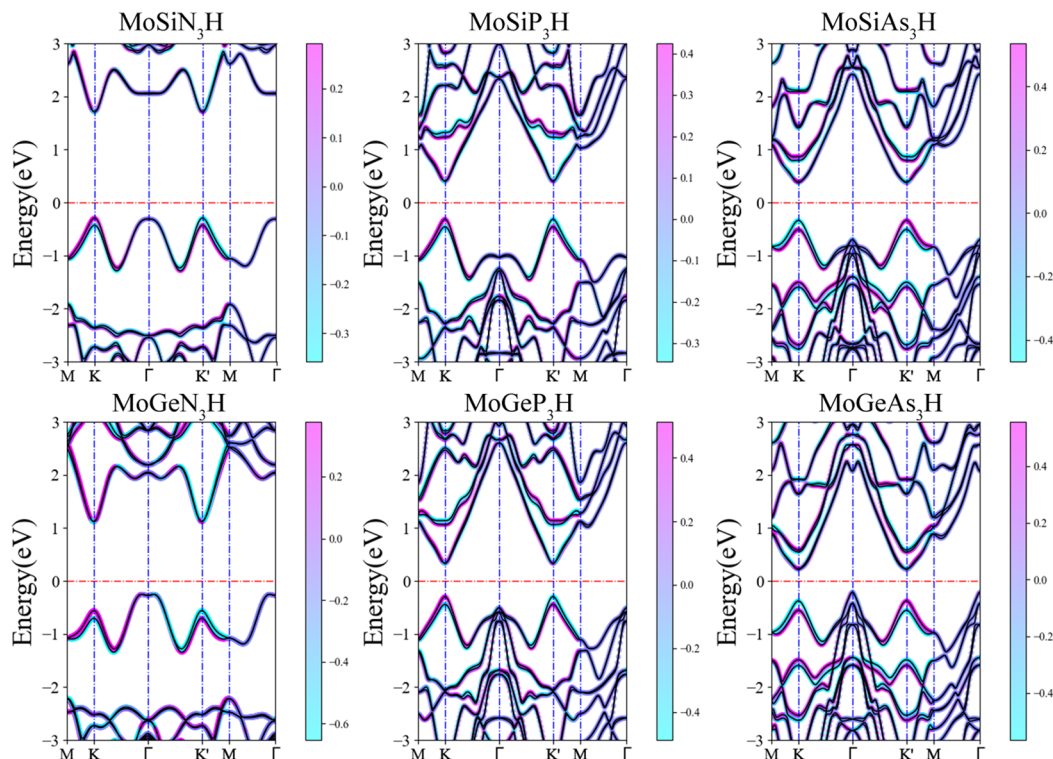


Fig. 3 Spin-resolved band structures of Janus MoAZ₃H MLs by the PBE+SOC method. Here, the Fermi levels are set to zero.



Fig. 4 Spin texture for the two highest spin-split valence bands in (a) MoSiP₃H and (b) MoGeAs₃H MLs calculated in the entire BZ, where (a) and (b) include the upper and lower valence bands, respectively. Here, the arrows show the in-plane components of spin polarization, and the colors represent the out-of-plane components of spin polarization.

spin-valley coupling when substituting Ge for Si or substituting P or As for N in the MoAZ₃H MLs. Among the six members, the

Table 1 Band gap E_g (eV) and spin-valley coupling ΔV (meV) for MoAZ₃H MLs

	$E_g^{\text{PBE+SOC}}$	$E_g^{\text{HSE+SOC}}$	$E_v^{\text{PBE+SOC}}$	$E_v^{\text{HSE+SOC}}$
MoSiN ₃ H	2.00	2.44	136	173
MoSiP ₃ H	0.73	0.95	143	203
MoSiAs ₃ H	0.69	0.83	172	267
MoGeN ₃ H	1.37	1.93	143	184
MoGeP ₃ H	0.63	0.78	145	211
MoGeAs ₃ H	0.43	0.69	180	283

MoSiN₃H ML has the smallest spin-valley coupling, about 173 meV, which will increase with both substituting Ge for Si and substituting P or As for N due to the larger radius and mass of the replaced atom. As a result, the largest spin-valley coupling is for MoGeAs₃H ML, up to 283 meV. It is worth noting that the replacement of the element in Group V has a greater impact on the spin-valley coupling than that in Group IV because there are more atoms with larger mass in Group V in MoAZ₃H MLs. Previous studies reported that the spin-valley coupling values were 170, 206 and 295 meV for MoSi₂N₄, MoSi₂P₄ and MoSi₂As₄ MLs,³⁸ respectively. This means that replacing one SiN or SiP layer with H atoms in the MoSi₂N₄ ML basically does not change the spin-valley coupling, whereas replacing the SiAs layer with H atoms can slightly reduce the spin-valley coupling due to the lighter replaced atoms.

Unlike the magnetic MLs with the broken time reversal symmetry, such VSi₂P₄³⁹ and Mn₂P₂X₃Y₃⁴⁰ MLs have spontaneous valley polarization. The valley characteristics of Janus

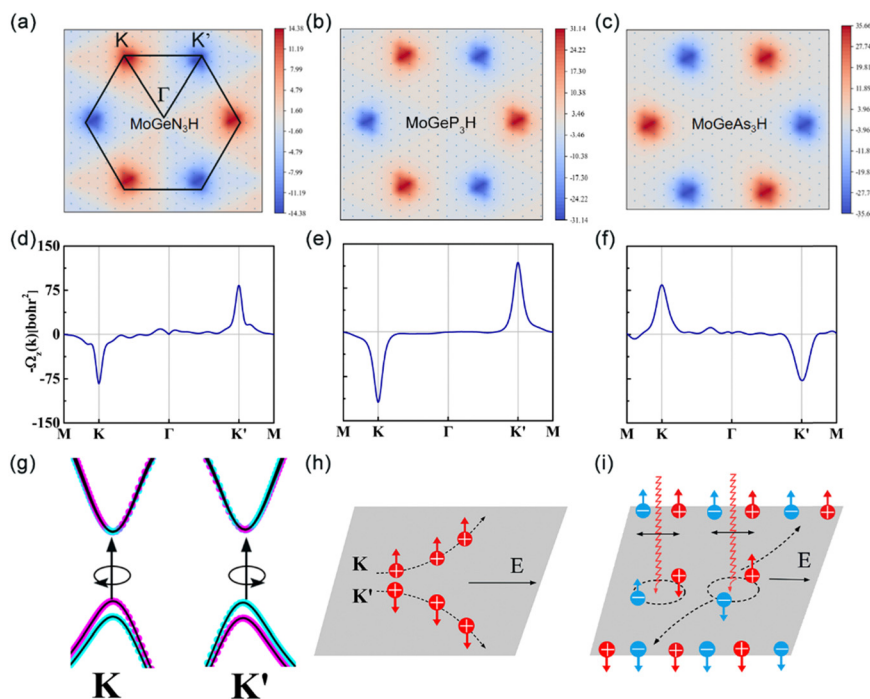


Fig. 5 (a)–(c) are Berry curvature diagrams of Janus MoGeA₃H (A = N, P, and As) MLs in the Brillouin zone. (d)–(f) are the corresponding Berry curvature curves along the high symmetry path. (g) Spin-resolved valley optical transition selection rules. (h) Schematic diagram of the valley Hall effect for *K* and *K'* valleys, where the + sign indicates a hole, and the red up and down arrows represent spin up and down, respectively. (i) Valley Hall effect excited by a linearly polarized optical field.

MoAZ₃H MLs arise from the spatial inversion symmetry breaking and strong SOC effects, which manifest as spin-valley coupling or opposite spin splitting at the *K*/*K'* point, protected by time reversal symmetry. As the atomic number of element A or Z increases, the spin-valley coupling of the MoAZ₃H MLs ranges from 173 to 283 meV, which is larger than that of the MoS₂ ML (150 meV),¹ while much smaller than those of H-Tl₂O (610 meV)⁴¹ and HfN₂ (314 meV)⁴² because of the stronger SOC of elements Tl and Hf.

To further demonstrate the valleytronic properties of MoAZ₃H ML, we also calculate the Berry curvatures of MAZ₃H MLs based on the Kudo formula:⁴³

$$\Omega(k) = -2 \sum_n \sum_{n' \neq n} f_n \frac{\text{Im} \langle \psi_{nk} | v_x | \psi_{n'-k} \rangle \langle \psi_{n'k} | v_y | \psi_{nk} \rangle}{(E_{n'} - E_n)^2}, \quad (4)$$

where f_n , $E_n(k)$, and $v_{x/y}$ are the Fermi-Dirac distribution function, eigenvalue of the Bloch state ψ_{nk} , and velocity operator along the x/y directions, respectively. Berry curvatures of MAZ₃H MLs in the 2D Brillouin zone are presented in Fig. S3(a)–(c) (ESI[†]) and Fig. 5(a)–(c). As expected, the Berry curvatures at the *K* and *K'* valleys exhibit opposite signs for the MAZ₃H systems, namely $\Omega(k) = -\Omega(k')$, which is also verified by the curve of the Berry curvatures of MAZ₃H MLs along the high symmetry path in Fig. S3(d)–(f) (ESI[†]) and Fig. 5(d)–(f). The values of Berry curvature at the *K* and *K'* valleys are non-zero and of opposite signs, spanning 75–120 bohr², which is further evidence of the valleytronic properties of the MAZ₃H MLs. Such valley nature gives rise to the valley-contrasting spin splitting,

inducing the spin-dependent valley optical selection rule,⁴⁴ as illustrated in Fig. 5(g). Additionally, the non-zero Berry curvature is similar to the effective magnetic field in the presence of an in-plane electric field. Due to the opposite Berry curvatures at the *K* and *K'* valleys, the electrons at the *K* and *K'* valleys can obtain two anomalous velocities:⁴⁵ $v_n(k) = \frac{\partial \epsilon_n(k)}{\hbar \partial k} - \frac{e}{\hbar} E \times \Omega(k)$, which are perpendicular to the electric field and move in opposite directions as shown in Fig. 5(h), leading to the valley Hall effect, which can also be excited by a linearly polarized optical field (Fig. 5(i)).

3.2 Piezoelectric properties

Next, we turn to explore both in-plane and out-of-plane piezoelectric effects in the MoAZ₃H MLs with a unique Janus structure. For the 2D ML with $P3m1$ symmetry, the elastic and piezoelectric tensors be reduced into:⁴⁶

$$C = \begin{pmatrix} C_{11} & C_{12} & 0 \\ C_{12} & C_{11} & 0 \\ 0 & 0 & \frac{C_{11} - C_{12}}{2} \end{pmatrix}, \quad (5)$$

$$e = \begin{pmatrix} e_{11} & -e_{11} & 0 \\ 0 & 0 & -e_{11} \\ e_{31} & e_{31} & 0 \end{pmatrix}, \quad (6)$$

$$d = \begin{pmatrix} d_{11} & -d_{11} & 0 \\ 0 & 0 & -2d_{11} \\ d_{31} & d_{31} & 0 \end{pmatrix}. \quad (7)$$

A uniaxial in-plane strain can induce both the in-plane and out-of-plane piezoelectric responses ($e_{11}/d_{11} \neq 0$ and $e_{31}/d_{31} \neq 0$), while a biaxial in-plane strain can only produce an out-of-plane piezoelectric response ($e_{11}/d_{11} = 0$ but $e_{31}/d_{31} \neq 0$). Solving equation $e_{ik} = d_{ij}C_{jk}$ can derive the independent d_{11} and d_{31} :

$$d_{11} = \frac{e_{11}}{C_{11} - C_{12}} \quad \text{and} \quad d_{31} = \frac{e_{31}}{C_{11} + C_{12}}. \quad (8)$$

Piezoelectric stress, strain and elastic tensors of MAZ₃H MLs can be obtained from eqn (5)–(8) using the orthorhombic supercell (Fig. 1(a)), as listed in Table 2. Compared to MA₂Z₄ MLs, the Janus MAZ₃H MLs break the reflection symmetry with respect to the central Mo atom due to the two different surface atoms in the vertical direction, leading to the non-zero e_{31}/d_{31} .

It is firstly found that the piezoelectric coefficients e_{11}/e_{31} of the MoSiN₃H and MoGeN₃H MLs are about 4.146/0.290 and 4.112/0.267 $10^{-10} \text{ C m}^{-1}$, respectively. Evidently, the two e_{11} coefficients are comparable to that of MoSi₂N₄ (MoGe₂N₄) ML (4.395 (4.218) $10^{-10} \text{ C m}^{-1}$), while significantly smaller than that of MoSiGeN₄ ML (5.116 $10^{-10} \text{ C m}^{-1}$).²⁴ Apart from the smaller e_{11} of the MoSiAs₃H ML than that of the MoGeAs₃H ML, the MoSiZ₃H MLs have larger e_{11} values than the MoGeZ₃H systems. The size order of e_{11} is MoSiP₃H > MoSiAs₃H > MoSiN₃H in the MoSiZ₃H MLs, whereas the e_{11} of the MoGeZ₃H ML increases with the increasing mass of Z element. The maximum e_{11} is 7.583 $10^{-10} \text{ C m}^{-1}$ for the MoSiP₃H ML. The MoSiZ₃H MLs have a slightly larger e_{31} than the MoGeZ₃H systems, and the e_{31} values of the MoAN₃H MLs are slightly larger than those of the MoAP₃H MLs, while much smaller than those of the MoAAs₃H MLs. In the e_{11}/e_{31} of MoAN₃H system, the electronic contribution has the opposite sign to the ionic contribution, while the electronic and ionic contributions dominate e_{11} and e_{31} , respectively, as shown in Fig. 6(a) and (b), respectively. However, for the MoAP₃H and MoAAs₃H MLs, the electronic and ionic contributions have the same signs in e_{11}/e_{31} . This may be why the e_{11}/e_{31} of the MoAN₃H systems are smaller.

As discussed in previous research,³⁰ the elastic constant of the MoAN₃H ML is the largest in all of the MoAZ₃H MLs, mostly larger than twice those of the other MoAZ₃H MLs, and the

Table 2 Elastic constants C_{11}/C_{12} (N m⁻¹) and piezoelectric coefficients e_{11}/e_{31} ($10^{-10} \text{ C m}^{-1}$) and d_{11}/d_{31} (pm V⁻¹) of MAZ₃H MLs

	C_{11}	C_{12}	e_{11}	d_{11}	e_{31}	d_{31}
MoSiN ₃ H	375.96	120.89	4.146	1.622	0.290	0.058
MoSiP ₃ H	159.70	44.38	7.583	6.576	0.257	0.126
MoSiAs ₃ H	130.42	43.16	6.884	7.890	0.440	0.254
MoGeN ₃ H	282.03	104.55	4.112	2.317	0.267	0.069
MoGeP ₃ H	149.76	46.82	7.080	6.877	0.227	0.115
MoGeAs ₃ H	128.56	42.15	7.429	8.598	0.418	0.325
MoSi ₂ N ₄ ²⁴	—	—	4.395	1.144	—	—
MoGe ₂ N ₄ ²⁴	—	—	4.218	1.050	—	—
MoSiGeN ₄ ²⁴	—	—	5.116	1.494	0.087	0.014

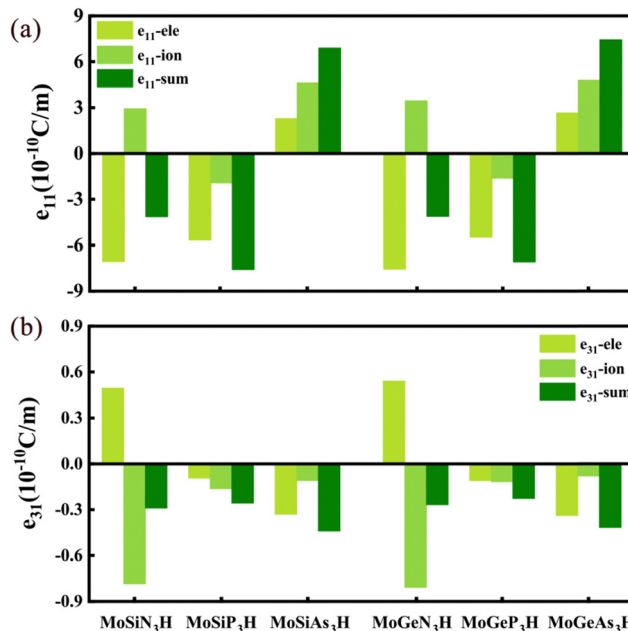


Fig. 6 Ionic and electronic contributions of the piezoelectric coefficients (a) e_{11} and (b) e_{31} in the MoAZ₃H ML, respectively.

MoAP₃H ML has a slightly larger elastic constant than the MoAAs₃H ML. Consequently, the values of $C_{11} + C_{12}$ and $C_{11} - C_{12}$ are decreasing with increasing atomic mass of A or Z element for the MoAZ₃H ML. The piezoelectric coefficients d_{11}/d_{31} are 1.62/0.058 pm V^{-1} for the MoSiN₃H ML and 2.32/0.069 pm V^{-1} for the MoGeN₃H ML, respectively, both much larger than that of the Janus MoSiGeN₄ ML (1.49/0.014 pm V^{-1}).²⁴ In particular, the MoSiN₃H and MoGeN₃H MLs have larger d_{11} than the MoSi₂N₄ (1.14 pm V^{-1}) and MoGe₂N₄ (1.05 pm V^{-1}) MLs.²⁴ As the atomic mass of A or Z element increases, the d_{11} value gets larger mainly because of the decreasing $C_{11} - C_{12}$, on which changing the element Z has a greater effect. Hence, the MoGeAs₃H ML has the maximum d_{11} of 8.60 pm V^{-1} . Furthermore, for MoAZ₃H MLs, increasing the atomic mass of Z element can greatly enhance the out-of-plane piezoelectric coefficient d_{31} , mainly resulting from the decreasing $C_{11} + C_{12}$. Increasing the atomic number of the A element can increase the d_{31} for the MoAN₃H and MoAAs₃H MLs whereas slightly reduce it for the MoAP₃H ML. The maximum d_{31} is 0.325 pm V^{-1} for the MoGeAs₃H ML.

The above discussion fully demonstrates that for MoA₂Z₄ MLs, forming MoAZ₃H Janus MLs is beneficial for improving the in-plane piezoelectric response d_{11} values and also for inducing larger out-of-plane piezoelectric responses, larger than forming MoSiGeN₄ Janus MLs.

3.3 Strain effect

Strain is an effective way to control the electronic properties of 2D materials because they can withstand large strain due to the unique crystal structure.⁴⁷ Below, we will investigate the strain effect on the spin-valley coupling and piezoelectric properties of Janus MoAZ₃H MLs. Because this work only focuses on the

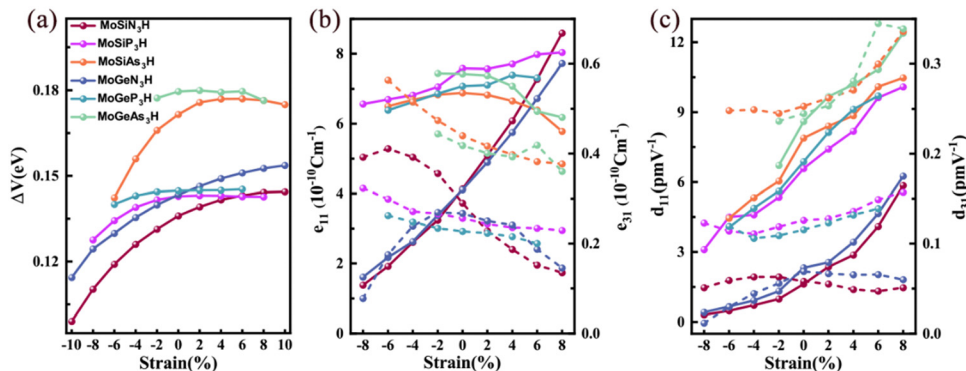


Fig. 7 (a) Spin-valley coupling at the K point, (b) piezoelectric coefficients e_{11}/e_{31} and (c) d_{11}/d_{31} under biaxial strain in the MoAZ₃H MLs. In the three panels, the solid lines in one color and the corresponding dashed lines indicate the results of the same material.

semiconducting characteristics of the MoAZ₃H MLs, it excludes the MoAZ₃H MLs transforming to metals under strain. Table 1 reveals that the increasing atomic number of element A or Z in the MoAZ₃H ML can gradually decrease the band gap, which would also narrow the strain range of maintaining the semiconducting properties. Thus, different strain ranges are considered for the MoAZ₃H MLs with different components. In addition, it was revealed that Janus MoAZ₃H MLs under zero strain exhibit good dynamic stability due to no imaginary frequency in the phonon spectra.³⁰ We also calculate the phonon spectra of strained MoAZ₃H MLs, and find that the phonon spectra have no imaginary frequency under the considered tensile strain and are prone to showing imaginary frequencies under large compressive strain. Fig. S4 (ESI†) presents the phonon spectra of the MoSiN₃H, MoSiAs₃H and MoGeN₃H MLs under the tensile strain of 10%, in which there are no imaginary frequencies. This means that MoAZ₃H MLs can sustain a larger tensile strain, whereas the compressive stress has a greater destructive force on the systems.

Fig. 7(a) shows the strain tunable spin-valley coupling of the highest valence bands at the K/k' points of MoAZ₃H MLs. There is little change in the spin-valley couplings of the MoGeAs₃H and MoGeP₃H MLs under strain. Besides, for the other four MoAZ₃H MLs, the spin-valley coupling is enhanced by the tensile strain, while weakened by the compressive strain, which indicates that strain can easily regulate spin-valley coupling strength, having potential applications in valleytronic devices. Fig. 7(b) and (c) present the responses of the piezoelectric coefficients to strain for the MoAZ₃H MLs, which obviously illustrates that the piezoelectric coefficients can be easily tailored by strain. Overall, among the four piezoelectric coefficients, the most strain-regulated is d_{11} , which basically increases and decreases with increasing tensile and compressive strains, respectively. The same strain regulation rule is followed by the e_{11} of the MoAN₃H and MoAP₃H MLs, whereas that of the MoAN₃H MLs changes more significantly with strain. The e_{11} of the MoSiAs₃H ML always reduces with both tensile and compressive strains, and that of the MoGeAs₃H ML gradually decreases with strain from -2% to 8%. The e_{31} of the MoSiN₃H ML gradually decreases with increasing tensile strain,

and increases with increasing compressive strain until it reaches -6% and then decreases. For the MoGeN₃H ML, the e_{31} has a maximum under the strain of -2%, decreasing with the strain from -2% to 8%. For the MoAP₃H and MoAA₃H MLs, the e_{31} increases and decreases with the compressive and tensile strains, respectively, while the d_{31} is the opposite. In addition, the fluctuation range of d_{31} under strain for the six MoAZ₃H MLs is not too large.

It is worth emphasizing that for the MoZ₂ MLs with poor stability, the H atoms or the AZ layer passivating can make the system more stable.^{48,49} More importantly, this means that this can transform the system into a semiconductor with valleytronic characteristics. Thus, we propose to construct stable Janus MoAZ₃H MLs by passivating the two surface Z atoms of MoZ₂ MLs with one AZ layer and one H atomic layer, respectively, which endows the systems with the unique nature induced by asymmetry of the surface atoms other than the semiconducting and valley properties, such as photovoltaic properties and piezoelectricity.

4. Conclusions

To sum up, using first-principles calculations, we find that valleytronic and piezoelectric properties coexist in Janus MoAZ₃H ML materials. The unique valleytronic properties arise from broken inversion symmetry and strong SOC effects, which brings about non-zero Berry curvatures with opposite signs at the K and K' valleys and the valley Hall effects. In addition, the in-plane piezoelectric responses of Janus MoAZ₃H MLs are stronger than those of the corresponding MoA₂Z₄ MLs. Surprisingly, the unique Janus structure induces obvious out-of-plane piezoelectric responses, and the out-of-plane piezoelectric coefficients e_{31}/d_{31} are high up to $0.418 \times 10^{-10} \text{ C m}^{-1}/0.325 \text{ pm V}^{-1}$. More importantly, strain can tailor both the spin-valley coupling and piezoelectricity of MoAZ₃H MLs. The coexisting valleytronic and piezoelectric properties win a wide application space in the valleytronics and energy conversion fields for the MoAZ₃H MLs.

Conflicts of interest

There are no conflicts of interest to declare.

Acknowledgements

This work was supported partly by the National Natural Science Foundation of China (Grant No. 11804082, 12074102 and 11774078), and by the Doctoral Foundation of Henan Polytechnic University (B2018-37). All the calculations were carried out at the Center for High Performance Computing of Henan Polytechnic University.

References

- D. Xiao, G.-B. Liu, W. Feng, X. Xu and W. Yao, *Phys. Rev. Lett.*, 2012, **108**(19), 196802.
- A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov and A. K. Geim, *Rev. Mod. Phys.*, 2009, **81**, 109–162.
- J. R. Schaibley, H. Yu, G. Clark, P. Rivera, J. S. Ross, K. L. Seyler, W. Yao and X. Xu, *Nat. Rev. Mater.*, 2016, **1**, 16055.
- B. Urbaszek and X. Marie, *Nat. Phys.*, 2015, **11**, 94–95.
- F. Amet and G. Finkelstein, *Nat. Phys.*, 2015, **11**, 989–990.
- X. Li and G. Moody, *Nat. Phys.*, 2017, **13**, 9–10.
- H. Yu and W. Yao, *Nat. Mater.*, 2017, **16**, 876–877.
- F. Zhang, *Nat. Phys.*, 2018, **14**, 111–113.
- L. Cao, G. Zhou, Q. Wang, L. K. Ang and Y. S. Ang, *Appl. Phys. Lett.*, 2021, **118**, 013116.
- B. Liu, *Natl. Sci. Rev.*, 2020, **7**, 1841–1842.
- S. Li, W. Wu, X. Feng, S. Guan, W. Feng, Y. Yao and S. Yang, *Phys. Rev. B*, 2020, **102**, 235435.
- K. Mak, C. Lee, J. Hone, J. Shan and T. Heinz, *Phys. Rev. Lett.*, 2010, **105**, 136805.
- K. F. Mak, K. L. McGill, J. Park and P. L. McEuen, *Science*, 2014, **344**, 1489–1492.
- Y. Shao, Y. Fang, T. Li, Q. Wang, Q. Dong, Y. Deng, Y. Yuan, H. Wei, M. Wang, A. Gruverman, J. Shield and J. Huang, *Energy Environ. Sci.*, 2016, **9**, 1752–1759.
- C. Yang, Z. Song, X. Sun and J. Lu, *Phys. Rev. B*, 2021, **103**, 035308.
- J.-S. Yang, L. Zhao, S.-Q. Li, H. Liu, L. Wang, M. Chen, J. Gao and J. Zhao, *Nanoscale*, 2021, **13**, 5479–5488.
- X. Y. Feng, X. L. Xu, Z. L. He, R. Peng, Y. Dai, B. B. Huang and Y. D. Ma, *Phys. Rev. B*, 2021, **104**, 075421.
- Q. R. Cui, Y. M. Zhu, J. H. Liang, P. Cui and H. X. Yang, *Phys. Rev. B*, 2021, **103**, 085421.
- Y. Duan, X. Zhao, M. Sun and H. Hao, *Ind. Eng. Chem. Res.*, 2021, **60**, 1071–1095.
- V. T. T. Vi, T. P. T. Linh, C. Q. Nguyen and N. N. Hieu, *Adv. Theory Simul.*, 2022, **5**, 2200499.
- Y. Yu, J. Zhou, Z. Guo and Z. Sun, *ACS Appl. Mater. Interfaces*, 2021, **13**, 28090–28097.
- M.-Y. Liu, Y. He, X. Li and K. Xiong, *Phys. Chem. Chem. Phys.*, 2023, **25**, 7278–7288.
- L. Wu, W. Zhou, D. Zhang and F. Ouyang, *J. Phys.: Conf. Ser.*, 2022, **2263**, 012014.
- S.-D. Guo, W.-Q. Mu, Y.-T. Zhu, R.-Y. Han and W.-C. Ren, *J. Mater. Chem. C*, 2021, **9**, 2464–2473.
- S. Sheoran, A. Phutela, R. Moulik and S. Bhattacharya, *J. Phys. Chem. C*, 2023, **127**, 11396–11406.
- S.-D. Guo, W.-Q. Mu, J.-H. Wang, Y.-X. Yang, B. Wang and Y.-S. Ang, *Phys. Rev. B*, 2022, **106**, 064416.
- Y. Li, M. Lan, S. Wang, T. Huang, Y. Chen, H. Wu, F. Li and Y. Pu, *Phys. Chem. Chem. Phys.*, 2023, **25**, 15676–15682.
- R. T. Sibatov, R. M. Meftakhutdinov and A. I. Kochaev, *Appl. Surf. Sci.*, 2022, **585**, 152465.
- P. T. L. Tran, N. V. Hieu, H. Bui D, Q. N. Cuong and N. N. Hieu, *Nanoscale Adv.*, 2023, **5**, 3104–3113.
- X. Cai, G. Chen, R. Li, W. Yu, X. Yang and Y. Jia, *Phys. Chem. Chem. Phys.*, 2023, **25**, 29594–29602.
- G. Kresse and J. Hafner, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 1993, **47**, 558–561.
- P. Hohenberg and W. Kohn, *Phys. Rev.*, 1964, **136**, B864–B871.
- J. P. Perdew, K. Burke and M. Ernzerhof, *Phys. Rev. Lett.*, 1996, **77**, 3865–3868.
- J. Heyd, G. E. Scuseria and M. Ernzerhof, *J. Chem. Phys.*, 2003, **118**, 8207–8215.
- N. Marzari, A. A. Mostofi, J. R. Yates, I. Souza and D. Vanderbilt, *Rev. Mod. Phys.*, 2012, **84**, 1419–1475.
- T. Fukui, Y. Hatsugai and H. Suzuki, *J. Phys. Soc. Japan.*, 2005, **74**, 1674–1677.
- V. Wang, N. Xu, J.-C. Liu, G. Tang and W.-T. Geng, *Comput. Phys. Commun.*, 2021, **267**, 108033.
- H. Ai, D. Liu, J. Geng, S. Wang, K. H. Lo and H. Pan, *Phys. Chem. Chem. Phys.*, 2021, **23**, 3144–3151.
- X. Feng, X. Xu, Z. He, R. Peng, Y. Dai, B. Huang and Y. Ma, *Phys. Rev. B*, 2021, **104**, 075421.
- Y. Xu, H. Liu, Y. Dai, B. Huang and W. Wei, *Appl. Phys. Lett.*, 2023, **122**, 242404.
- Y. Ma, L. Kou, A. Du, B. Huang, Y. Dai and T. Heine, *Phys. Rev. B*, 2018, **97**, 035444.
- M. K. Mohanta and A. De Sarkar, *Phys. Rev. B*, 2020, **102**, 125414.
- D. J. Thouless, M. Kohmoto, M. P. Nightingale and M. den Nijs, *Phys. Rev. Lett.*, 1982, **49**, 405–408.
- D. Xiao, G.-B. Liu, W. Feng, X. Xu and W. Yao, *Phys. Rev. Lett.*, 2012, **108**, 196802.
- D. Xiao, M.-C. Chang and Q. Niu, *Rev. Mod. Phys.*, 2010, **82**, 1959–2007.
- M. Blonsky, H. L. Zhuang, A. K. Singh and R. G. Hennig, *ACS Nano*, 2015, **9**(10), 9885–9891.
- X. H. Peng, Q. Wei and A. Copple, *Phys. Rev. B: Condens. Matter Mater. Phys.*, 2014, **90**, 085402.
- J. Yuan, Q. Wei, M. Sun, X. Yan, Y. Cai, L. Shen and U. Schwingenschlgl, *Phys. Rev. B*, 2022, **105**, 195151.
- Y. Wang and Y. Ding, *J. Mater. Chem. C*, 2016, **4**, 7485–7493.