The Rashba effect has recently attracted great attention owing to emerging physical properties associated with it. The interplay between the Rashba effect and the Zeeman effect, being produced by the exchange field, is expected to broaden the range of these properties and even result in novel phenomena. Here we predict an insulator-to-conductor transition driven by the Rashba–Zeeman effect. We first illustrate this effect using a general Hamiltonian model and show that the insulator-to-conductor transition can be triggered under certain Rashba and exchange-field strengths. Then, we exemplify this phenomenon by considering an Ag₂Te/Cr₂O₃ heterostructure, where the electronic structure of the Ag₂Te monolayer is affected across the interface by the proximity effect of the Cr₂O₃ antiferromagnetic layer with well-defined surface magnetization. Based on first-principles calculations, we predict that such a system can be driven into either insulating or conducting phase, depending on the surface magnetization orientation of the Cr₂O₃ layer. Our results enrich the Rashba–Zeeman physics and provide useful guidelines for the realization of the insulator-to-conductor transition, which may be interesting for experimental verification.

INTRODUCTION

The Rashba effect is a momentum-dependent spin splitting of the energy bands driven by spin-orbit coupling (SOC)\(^1\). This phenomenon has recently stimulated vigorous research, owing to its potential application in spintronics\(^7\). The Rashba effect occurs in material systems with broken space-inversion symmetry such as surfaces\(^9\), interfaces\(^5\), and certain bulk materials\(^6,7\). The SOC effect allows an electrical control of the spin degree of freedom that is interesting for device applications. For example, using the Rashba effect has been proposed for design of a spin field-effect transistor\(^8\). Electrically switchable SOC parameter has been explored to design valley-spin valves\(^3\) and valley-spin logic gates\(^10\). Furthermore, various physical phenomena such as current-induced spin polarization\(^11\), the spin Hall effect\(^12\), and the spin galvanic effect\(^13,14\) have been inspired or reinvigorated.

The Rashba-affected material systems may also exhibit a Zeeman effect. The Zeeman effect is characterized by the momentum-independent spin splitting of the energy bands and is associated with the interaction of spin with an external magnetic field or an exchange field. The Zeeman energy is typically \(-0.1\) meV/T and therefore is relatively small for applied external fields of a few Tesla or less. In contrast, the internal exchange fields arising from intrinsic magnetization\(^15\), doped magnetic transition metals\(^16\) or ferromagnetic (FM)\(^17\), antiferromagnetic (AFM)\(^18\), and multiferroic\(^19\) insulator substrates owing to magnetic proximity effects\(^20\) can be sizable \((-10^{-5}–10^{-3} \text{ T})\) and hence produce a non-negligible Zeeman splitting of the energy bands.

The interplay between the Rashba and Zeeman effects (abbreviated below as the Rashba–Zeeman effect) is expected to produce novel features not found in pure Rashba- or Zeeman-affected systems. For example, the recent experimental work on Mn-doped GeTe has demonstrated that the Rashba spin helicity can be altered by magnetization switching\(^22\), and conversely, the magnetization can be reversibly polarized by spin-orbit torque\(^24\) or by the current-induced spin-orbit torque\(^23\). Moreover, the Rashba–Zeeman effect can also affect the quantum transport properties. For example, it has been demonstrated that in quantum-point-contact InSb nanowires with sizable Rashba SOC, the measured conductance plateau could be tuned from \(e^2/h\) to \(2e^2/h\) by the magnetic field orientation\(^25\).

In this work, we predict another striking phenomenon—an insulator-to-conductor transition induced by the Rashba–Zeeman effect in a two-dimensional (2D) system. The band structure of the 2D material can be controlled by the exchange field orientation, and under certain Rashba and exchange field strengths exhibits an insulator-to-conductor transition. We explore this phenomenon for a realistic system—a monolayer of Ag₂Te deposited on an AFM Cr₂O₃ (0001) substrate. Owing to broken inversion symmetry, an Ag₂Te monolayer exhibits a sizable Rashba band splitting, while the Cr₂O₃ substrate has a robust surface magnetization coupled to the AFM order parameter and provides an exchange field affecting the electronic structure of the Ag₂Te through the proximity effect. Based on density-functional theory (DFT) calculations, we demonstrate that such a system can be driven into either insulating or conducting phase, depending on the boundary magnetization orientation of the Cr₂O₃ layer.

RESULTS AND DISCUSSION

Hamiltonian model and phase diagram

We first illustrate the insulator-to-conductor transition using a general Hamiltonian model. We consider a 2D direct band-gap semiconductor with the Rashba effect dominating at the band edges, affected by the exchange field arising from a magnetic insulator substrate (Fig. 1a). A single-band \(k\mathbf{p}\) Hamiltonian of this...
The energy spectrum represents four bands for typical parameters corresponding to the substrate. It is seen that the energy spectrum represents four bands for typical parameters corresponding to the substrate. Their electronic structure is expected to be well captured by Eq. (1) provided that the effect of the magnetic insulator substrate, which is expected to be valid for a sufficiently wide band-gap insulator.

To elucidate this phase transition in more detail, we derive an analytic expression for the band gap. For $\hat{m}|\hat{z}$, the band gap $E_{gz}$ is given by (see Supplementary Note 1)

$$E_{gz} = E_0 - \frac{\hbar^2 \Delta^2}{2m_c} \left( \frac{1}{m_c a_c^2} - \frac{1}{m_v a_v^2} \right) - \frac{1}{2\hbar^2} \left( m_c a_c^2 - m_v a_v^2 \right).$$

where $E_0 = E_c - E_v$ is the band gap in the absence of the Rashba-Zeeman effect. For $\hat{m}|\hat{y}$ (or $\hat{m}|\hat{x}$), the band gap $E_{gy}$ (or $E_{gx}$) reads

$$E_{gy} = E_0 - 2\Delta - \frac{1}{2\hbar^2} \left( m_v a_v^2 - m_c a_c^2 \right).$$

Note that in Eqs. (2) and (3), the negative sign of the band gap implies band inversion and thus no band gap.

Using Eqs. (2) and (3), we obtain the band gaps $E_{gz}$ and $E_{gy}$ depending on parameters of the model. Figure 1c, d shows the resulting phase diagrams in the $(E_0, \Delta)$ and $(E_0, a)$ planes, respectively. It is seen that there are three distinctly different phases: I, II, and III classified according to the sign of the band gaps $E_{gz}$ and $E_{gy}$. The two-phase boundaries (shown by black lines in Fig. 1c, d) are determined by $E_{gz} = 0$ or $E_{gy} = 0$. For phases I and III, both band gaps are positive (phase I) or negative (phase III), indicating the trivial phase transition from insulator-to-insulator (phase I) or from conductor to conductor (phase III). For phase II, we observe a non-trivial insulator-to-conductor transition or via versa as a result of changing the exchange field orientation from the $z$ axis to the $y$ ($x$) axis. The illustration of this transition is revealed in the band structure of Fig. 1b, which corresponds to a set of parameters indicated by the red star in Fig. 1c.

It is evident that there is a certain range of parameters for which the insulator-to-conductor transition occurs. A smaller $E_0$ always yields the conductor phase, whereas larger $E_0$ requires the strong exchange field to induce the insulator-to-conductor transition. A larger Rashba parameter favors the transition for the system with larger $E_0$. Supplementary Figure 2 shows that the insulator-to-

**Fig. 1** Phase diagram for Rashba-Zeeman model. a Schematic illustration of the Rashba 2D system on top of a magnetic insulator. Red arrows denote the exchange field whose orientation is determined by the unit vector $\hat{m} = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta)$ in spherical coordinates. b 3D plot of the calculated band structure with $\hat{m}$ being parallel to $z$ axis $\hat{m}|\hat{z}$ or $y$ axis $\hat{m}|\hat{y}$ for $m_c = -m_v = 0.5 m_o$, $\alpha_c = \alpha_v = 1.0$ eV Å, $E_0 = 0.1$ eV, $\Delta = 0.03$ eV. c, d Phase diagram in the $(E_0, \Delta)$ plane for $\alpha_c = \alpha_v = 1.0$ eV Å. c and in the $(E_0, a)$ plane for $a = \alpha_c = \alpha_v$ and $\Delta = 0.01$ eV d. The phase boundaries are determined by $E_{gz} = 0$ or $E_{gy} = 0$. The red star in indicates a set of parameters corresponding to the band structure in b.
conductivity transition is not only limited by equal Rashba parameters \( \alpha_x \) and \( \alpha_y \) and effective masses \( m_x \) and \( m_y \) but can also occur for non-equal parameters (see Supplementary Note 2).

Electrical conductivity and anomalous Hall conductivity

The predicted insulator-to-conductor transition can be probed by measuring electrical conductivity. We calculate the conductivity \( \sigma_{xx} \) of the 2D system within the approximation of a constant relaxation time \( \tau \), as discussed in Supplemental Note 3. Figure 2a shows \( \sigma_{xx} \) as a function of Fermi energy \( E_F \). In the absence of the exchange field, \( \Delta = 0 \), \( \sigma_{xx} \) for conduction bands can be expressed analytically as follows (see Supplementary Note 3)

\[
\sigma_{xx}/\sigma_0 = \left\{ \begin{array}{ll} \sqrt{(E_F - E_c)/E_R + 1}, & E_c < E_R \leq E_F \\ (E_F - E_c)/E_R + 1, & E_R < E_F \end{array} \right.,
\]

where \( E_R = m_x \alpha_x^2/(2\hbar^2) \) is the Rashba energy and \( \sigma_0 = e^2 \tau E_R/(\hbar^2) \) is the conductivity unit. This limiting case is shown in Fig. 2a by the dashed line. We see distinct energy dependent behaviors below and above the conduction band minimum. When \( \Delta \neq 0 \), \( \sigma_{xx} \) depends on the exchange field orientation \( \mathbf{m} \). It is seen that around \( E_F = 0 \), the conductivity is zero for \( \mathbf{m} \parallel \mathbf{y} \) (red line in Fig. 2a), whereas the conductivity is nonzero for \( \mathbf{m} \parallel \mathbf{y} \) in the whole energy range (blue line in Fig. 2a). For higher Fermi energy, \( \sigma_{xx} \) scales linearly with \( E_F \), as expected from Eq. (4).

Figure 2b shows \( \sigma_{xx} \) as a function of azimuthal angle \( \theta \) for \( \varphi = 90^\circ \) and \( E_F = 0 \). The critical points for the insulator-conductor transition are around \( \theta = 0.13\pi \) and \( \theta = 0.87\pi \). In the conducting phase (aqua color), \( \sigma_{xx} \) versus \( \theta \) can be well described by \( \sigma_{xx}(\theta) = \sigma_{xx}(0) + (\sigma_{xx}(\pi/2) - \sigma_{xx}(0))\sin 2\theta \) (blue solid line), which is the conventional behavior known for anisotropic magnetoresistance\(^{29}\). Overall, changing the magnetization orientation of the substrate reveals perfect anisotropy in the conductivity of the 2D system.

Probing the anomalous Hall conductivity \( \sigma_{xy} \) provides another way to explore the phase transition. We calculate \( \sigma_{xy} \) assuming that there is only an intrinsic contribution to the anomalous Hall conductivity\(^{30}\). This contribution is determined by the Berry curvature as discussed in the Supplemental Note 4. Figure 2c shows the calculated \( \sigma_{xy} \) of the 2D system as a function of \( E_F \) for different angles \( \theta \) (determined in Fig. 1a). It is seen that \( \sigma_{xy} \) is zero in the energy gap region when \( \mathbf{m} \parallel \mathbf{z} \) (\( \theta = 0^\circ \) or \( \theta = 180^\circ \)). For \( \theta = 45^\circ \) or \( \theta = 135^\circ \), the gap is closed and \( \sigma_{xy} \) is nonzero in the whole energy range.

Figure 2d shows \( \sigma_{xy} \) as a function of \( \theta \) changing continuously from \( 0^\circ \) to \( 180^\circ \). For \( E_F = 0 \) (blue circles and line in Fig. 2a), we observe the same critical points for the insulator-conductor transition at around \( \theta = 0.13\pi \) and \( \theta = 0.87\pi \). This transition disappears at \( E_F = 0.05 \) eV (red circles and line in Fig. 2d) consistent with Fig. 2c. For any Fermi energy, there is a sign change in \( \sigma_{xy} \) at \( \theta = 90^\circ \). This sign change is explained by the properties of the Berry curvature \( \Omega_{xy} \), as demonstrated in Supplementary Fig. 4.

The above approach can be expanded to other types of SOC, such as the Dresselhaus SOC\(^{31} \) or the Rashba-Dresselhaus SOC\(^{32,33} \). The analysis of the 2D systems, which exhibit these types of SOC shows that a similar insulator-to-conductor transition can be observed in both models (see Supplementary Note 5 for details).

DFT results for Ag$_2$Te/Cr$_2$O$_3$

Next, we discuss a possible realization of the insulator-to-conductor transition in a realistic system, namely a monolayer of Ag$_2$Te deposited on a magnetic Cr$_2$O$_3$ (0001) substrate. A buckled Ag$_2$Te monolayer possesses a 2D hexagonal lattice of the P6mm symmetry and has a sizable band gap of 150 meV\(^{25} \). Owing to broken inversion symmetry, an Ag$_2$Te monolayer exhibits Rashba band splitting with a large Rashba parameter of 3.84 eV Å\(^{-1} \) (see Supplementary Note 6 for details). In a non-centrosymmetric corundum structure, Cr$_2$O$_3$ is a magnetoelectric AFM insulator which belongs to the magnetic space group is \( \text{R}^3\text{c}' \). It exhibits the surface magnetization, which is an intrinsic property of all magnetoelectric antiferromagnets\(^{35,36} \). This magnetization is
electrically switchable with an AFM order parameter of Cr$_2$O$_3$, as has been demonstrated in experiment$^{37}$. The exchange coupling between Cr$_2$O$_3$ and Ag$_2$Te across the interface in the Ag$_2$Te/Cr$_2$O$_3$ structure is mediated by the surface magnetization through the proximity effect. The recent work has shown that a topological phase of graphene can be tuned by magnetization orientation in a graphene/Cr$_2$O$_3$ system$^{38}$.

Figure 3a shows the atomic structure (produced using the VESTA software$^{39}$ of the Ag$_2$Te/Cr$_2$O$_3$(0001) system consisting of monolayer Ag$_2$Te and Cr$_2$O$_3$ substrate composed of 6 and 12 atomic layers of O and Cr, respectively. The magnetic moments of Cr atoms in Cr$_2$O$_3$ are aligned parallel in the (0001) plane and antiparallel along the (0001) direction. The Cr$_2$O$_3$ surface is terminated by a single layer of Cr, which has the lowest surface energy$^{40}$. As seen from Fig. 3b, the interface atomic configuration has one Te atom and one Ag atom located at the hollow (H) sites and another Ag atom located at the top (T) site of the Cr$_2$O$_3$ (0001) surface. This atomic configuration is among three possible highly symmetric atomic structures which have the lowest energy (see Supplementary Note 7).

Figure 3b shows the top view of the Ag$_2$Te/Cr$_2$O$_3$ structure. H1/H2 and T represent hollow and top sites, respectively. The black lines denote the unit cell, where the primitive vectors are given by $a_1 = ax$, $a_2 = -a/2x + \sqrt{3}a/2y$, and $a$ is the lattice constant. The Brillouin zone with high-symmetry $k$ points indicated, where the primitive vectors are given by $b_1 = 2\pi/ax + 2\pi/(\sqrt{3}a)y$, $b_2 = 4\pi/(\sqrt{3}a)y$.

Figure 3c shows the Brillouin zone with high-symmetry $k$ points indicated, where the primitive vectors are given by $b_1 = 2\pi/ax + 2\pi/(\sqrt{3}a)y$, $b_2 = 4\pi/(\sqrt{3}a)y$.

Figure 4a shows the atomic structure (produced using the VESTA software$^{39}$ of the Ag$_2$Te/Cr$_2$O$_3$(0001) system consisting of monolayer Ag$_2$Te and Cr$_2$O$_3$ substrate composed of 6 and 12 atomic layers of O and Cr, respectively. The magnetic moments of Cr atoms in Cr$_2$O$_3$ are aligned parallel in the (0001) plane and antiparallel along the (0001) direction. The Cr$_2$O$_3$ surface is terminated by a single layer of Cr, which has the lowest surface energy$^{40}$. As seen from Fig. 3b, the interface atomic configuration has one Te atom and one Ag atom located at the hollow (H) sites and another Ag atom located at the top (T) site of the Cr$_2$O$_3$ (0001) surface. This atomic configuration is among three possible highly symmetric atomic structures which have the lowest energy (see Supplementary Note 7).

Figure 4a shows the calculated band structure of Ag$_2$Te/Cr$_2$O$_3$ for magnetization parallel to $z$ axis. The red and blue circles denote the projection onto the Cr$_2$O$_3$ and Ag$_2$Te layers, respectively. Inset: spin projected band structure with color quantifying the expectation value of $s_z$ component. Spin textures around the $\Gamma$ point at the bottom two conduction bands denoted by b CB1 and c CB2. The in-plane spin components $s_x$ and $s_y$ are shown by arrows while the out-of-plane spin component $s_z$ is indicated by color.

Figure 4 shows the band structure and spin textures. a Layer projected band structure of Ag$_2$Te/Cr$_2$O$_3$(0001) for magnetization parallel to $z$ axis. The red and blue circles denote the projection onto the Cr$_2$O$_3$ and Ag$_2$Te layers, respectively. Inset: spin projected band structure with color quantifying the expectation value of $s_z$ component. Spin textures around the $\Gamma$ point at the bottom two conduction bands denoted by b CB1 and c CB2. The in-plane spin components $s_x$ and $s_y$ are shown by arrows while the out-of-plane spin component $s_z$ is indicated by color.

Next, we investigate the effect of magnetization orientation on the electronic band structure. Figure 5 shows the calculated...
Fig. 5  Magnetization control of band dispersion. Band structure around the Γ point for magnetization parallel to a, d x axis (\(\hat{m}\)|\(\hat{x}\)), b, e, y axis (\(\hat{m}\)|\(\hat{y}\)), c, f z axis (\(\hat{m}\)|\(\hat{z}\)). a–c Band dispersion along certain k paths. d–f 3D plot of the band structures around the Γ point. d, e Fermi contours with the red (blue) line representing the hole (electron) pocket. c Fitting to the conduction band around the Γ point is shown by the red line.

It is seen that for the in-plane magnetization, i.e., when \(\hat{m}\)|\(\hat{x}\) (Fig. 5a) or \(\hat{m}\)|\(\hat{y}\) (Fig. 5b), the band structure reveals a conducting phase characterized by electron and hole pockets crossing the Fermi energy. In contrast, for the out-of-plane magnetization \(\hat{m}\)|\(\hat{z}\), a band gap of 16 meV opens and the system is driven into an insulator phase (Fig. 5c). Thus, the Ag₂Te/Cr₂O₃ system can be either a conductor or an insulator depending on the surface magnetization direction of Cr₂O₃ substrate.

We note that in the above calculations, the polarization of Ag₂Te was pointing downward. For polarization pointing upward, the buckling height between Ag and Te layers is suppressed and the bond length between Te and Cr increases, suggesting that the Rashba effect and Zeeman field are both suppressed. The insulator-to-conductor transition does not occur. Also, it is noteworthy that the insulator-to-conductor transition is Cr₂O₃ thickness independent, as expected from the exchange field.

Figure 5d–f show 3D plots of the band structure for different magnetization orientations. The Fermi contours, which are shown in insets of Fig. 5d, e, suggest that the hole pocket is nearly a circle centered around the Γ point (red lines), whereas the electron pocket (blue lines) appears in the \(k_z\) < 0 (\(k_z\) > 0) quadrant for \(\hat{m}\)|\(\hat{x}\) (\(\hat{m}\)|\(\hat{y}\)). This behavior can be well explained by the Rashba–Zeeman model proposed earlier. According to Eq. (1), around the conduction band minimum, the dispersion along the \(k_z\) direction for \(\hat{m}\)|\(\hat{x}\) can be expressed as

\[
E_c = \frac{\hbar^2 k_x^2}{2m_z} + E_F - \sqrt{\left(\alpha k_x + \Delta\right)^2},
\]

where \(\Delta\) is negative owing to a higher band energy for spin up than for spin down (inset in Fig. 4a). Thus, we have \(E_c\) (\(k_x < 0\)) < \(E_c\) (\(k_x > 0\)), indicating that the band energy at \(k_x < 0\) is lower than that at \(k_x > 0\), which yields the band branch at \(k_x < 0\) crossing the Fermi energy. The appearance of the electron pocket at \(k_x > 0\) for \(\hat{m}\)|\(\hat{y}\) can be explained in the same way. We note that the shapes of the electron pockets are different for \(\hat{m}\)|\(\hat{x}\) and \(\hat{m}\)|\(\hat{y}\) owing to a higher \(k\)-order contribution.

Our \(k\)·\(p\) model can be used to describe the DFT calculated band structure of Ag₂Te/Cr₂O₃. Using Supplementary Eq. (1), we fit the conduction band around the Γ point (red line in Fig. 5c). The fitting yields the following Hamiltonian parameters: \(m_z = 0.5\) m₀, \(\alpha = 1.89\) eV Å⁻¹, \(E_F = 0.03\) eV. According to Supplementary Eqs. (5) and (12), the insulator-to-conductor transition can occur under the condition \(E_c < \Delta + m_0^2/2\hbar^2\). This condition is indeed satisfied, which is seen by plugging the fitted parameters into the above inequality.

Experimentally, the predicted insulator-to-conductor transition can be observed in the Ag₂Te/Cr₂O₃ (0001) heterostructure where a 180° AFM domain wall is formed in Cr₂O₃ between two domains with a uniform perpendicular-to-plane Néel vector pointing in opposite directions. In this case, in the domain wall region, the continuous rotation of the surface magnetization in Cr₂O₃ results in the formation of a conducting phase of Ag₂Te, whereas within the domains, Ag₂Te remains insulating (semiconducting). Thus, the enhancement of the electrical conductivity is expected in the domain wall region.

It is noteworthy that the predicted insulator-to-conductor transition in Ag₂Te/Cr₂O₃ may only be observed in the low temperature regime owing to the small band gap of ~16 meV (see Supplementary Note 9). Even though, as seen from Supplementary Fig. 10b, a sizable difference in conductivity between \(\hat{m}\)|\(\hat{z}\) and \(\hat{m}\)|\(\hat{y}\) does exist even at room temperature.

In addition to the Ag₂Te/Cr₂O₃ system, there are other potential candidates with different 2D materials and magnetic substrates to explore the insulator-to-conductor transition. For example, the above mentioned Bi₂Sb and LiAlTe monolayers have a smaller band gap and giant Rashba parameters. The magnetic insulator materials can be extended to FM EuO and CrI₃, and ferrimagnetic YIG. In comparison with AFM Cr₂O₃, these
magnetic insulators have an advantage of controlling their magnetization by an external magnetic field.

Noteworthy is the fact that the predicted insulator-to-conductor transition is different from the conventional metal–insulator transitions driven by structural distortions, magnetic ordering, and electron correlations via Peierls, Mott, and Slater mechanisms. Within the proposed mechanism, neither the structural distortions nor magnetostuctural transitions or electron correlations are essential. The proposed mechanism is also different from the recently predicted insulator-to-conductor transition in van der Waals spin valves. For the latter, gap closing or opening at the Dirac point is due to a change of the on-site potentials via the Zeeman effect and SOC is absent.

In summary, we have predicted the insulator-to-conductor transition that can be triggered by the exchange field via the Rashba–Zeeman, Dresselhaus-Zeeman or Rashba-Dresselhaus-Zeeman effect in 2D/FM or 2D/AFM systems and demonstrated its possible realization for a realistic Ag2Te/Cr2O3 heterostructure using first-principles calculations. We hope that our work will enrich the Rashba–Zeeman physics and stimulate experimental studies of the predicted phenomenon.

METHODS
DFT calculations
Our atomic and electronic structure calculations were performed using the projector-augmented wave method implemented in the Vienna ab initio simulation package. An energy cutoff of 400 eV for the plane wave expansion, generalized gradient approximation for the exchange and correlation functional with Hubbard-U correction were used for self-consistent electronic structure calculations. The optimized in-plane lattice constant of 4.86 Å for Ag2Te was found close to the optimized in-plane lattice constant of 4.97 Å (experimental value 4.95 Å) for bulk Cr2O3, so that the lattice mismatch was ~2%. We fixed the in-plane lattice constant to be 4.95 Å in all our calculations. The atomic coordinates were fully relaxed in the absence of SOC with the force tolerance of 0.01 eV/Å. The DFT-D3 method with Becke-Jonson damping was used to include the van der Waals corrections. A vacuum region of >20 Å along the z direction was imposed in the supercell calculations.

DATA AVAILABILITY
The data that support the findings of this study are available from the corresponding author upon reasonable request.

CODE AVAILABILITY
The related codes are available from the corresponding authors upon reasonable request.

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AUTHOR CONTRIBUTIONS

L.L.T. and E.Y.T. conceived the project. L.L.T. carried out numerical calculations. Both authors discussed the results and wrote the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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