

Advances on jacutingaite (Pt_2HgSe_3)-based materials: Natural mineral to tunable topological phases

Pradip Basnet  and Madhav Prasad Ghimire 

Central Department of Physics, *Tribhuvan University*, Kirtipur, Kathmandu 44613, Nepal



(Received 20 February 2026; accepted 8 September 2026; published 19 October 2026)

Jacutingaite, Pt_2HgSe_3 , has emerged as a model van der Waals material linking mineralogy, solid-state chemistry, and topological quantum physics. Single crystals of bulk Pt_2HgSe_3 experimentally synthesized under high-pressure and high-resolution angle-resolved photoemission spectroscopy reveal a gapped Dirac nodal-line structure along with the surface states with multiple saddle points and van Hove singularities. Furthermore, under hydrostatic pressure, transport measurements show a structure phase transition accompanied by superconductivity, with T_c reaching approximately 4.4 K at 88.8 GPa. Density functional theory calculations predict bulk Pt_2HgSe_3 to possess dual topology, characterized by weak Z_2 topology and mirror-symmetry-protected crystalline topology. Monolayer Pt_2HgSe_3 was predicted to realize a Kane–Mele-type quantum spin Hall state with a spin-orbit induced gap of $\sim 0.15\text{--}0.5$ eV, a result supported by early experimental signatures. Other theoretical studies predicted that the electronic structure and topological properties can be tuned by layer thickness, strain, electric fields, and pressures. Bilayers are shown to be initially trivial due to layer-internal inversion asymmetry, but with encapsulation within hexagonal boron nitride undergoes an electronically driven topological phase transition which narrows the trivial band gap, and a modest out-of-plane electric field reinverts the bands to restore their topology, though these mechanisms remain to be verified experimentally. This research update consolidates the theoretical and experimental advances across bulk, monolayer, and bilayer forms, with a particular focus on chemical doping, heterostructure engineering, and pressure-induced superconductivity, the last of which has been experimentally observed in bulk Pt_2HgSe_3 . Benchmark values such as band gaps, valley splittings, and critical temperatures are summarized to provide a reference for ongoing studies. We evaluate the prospects of jacutingaite-based materials for realizing quantum spin Hall, quantum anomalous Hall, and topological superconducting states with the major challenges associated with their synthesis, structural stability, and device integration. This study brings together the experimentally established properties and theoretically predicted tunability and highlights strategic directions for advancing jacutingaite-based systems toward practical applications in spintronics, valleytronics, and emerging quantum technologies.

DOI: [10.1103/nm6m-pp8c](https://doi.org/10.1103/nm6m-pp8c)

I. INTRODUCTION

Beyond the conventional classification into solids, liquids, and gases, condensed matter hosts phases governed by quantum correlations and symmetry principles. Examples include superconductors, magnets, and superfluids, which are distinguished not only by composition but also by the collective organization of their microscopic degrees of freedom. Such organizing principles are described as orders in the materials [1]. For decades, the Landau theory of symmetry breaking has provided a central framework to classify these orders and to describe phase transitions in materials [2]. However, by the late 1980s it became evident that Landau's framework was incomplete. A key example is the chiral spin state [3,4], proposed in the context of superconductivity [5,6]. Despite

sharing identical symmetries, distinct chiral spin liquids exist, demonstrating that symmetry alone cannot distinguish them. This motivated Wen *et al.* [4] to introduce quantum order and later topological order [7], characterized by long-range entanglement and global invariants such as Z_2 . As illustrated schematically in Fig. 1(a), Landau symmetry-breaking phases (e.g., ferromagnets) are described by a local order parameter, with the uniform spin alignment. On the other hand, the topological order, phases are characterized by long-range entanglement and global invariants, giving rise to protected boundary excitations as shown in Fig. 1(b).

The significance of these breakthroughs was underscored by the groundbreaking theory of topological phase transitions and phases of matter. For these pioneering contributions, in 2016, the Nobel Prize in physics was awarded to Thouless, Haldane, and Kosterlitz [8]. Their influential studies introduced quantized conductance, vortex unbinding, and topological invariants as central tools in condensed-matter physics. This laid the foundation for the emergence of topological insulators (TIs), topological superconductors, and topological semimetals [9–11].

Topology has become a cornerstone, offering a framework to classify materials based on properties that remain invariant

*Contact author: madhav.ghimire@cdp.tu.edu.np

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

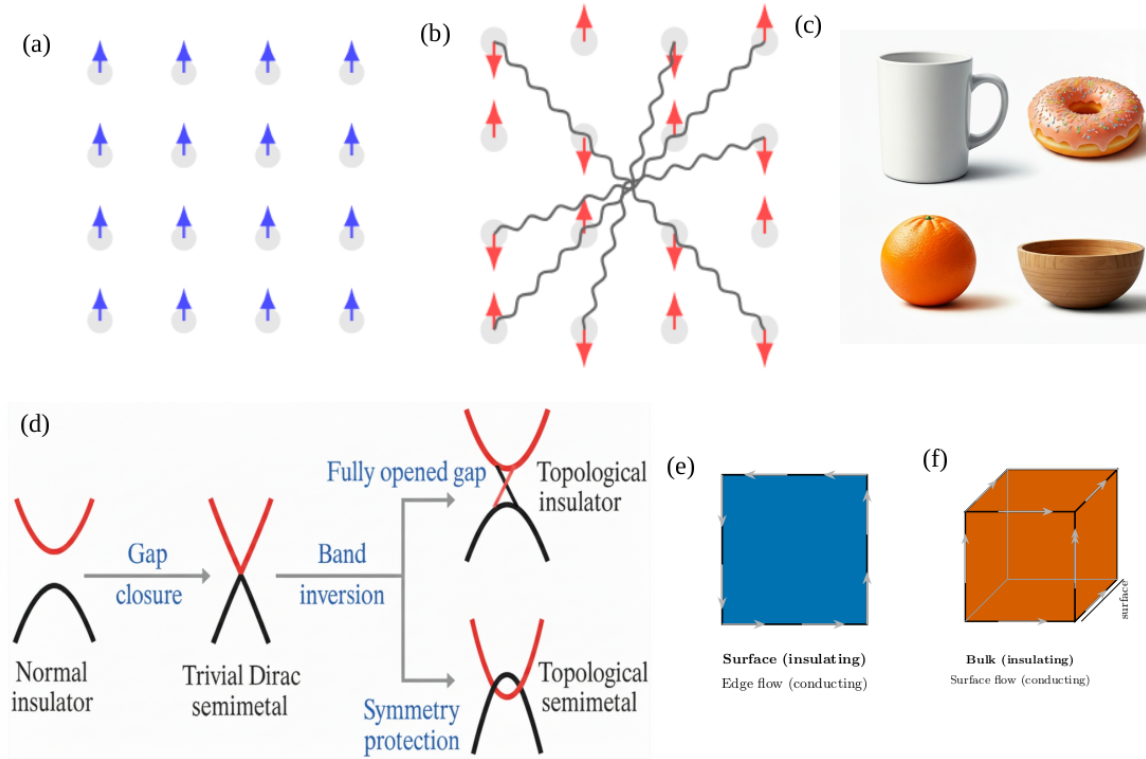


FIG. 1. Key concepts in topological phases. (a) Landau symmetry breaking. (b) Topological order. (c) Concept of topology. (d) Topological phases based on band inversion. (e) 2D TI (conducting edges) and (f) 3D TI (conducting surface states).

under continuous distortions (e.g., bending or stretching) but not discontinuous operations such as tearing or gluing [12]. In mathematics, the genus (g) of a surface captures the topology (number of holes) and relates to the Gaussian curvature (κ) by the Gauss–Bonnet theorem [13]:

$$\int \kappa dA = 4\pi(1 - g), \quad (1)$$

where the integral is over the surface area A . Under smooth deformations, two surfaces of equal genus are considered topologically equivalent and can be continuously deformed into one another. For example, an orange has genus $g = 0$, the same as a bowl has genus $g = 0$. By contrast, a donut and a cup with a handle have genus $g = 1$ [see Fig. 1(c)]. Therefore, genus-0 objects (orange/bowl) cannot be smoothly deformed into genus-1 objects (donut/cup), and vice versa. These topological features provide the foundation for understanding topological phases in materials. The study of Hall effects has been pivotal in the development of topological materials (TMs) [14,15]. Classical Hall effects [16] revealed the transverse voltage generated under a magnetic field, while the quantum Hall effect (QHE) [17] demonstrated quantized conductance. Further developments in spin-dependent transport, including spin Hall effect (SHE) [18] and anomalous Hall effect (AHE) [19], paved the way for the discovery of the QSH effect [20] and QAH effect [21] in which strong spin-orbit coupling (SOC) and magnetic doping produce dissipationless edge states defining TMs.

TMs broadly include insulators and semimetals [22] exhibiting nontrivial band topology driven by SOC [see

Fig. 1(d)]. In both two-dimensional (2D) and three-dimensional (3D) TIs, spin-momentum locking results in the edge and surface states protected from backscattering via time reversal symmetry (TRS) [23] as illustrated in Figs. 1(e) and 1(f). These phases are characterized by a Z_2 invariant, distinguishing trivial from nontrivial topological phases. Strong and weak 3D TIs are classified by their topological surface states [24]. Strong 3D TIs host gapless, topologically protected 2D Dirac cones on all the surfaces. These states display spin-momentum locking and suppressed backscattering. When the Fermi level (E_F) is located within the bulk energy gap, conduction occurs solely through these metallic surfaces. Weak 3D TIs are constructed from stacked 2D TIs with weak inter-layer coupling. Since a 2D TI possesses 1D helical edge states but no states on its interior, the side surfaces parallel to the stacking direction become metallic from these combined edge channels. Surfaces perpendicular to the stacking direction remain insulating surfaces without topological states [25,26]. The QSH effect was initially predicted and observed in platforms based on semiconductor quantum wells, for example, HgTe/CdTe [27] and InAs/GaSb/AlSb [28]. While graphene initially appeared promising due to its Dirac fermions and Z_2 topology [29–31], its weak SOC (~ 10 meV) limits practical applications. Approaches to enhance SOC using heavy adatoms or substrates yielded only modest improvements. Alternative materials with strong intrinsic SOC, such as bismuthene on a SiC substrate, offer larger gaps (0.8 eV) but face challenges like substrate interactions or structural stability [32]. Certain transition metal dichalcogenides (e.g., MoS₂, WSe₂, WTe₂) show QSH-like edge states but suffer from

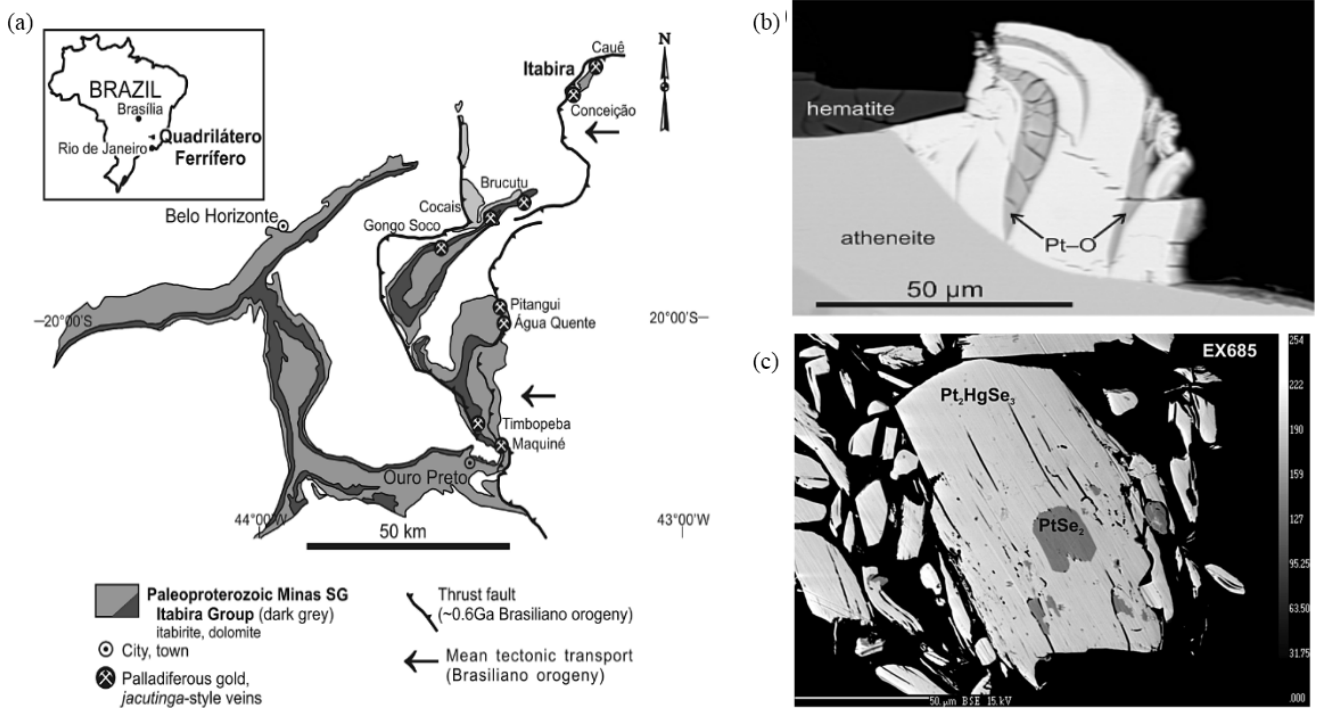


FIG. 2. (a) Geological overviews for the Quadrilátero Ferrífero in Minas Gerais, Brazil, include the Caue iron-ore deposit situated in the Itabira district, as well as other locations with hematitic auriferous veins referred to as jacutinga. (b) A polished section reveals a roughly 50 μm grain occurring together with atheneite, potarite, and hematite (adapted from Ref. [50]). (c) Back-scattered electron micrograph showing Pt₂HgSe₃ (bright) along with dark PtSe₂ inclusions, synthesized at 400 °C. The scale bar of 50 μm is shown at the lower left corner (adapted from Ref. [51]).

phase instability and oxidation. Weak 3D TIs like Bi₁₄Rh₃I₉ [33,34] and Bi₁₂Rh₃Sn₃I₉ [35,36] are more stable but difficult to exfoliate. Magnetic doping can induce topological phase transitions, as seen in Bi₂TeI [37] and Cr-doped (Bi, Sb)₂Te₃ [21,38]. Cr and Fe dopants in Bi₂Se₃ have shown to induce ferromagnetism suitable for QAHE or antiferromagnetism, while preserving the insulating nature [39,40]. Additional topological phenomena, including AHE and Weyl-induced anomalous Hall conductivity, have been observed in Fe₃Sn [41], Fe₅Sn₃ [42], TbMn₆Sn₆ [43], magnetization rotation [44], and Cr₂FeCoAs₂ [45]. PtNiO₂ and Co₃Sn₂S₂ show magnetic Weyl effects [46,47], low-dimensional systems exhibit nonlinear Hall responses [48], and kagome magnets RFe₆Ge₆ ($R = Y, Tb, Dy$) display topological magnetism [49].

Within the broader class of TMs, jacutingaite (Pt₂HgSe₃) has become a promising material because of its layered, buckled crystal structure and strong SOC [50,52]. Its monolayer hosts a Kane–Mele-type QSH phase [53], while the bulk exhibits dual topology, acting as both a weak TI and a TCI [54–56]. In Pt₂HgSe₃, doping and heterostructure engineering enable a wide variety of topological phenomena.

In this research update, we survey a comprehensive knowledge of the crystal structure, electronic structure, and topological features of jacutingaite and related compounds. We emphasize external controls such as pressure, carrier doping, chemical functionalization, van der Waals (vdW) heterostructures, and light that can drive the system across regimes, including the QSH state, the QAH effect, unconventional superconductivity, and valleytronic phases. We

conclude that, like other TIs, Pt₂HgSe₃ is found to be a promising platform for next-generation spintronics, quantum computing, low-power electronics, optoelectronics, and magnetoelectronics [57].

II. MINERAL ORIGIN AND DISCOVERY

The rich mining history of the Quadrilátero Ferrífero shaped the path that ultimately led to the discovery of jacutingaite and related platinum-group minerals. Concentrates derived from jacutinga-type ores eventually revealed several rare phases, including jacutingaite, first identified at the Caue iron-ore deposit, Itabira district, Brazil. The mineral gets its name from the jacutinga vein-type gold mineralization, which is rich in hematite. Palladiferous gold, along with Pd and Pt minerals in hematite-quartz veins, is a characteristic of jacutinga [see the geographical overview in Fig. 2(a)].

Cabral *et al.* [52] (2008) made an initial observation of the mineral species. On a combination of atheneite, potarite, and hematite, Pt₂HgSe₃ was noticed as a single grain that spans approximately 50 μm [see Fig. 2(b)]. It partially transformed to a Pt–O phase. To better understand the mineral's formation and stability, Drábek *et al.* investigated phase relations in the Hg–Pt–Se ternary system experimentally between 400 °C and 800 °C using evacuated silica-glass tubes [51]. In this system, Pt₂HgSe₃ was found to be the only ternary compound that occupies a central stability field. The phase Pt₂HgSe₃ occurs as plate-shaped crystals with a visible cleavage [see Fig. 2(c)].

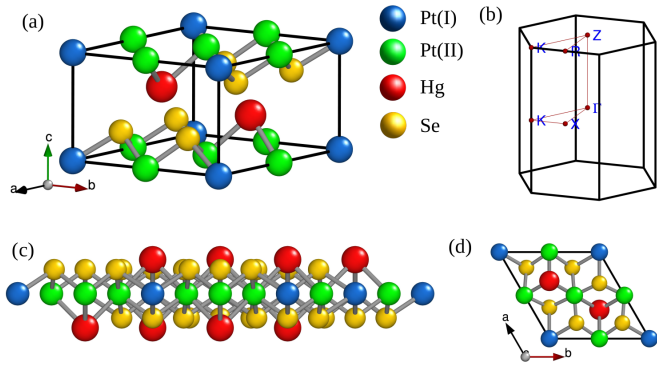


FIG. 3. Crystal structure and Brillouin zone of Pt_2HgSe_3 . (a) Three-dimensional view with inequivalent Pt sites Pt(I) (blue) and Pt(II) (green), Hg (red), and Se (yellow). (b) Schematic of the first Brillouin zone of a trigonal lattice, highlighting the high-symmetry points. (c) Side view emphasizing buckled layer stacking and vdW gaps between layers. (d) Top view showing the hexagonal in-plane Pt–Se network with Hg at the hexagon centers.

III. SYNTHESIS AND CHARACTERIZATION

Initially, the detailed structural and physical characterization was not possible to perform because the natural Pt_2HgSe_3 was available only in micrometer-sized grains,

though the material was discovered in 2008. The synthesis of Pt_2HgSe_3 was reported in 2012 by Vymazalová *et al.* [50] using the high-purity selenium (99.999%), mercury (99.999%), and platinum (99.95%) in evacuated silica tubes, following Kullerød's method [58]. A multistage annealing process at 1200 °C, 800 °C, and 400 °C produced synthetic jacutingaite with phase, composition, and structure verified through x-ray diffraction, EBSD, and microprobe techniques. Synthetic Pt_2HgSe_3 was found to be opaque with a gray metallic luster, brittle, and exhibits {001} cleavage. The separated interlayer distance was 5.3 Å, having a binding energy of 60 meV Å^{−2} [53,59], comparable to other exfoliable layered materials such as graphene, CrGeTe₃, and phosphorene [60,61].

Jacutingaite consists of two inequivalent Pt atoms (Pt(I) and Pt(II)), one Hg atom, and one Se atom in a symmetric crystal structure with trigonal space group $P\bar{3}m1$ (No. 164) having a total of 12 atoms per unit cell. The experimental lattice parameters are $a = b = 7.3477\text{Å}$, $c = 5.2955\text{Å}$, with $\alpha = \beta = 90^\circ$ and $\gamma = 120^\circ$ [50]. It belongs to the M_2NX_3 family, where $M = \text{Ni, Pd, or Pt}$; $N = \text{Cd, Hg, or Zn}$; and $X = \text{Se, Te, or S}$. The crystal structure of the material is illustrated in Fig. 3, which is derived from the $1\text{T-}MX_2$ layered transition-metal dichalcogenides, with partial replacement of chalcogen atoms by transition metal N , causing the formation of a buckled $N\text{-}M\text{-}N$ bonds [62]. It consists of buckled Pt–Se layers arranged in a hexagonal network [see Fig. 3(d)], with

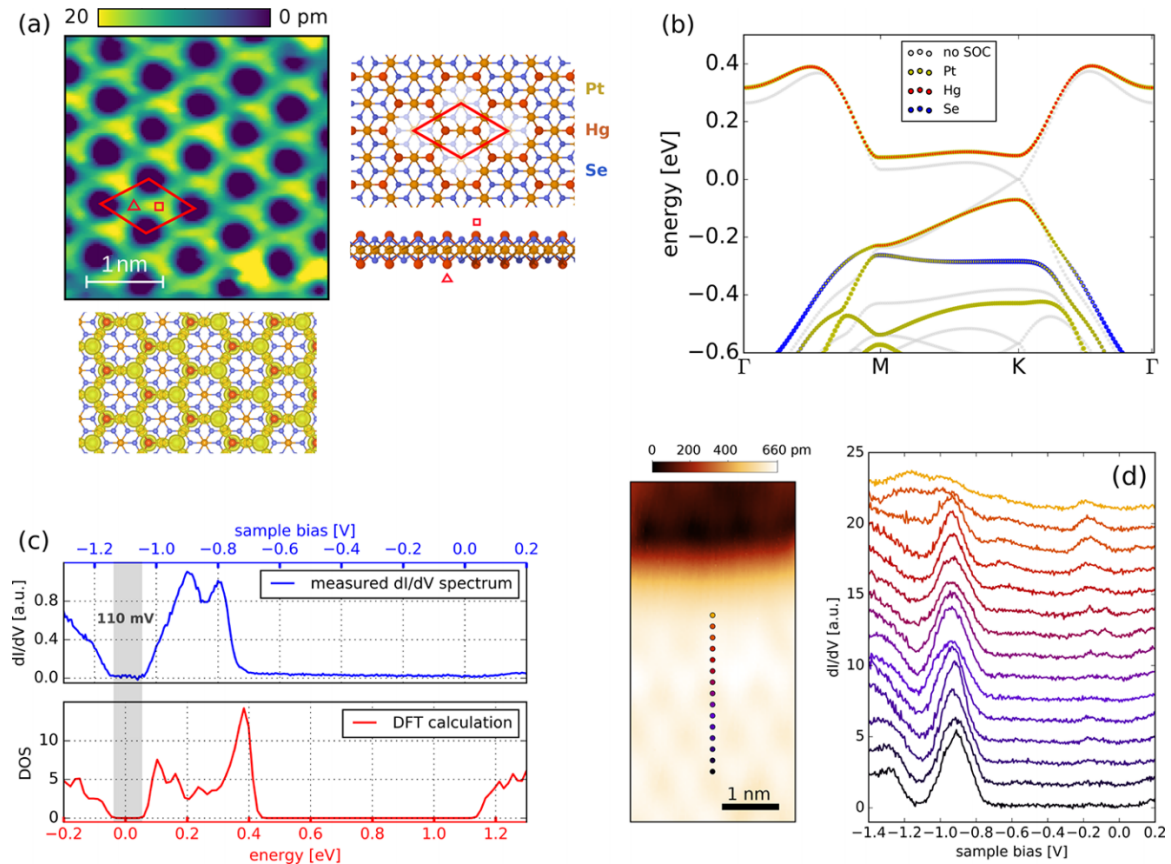


FIG. 4. (a) Atomic-resolution STM topograph of Pt_2HgSe_3 . (b) DFT band structure results for both cases with and without SOC. (c) Comparison between the measured differential conductance (dI/dV) in blue on a pristine surface and the calculated DOS (red) for the monolayer, with the band gap shaded gray. (d) Spatially resolved spectra of dI/dV measured across the step edge on the basal plane. The topographic image on the left shows the step location, and the colored dots indicate the positions of each spectrum. (Adapted from Ref. [63].)

Hg atoms occupying the center of the Pt–Se hexagons. Strong in-plane Pt–Se bonds with weak vdW coupling between layers enable mechanical exfoliation down to the monolayer limit.

Kandrai *et al.* [63] provided experimental evidence based on scanning tunneling microscopy (STM) measurements, as shown in Fig. 4, by performing measurements on exfoliated multilayer crystals of Pt_2HgSe_3 on the free defect basal plane. They also reported a bulk band gap of 110 meV with edge states located within the gap. These edge states are found to be localized at the monolayer step edges and exhibit a short decay length around 5 Å into the bulk. Their measurements are in good agreement with the density functional theory (DFT) results for the monolayer reported in Ref. [53], which reproduces the band gap, DOS, and spatial characteristics of the edge states. Their experiments showed that Pt_2HgSe_3 remains stable under ambient conditions over extended periods, ranging from several months to even a year, both in the bulk and in the exfoliated crystal layers. This long-term stability is expected to withstand not only room temperature and pressure but also the extreme conditions found in geological environments. Further, the basal plane high-resolution STM images reveal the honeycomb structure of Pt_2HgSe_3 . The measured unit cell size was reported to be 7.3 Å, which closely matches the value (7.34 Å) obtained from x-ray diffraction.

A key step in characterizing Pt_2HgSe_3 was the polarization-resolved Raman spectroscopy. This was performed by Longuinhos *et al.* [64] to establish its vibrational properties and symmetry characteristics. Measurements were carried out in a backscattering configuration. A 532 nm laser line was used for the excitation source with the power kept below 220 μW to minimize sample heating and degradation, and the laser diameter size was approximately 1 μm. Spectra were collected from 50–300 cm^{-1} range with six accumulations of 5 s. Lateral dimension of grain was ~5–10 μm, which exhibited single-crystal behavior under these conditions. Polarized Raman measurements were performed in both parallel and cross geometries with light propagating along the c axis. In accordance with Raman tensor selection rules for the centrosymmetric trigonal space group $P\bar{3}m1$, A_{1g} modes were completely suppressed in the cross-polarized configuration, whereas doubly degenerate E_g modes remained visible in both geometries. Using this polarization-dependent behavior, the authors observed nine out of eleven expected Raman-active vibrational modes, thoroughly assigned their symmetries and corresponding selection rules. The characteristic Raman features were identified at ~90.7 cm^{-1} (A_{1g}^3), 130.1 cm^{-1} (E_g^3), 180.9 cm^{-1} (E_g^2), ~201.5 cm^{-1} (A_{1g}^2 , shoulder), 205.3 cm^{-1} (A_{1g}^1), and 210.5 cm^{-1} (E_g^1), while a low-frequency E_g^4 mode predicted near 74.2–75.8 cm^{-1} was not detected, likely due to an intrinsic lower scattering efficiency. This polarization-resolved approach (as illustrated in Fig. 5) provides a reliable vibrational fingerprint for Pt_2HgSe_3 , enabling precise phase identification and serving as a sensitive probe of structural modifications, defects, strain, and interlayer interactions in both bulk and few-layer forms of the material. Additional computational details related to this study can be found in Ref. [64].

Lima *et al.* [62] proposed an extended family of Pt_2HgSe_3 , like $M_2\text{NX}_3$ materials. These materials retain the

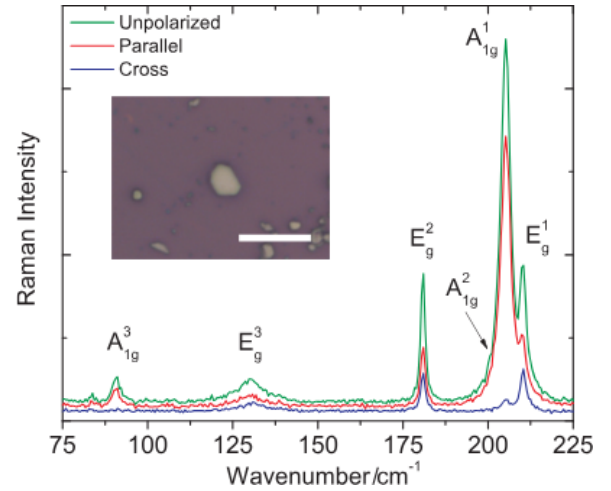


FIG. 5. Raman spectra of bulk Pt_2HgSe_3 crystals measured under unpolarized (green), parallel (red), and cross (blue) polarization configurations. The inset shows an optical micrograph of a freshly cleaved crystal (center) used for measurement (scale bar: 10 μm). (Adapted from Ref. [64].)

buckled honeycomb geometry and strong SOC of Pt_2HgSe_3 . First-principles calculations show that many members are thermodynamically stable, convex-hull analysis placed several members of the family on or close to the stability line, and their cleavage energies are comparable to graphene, suggesting that mechanical exfoliation is experimentally feasible. For example, Pt_2HgSe_3 possesses a cleavage energy of 0.46 J/m², close to the value of graphene (0.39 J/m²) [65]. In the absence of SOC, they found the appearance of Dirac cones from the hexagonal N - M - N buckled lattice near E_F and composed by transition metal $N(s)$ and $M(d)$ states, i.e., Ni (3d), Pd (4d), and Pt (5d). The energy bands display a linear dispersion in different high symmetries path, leading to a Dirac point. However, the contribution of SOC induced energy band gaps at the Dirac points, whose magnitude depends on the metal and chalcogen composition. Further, their Z_2 calculations showed that all Hg-based materials depict a nontrivial topological phase, while N_2ZnX_3 and Pd_2CdX_3 transformed from trivial to nontrivial topological phases for $X = \text{S} \rightarrow \text{Te}$. Moreover, they calculated other properties such as mechanical strain and work functions. The family compounds were found to be robust against biaxial strain. The presence of strain further increased the SOC-induced energy band gap, such as in the case of Pt_2ZnSe_3 it increased from 178 meV to 185 meV under compression of 2%, and it reached up to 194 meV in Pt_2ZnTe_3 by 2.5% compression. Another key property was work functions of these materials, for example, 4.90 eV in Pt_2HgSe_3 , 4.70 eV in Pt_2ZnSe_3 , 4.73 eV Pt_2HgTe_3 , and 4.43 eV in Pt_2ZnTe_3 . These properties make this family promising for spintronic and valleytronic devices, extending the Kane-Mele model to a broader class of experimentally accessible materials

IV. INTRINSIC TOPOLOGICAL CHARACTER

A. Bulk: A dual topological insulator

We carried out first-principles calculations using the (FPLO) code (v22.00-62) [66] within DFT formalism,

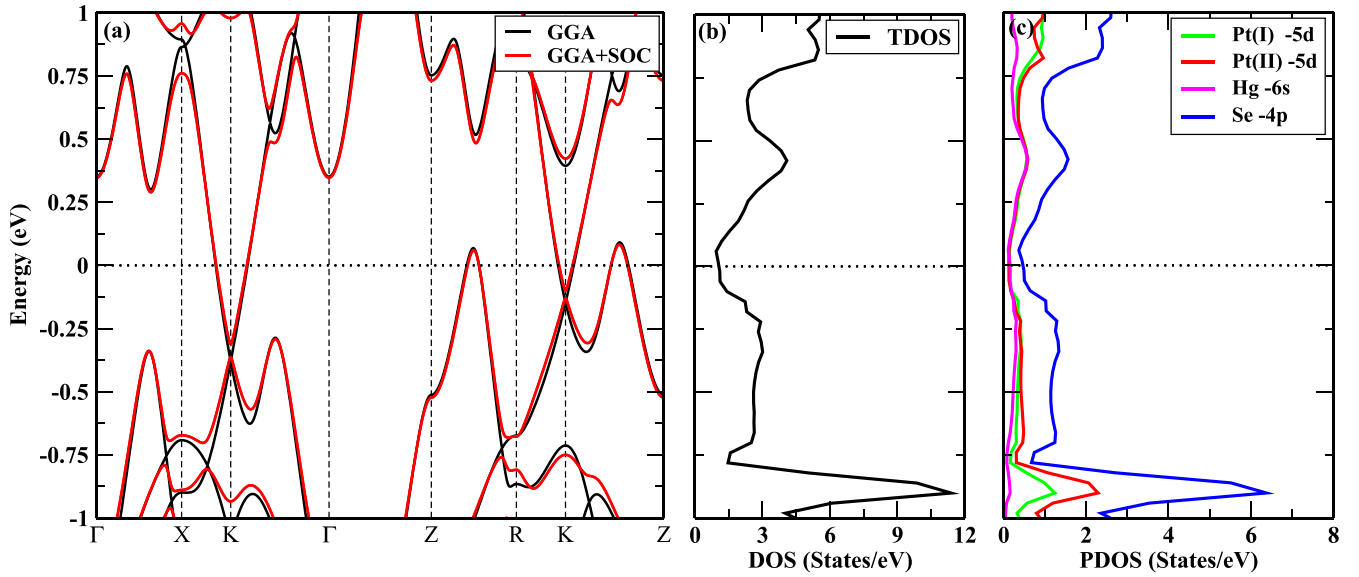


FIG. 6. (a) Band structure of Pt_2HgSe_3 (GGA and GGA + SOC). (b) Calculated total density of states (TDOS) and (c) projected density of states (PDOS) for the system showing contributions from Pt(I), Pt(II), Hg, and Se orbitals.

using the generalized-gradient approximation parametrizations of Perdew–Burke–Ernzerhof (GGA-PBE) for the exchange–correlation functional [67]. Both scalar-relativistic (without SOC) and full relativistic (with SOC) calculations were carried out. Figure 6(a) illustrates the band structure along the Brillouin zone’s high-symmetry paths. Without SOC, Pt_2HgSe_3 shows the Dirac-like cone with a Dirac point at the high symmetry points K and K' , and along with the appearance of electron as well as hole pockets around E_F . The contribution of SOC induced the energy band gap at the Dirac point, lifting degeneracies and indicating a topologically nontrivial phase. Notable SOC effects occur along the valence band (Γ –X, X–K, Z–R) within -0.65 eV and conduction band (X–K, K– Γ , K–Z) within $+0.55$ to $+0.9$ eV. Total and projected density of states (DOS) are shown in Figs. 6(b) and 6(c) indicate a clear reduction in the total DOS near the Fermi level supporting semimetallic character, with partial DOS revealing dominant contributions from Pt(I) and Pt(II) of $5d$ orbitals, Se of $4p$ orbitals, and Hg of $6s$ orbitals. The electronic structure of Pt_2HgSe_3 reveals topological features arising from the interplay of SOC, inversion symmetry, and its layered crystal structure. Here, we systematically analyze the bulk topological properties, including Z_2 invariants, mirror and weak indices, and the manifestation of surface states. The Z_2 topological invariants are fundamental for classifying topological phases in 3D systems. Using the Fu–Kane parity criterion at the time-reversal invariant momenta (TRIM) [24,68], Z_2 invariants are determined based on the parity eigenvalues of the occupied states. The four independent indices ($\nu_0; \nu_1, \nu_2, \nu_3$) define the topology: $\nu_0 = 1$ indicates a strong TI, while $\nu_0 = 0$ with at least one nonzero weak indices (ν_1, ν_2, ν_3) corresponds to a weak TI. The calculated Z_2 index set of Pt_2HgSe_3 is $(0; 001)$, confirming its classification as a weak TI, in agreement with previous studies [54–56,62,69].

Facio *et al.* (2019) [54] demonstrated that bulk Pt_2HgSe_3 possesses both a weak topological insulating phase and a mirror-protected topological crystalline phase. To capture the

key features of this dual topological character in materials with threefold rotational symmetry, they developed minimal tight-binding (TB) models. Initially, their focus was on evaluating the Z_2 time-reversal polarization invariants and observed weak indices, i.e., $(0; 001)$. Additionally, mirror symmetries play a crucial role in defining the topological properties of Pt_2HgSe_3 . The authors identified three mirror planes in momentum space, allowing the classification of Bloch states by mirror eigenvalues ($\pm i$). This separation enables the calculation of mirror Chern numbers, where a nonzero value indicates the presence of symmetry-protected surface states. In Pt_2HgSe_3 , the mirror Chern number is -2 for all three mirror planes, establishing a TCI phase. This dual topology arises from the interplay between time-reversal and mirror symmetries. Note that the term weak TI, TCI, and semimetal applied to bulk Pt_2HgSe_3 , were used interchangeably in the literatures. The classification as a weak TI, characterized by the Z_2 indices $(0; 001)$, and as a TCI, characterized by a mirror Chern number of -2 , both describe the symmetry-protected band topology, derived from time-reversal and mirror-symmetry considerations [54]. These classifications represent two complementary and simultaneous topological characteristics of the same band structure, giving rise to dual topology. The term semimetal, on the other hand, refers to the electronic character of the bulk near E_F reflects negligible density of states [see Figs. 6(b) and 6(c)] and does not constitute to topological classification. Thus, bulk Pt_2HgSe_3 can simultaneously exhibit weak TI and TCI character while displaying semimetallic electronic behavior, consistent with its vanishingly small bulk band gap (~ 0 eV; see Table I).

Surface spectral densities calculations for semi-infinite systems were produced by cleaving the crystal perpendicular to the $[100]$ or $[001]$ directions. In both cases, Facio *et al.* [54] used Hg-terminated surfaces. A TB Hamiltonian built from Wannier functions (Hg/Pt $6s, 6p, 5d$; Se $4p$) was employed. The momentum-resolved spectral density of the $[100]$ surface along the surface-TRIM path $\bar{\Gamma} \rightarrow \bar{X} \rightarrow \bar{R} \rightarrow \bar{Z}$ is shown in

TABLE I. DFT-derived band gap at the K point and vertical offset Δz between Hg and Pt atoms in various Pt_2HgSe_3 structures [76].

Structure	Gap at the K point (meV)	Δz (Hg–Pt) (Å)
Bulk	<1	1.84
Monolayer	168	1.73
Bilayer	290	1.81 (inner Hg) 2.02 (outer Hg)
BN/Bilayer	44	1.78 (outer Hg, capped) 1.80 (inner Hg, capped) 1.78 (inner Hg, free) 1.90 (outer Hg, free) BN/Bilayer/BN
		1.78 (outer Hg)
		1.80 (inner Hg)
		1.84 (middle layer)
		1.81 (inner Hg, outer layer)
		2.02 (outer Hg, outer layer)
Trilayer	<1	

Fig. 7(a) has an appearance of two Dirac cones at the centered of $\bar{X}$ and $\bar{R}$. For the [001] surface [see Fig. 7(b)], two Dirac cones are found at $\bar{X}$, consistent with a mirror Chern number $|C_M| = 2$, even though projected bulk states close the overall surface gap.

Following up a year later, Cucchi *et al.* (2020) [70] employed high-resolution angle-resolved photoemission spectroscopy (ARPES) combined with DFT for the investigation of the momentum-resolved electronic structure in Pt_2HgSe_3 , providing experimental evidence of its dual topological nature. Building on ARPES measurements, they reported that topological surface states (TSS) of Pt_2HgSe_3 show an unusual energy–momentum behavior. Figure 8 shows constant-energy maps around the M points. As the energy moves from E_F to higher binding energy and passes the Dirac point, the intensity pattern changes abruptly. At low binding energies, the TSS forms paired, croissant-shaped contours stretched along k_x ; at higher energies, they become almost elliptical and extend along k_y . The dispersion cuts show that along k_y the bands resemble a Rashba-type spin-split surface state, whereas along k_x the upper branch bends slightly with shallow peaks far from the Dirac point. By fitting the energy positions of the two branches for several k_x values around M , the full energy–momentum surface was reconstructed, revealing a complex shape with several saddle points. These produce a couple of clear van Hove singularities (vHs_1 and vHs_2), sharp peaks at about -266 meV and -239 meV.

B. Monolayer: A large gap QSH insulator

As reported by Bafekry *et al.* [71], the monolayer Pt_2HgSe_3 crystallizes in a hexagonal primitive cell (trigonal $P\bar{3}m1$, No. 164) having a similar form as a $2 \times 2 \times 1$ PtSe_2 supercell, with Hg atoms occupying anticubo-octahedral voids in the Se framework. The atomic structure is illustrated in Fig. 9(a), where the red parallelogram shows the hexagonal primitive cell and the lattice constant is 7.60 Å. They present the charge density difference map in Fig. 9(a), with blue (accumulation) and yellow (depletion). The electrons concentrated around Se

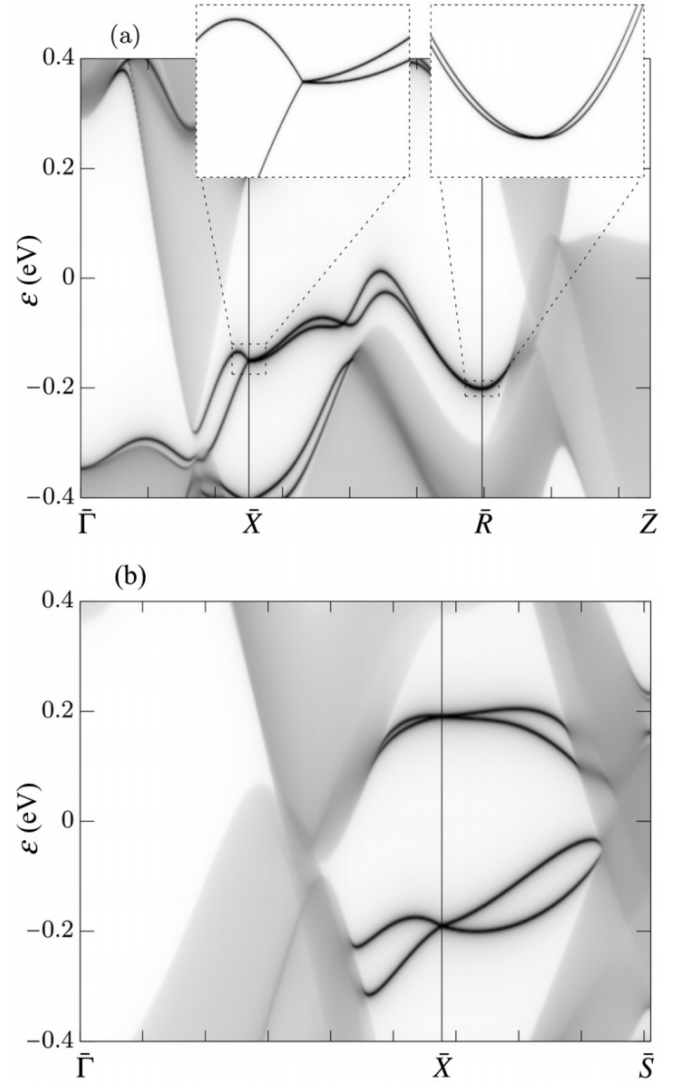


FIG. 7. Surface spectral densities resolved by momentum. (a) [100] surface: Dirac cones tied to the weak topological index appear at $\bar{X}$ and $\bar{R}$, (b) [001] surface: two Dirac cones at $\bar{X}$ reflect the mirror Chern number $|C_M| = 2$. (Adapted from Ref. [54].)

in accordance with the Pauling electron negativity (Pt for 2.28, Hg for 2.00, Se for 2.55); this difference in electron negativity defines electron transfer from Pt/Hg toward Se. Their Mulliken analysis yields charges of $+0.18e$ for Pt, $+0.17e$ for Hg, and $-0.19e$ for Se. Positive values correspond to electron loss and negative values to electron gain. As shown in Fig. 9(b), the freestanding monolayer exhibits no imaginary phonon modes, confirming dynamical stability. Further, their calculation shows that in the case of without SOC, the band structure of monolayer Pt_2HgSe_3 is gapless semiconductor having linear band dispersion at the high-symmetry K point (massless Dirac fermions), whereas including the effects of SOC results in a gapped and continuous band gap of ~ 160 meV between valence and conduction bands. The valence band maximum (VBM) and the conduction band minimum (CBM) lie at the K point; projected DOS assigns VBM mainly to Hg- s /Se- p_z and the CBM to Pt- d_{xz} and Hg- s contribution [see Figs. 9(c)–9(e)].

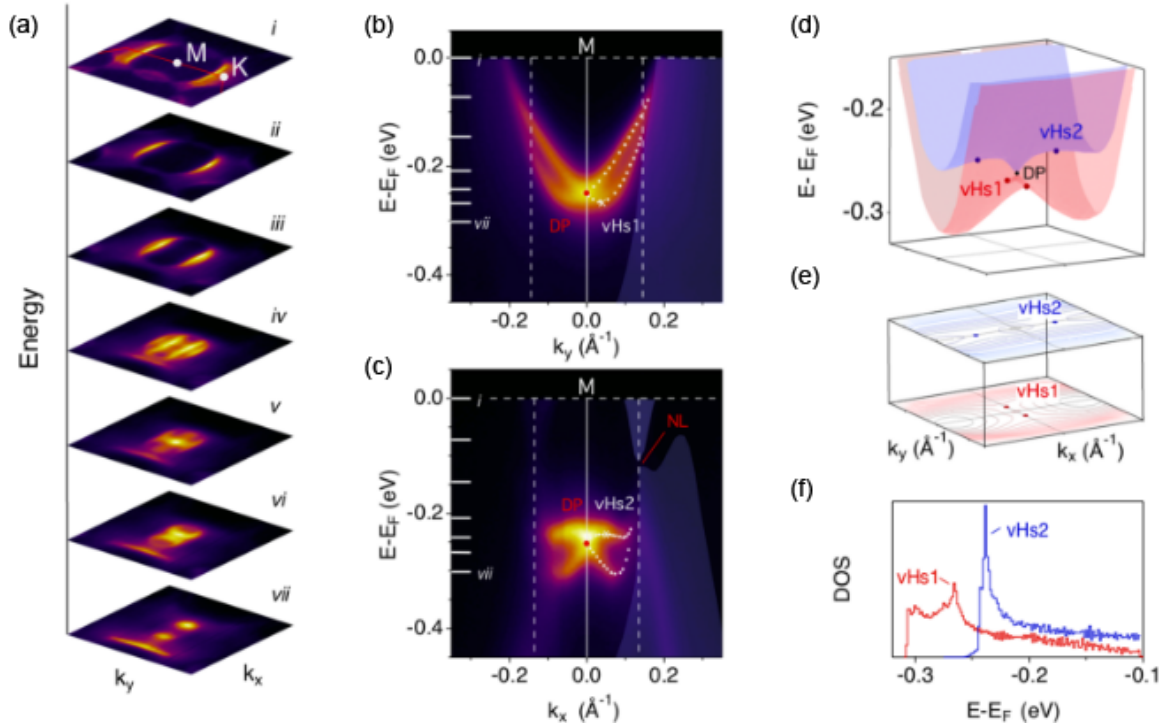


FIG. 8. TSS dispersion. (a) Constant-energy maps near M . (b), (c) Cuts along KMK (k_y) and $\Gamma M\Gamma$ (k_x) with surface/bulk fits. (d) Reconstructed 3D $E-k$ surface over the marked window. (e) Isoenergy contours of lower/upper branches. (f) $\varepsilon(k)$ histograms showing van Hove peaks. (Adapted from Ref. [70].)

Marrazzo *et al.* [53] constructed a two-band TB model from maximally localized Wannier functions (MLWFs) [72,73] to capture the low-energy electronic structure of monolayer Pt_2HgSe_3 . Without SOC at the DFT level, the

system displays Dirac-like dispersion at the K point. In contrast, inclusion of SOC opens an indirect band gap on the order of 0.15 eV, originating from relativistic effects of Pt and Hg atoms. The resulting Kane–Mele-type Hamiltonian

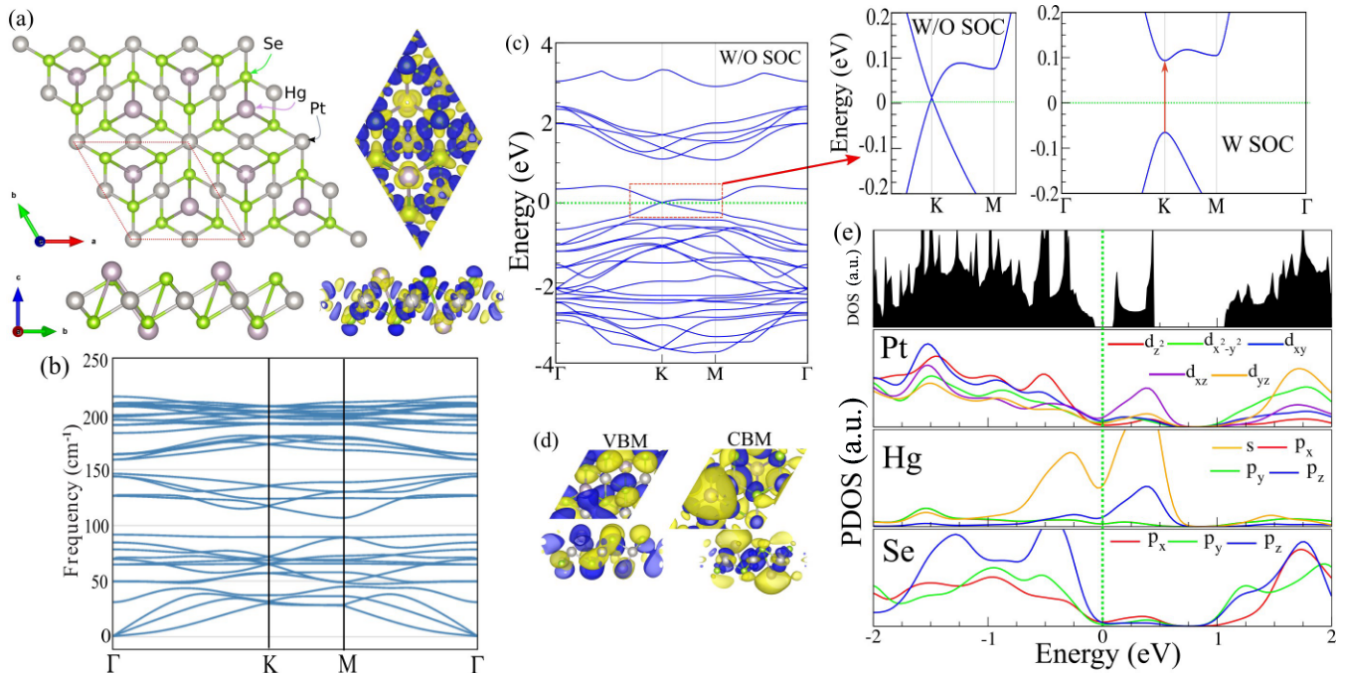


FIG. 9. (a) Atomic structure of the monolayer Pt_2HgSe_3 . (b) Phonon band dispersion. (c) Electronic band structures of monolayer Pt_2HgSe_3 computed without and with SOC; insets enlarge the region near the Fermi level. (d) Electronic states corresponding to the VBM and CBM. (e) DOS and orbital-projected DOS (with SOC). (Adapted from Ref. [71].)

preserves crystalline symmetries and produces a nontrivial Z_2 invariant that confirms the quantum spin Hall insulator (QSHI) nature. Further, to assess the results of DFT, they perform many-body G_0W_0 calculations in the case of SOC, which increases the band gap up to 0.53 eV and shows a direct band gap at K point. Their edge state calculations show linearly dispersing modes bridging the bulk gap, providing further evidence of topologically protected conduction channels. For the mechanical stability, they used density functional perturbation theory (DFPT). In the case of SOC, it shows dynamically stable phonon spectra across the Brillouin zone while DFPT calculations without SOC reveal a soft phonon mode at the Γ point, which breaks inversion symmetry, resulting in a reduction of space group from $P\bar{3}m1$ (No. 164) to $P3m1$ (No. 156). They also studied the effect of encapsulating the monolayer with hexagonal boron nitride (h-BN). The resulting BN/Pt₂HgSe₃/BN heterostructure remains QSHI, showing a DFT calculated band gap of approximately 0.16 eV, which is identical to the 0.15 eV gap of the pristine Pt₂HgSe₃ monolayer. Such encapsulation can be advantageous, as it helps protect the monolayer from environmental degradation, particularly from oxygen exposure, similar to its role in stabilizing other well-known 2D materials [74,75].

V. ENGINEERING QUANTUM PHASES THROUGH EXTERNAL CONTROL

A. Layer-dependent topology

Bafekry *et al.* [71] mapped practical control knobs for Pt₂HgSe₃ using full relativistic first principles calculations. The presence of a buckling lattice in a monolayer provides potential difference between two sublattices, giving a path to tuning electronic properties in the application of perpendicular electric field. The freestanding monolayer is dynamically stable and shows a topological insulating state with SOC band gap of 160 meV. With increasing the electric field from 0.0 V Å⁻¹ to 0.5 V Å⁻¹ the gap narrows to 10 meV at 0.5 V Å⁻¹ and regains its original value at 1.0 V Å⁻¹. Their results show that a V-shaped band gap tuning versus perpendicular field centered at 0.5 V Å⁻¹.

They observed that increasing the number of layers only slightly alters the electronic structure, with the band gap showing a minor reduction as the thickness increases. The band gap decreases from 150 meV in the bilayer to 140 meV in the trilayer, and remains 140 meV in the tetralayer and pentalayer. In bilayers, decreasing the interlayer spacing drives a direct to indirect transition while maintaining gaps of about 150 meV for separations 5.31–5.01 Å. Their findings show that applying either tensile or compressive strain leads to a notable modification of the band gap. In-plane strain provides additional tuning: under uniaxial compression, the gap evolves from 158 meV (1%) to the 125 meV (6%) and then recovers to 145 meV at 10%; under biaxial compression it first increases from 165 meV (1%) to 177 meV (4%), but then decreases from 170 meV at 6% to 0 meV at 8%, signaling a metalization threshold. Together, field, thickness, interlayer coupling, and strain define a practical parameter space for engineering Pt₂HgSe₃ [71]. Bilayer Pt₂HgSe₃, composed of two stacked monolayers of Pt₂HgSe₃, is typically expected

to behave as a topologically trivial insulator due to the cancellation of edge states from each layer. This outcome aligns with the fact that the Z_2 topological invariant only distinguishes between odd and even numbers of edge state pairs, meaning $\nu_{bi} = 1 + 1 \equiv 0 \pmod{2}$. However, stacking three layers produces a nontrivial system. As the number of layers increases, the topological character alternates between trivial and nontrivial, and in the limit of many layers, this pattern leads to a weak TI phase that depends on the periodicity of the system along the stacking direction [24]. Rademaker and Gibertini [76] investigated the electronic and topological properties of freestanding, capped, and encapsulated bilayer Pt₂HgSe₃ using first-principles calculations. They found that the freestanding bilayer is a large-gap trivial insulator. At the level of the generic stacking argument, the Z_2 topology of two identical layers can cancel when the layers are combined, so an even number of topological layers does not necessarily yield a nontrivial Z_2 index. In the actual bilayer, however, the triviality has an additional microscopic origin: sublattice imbalance and the resulting inversion-symmetry breaking modify the spin-orbit coupling and compete with sublattice-dependent next-nearest-neighbor hopping, yielding a $0 + 0$ state in which both layers are trivial. Interestingly, when the bilayer is placed between h-BN sheets, i.e. encapsulation takes place, it reduces the energy gap significantly to small value due to the competition between sublattice-symmetry breaking and sublattice-dependent next-nearest-neighbor hopping. As shown in Fig. 10, different stacking configurations, free-standing, capped h-BN, and encapsulated h-BN significantly impact the electronic band structure. Table I summarizes the corresponding band gaps and vertical displacements between Hg and Pt atoms.

Full h-BN encapsulation restores sublattice symmetry and reduces the band gap to 27 meV, enabling a field-induced topological phase transition. Small application of a perpendicular electric field to the encapsulated bilayer drives the system back into a topological phase, resulting in a QSHI. Figure 11 demonstrates that a perpendicular electric field closes the band gap near the K point at approximately 0.3 V/Å and reopens it with band inversion, marking the onset of a QSHI phase. These findings suggest that encapsulated bilayer Pt₂HgSe₃ could serve as a gate-tunable topological material for future quantum device applications. They also examined the trilayer; unlike the bilayer cases, the trilayer is metallic, mainly due to strong interlayer coupling between the outer layers [76], similar to the second-nearest-layer hopping in bulk Pt₂HgSe₃ [56].

B. Chemical modification and doping

To assess the robustness of the topological phase transition in the jacutingaite family, we carried out bulk calculations combining DFT and a Wannier-based Wilson loops analysis within a tight-binding framework implemented in FPLQ. We studied the alloy series Pt₂Hg_{1-x}Tl_xSe₃ ($x = 0.25, 0.50, 0.75, 1$): we identified Pt₂HgSe₃ ($x = 0$) is a weak topological semimetal phase with $Z_2 = (0; 001)$. However, Pt₂TlSe₃ ($x = 1$) is a strong topological metal with $Z_2 = (1; 000)$ [69]. Building on this baseline, we checked that the transition holds across the jacutingaite family. We then explored Pt₂HgTe₃

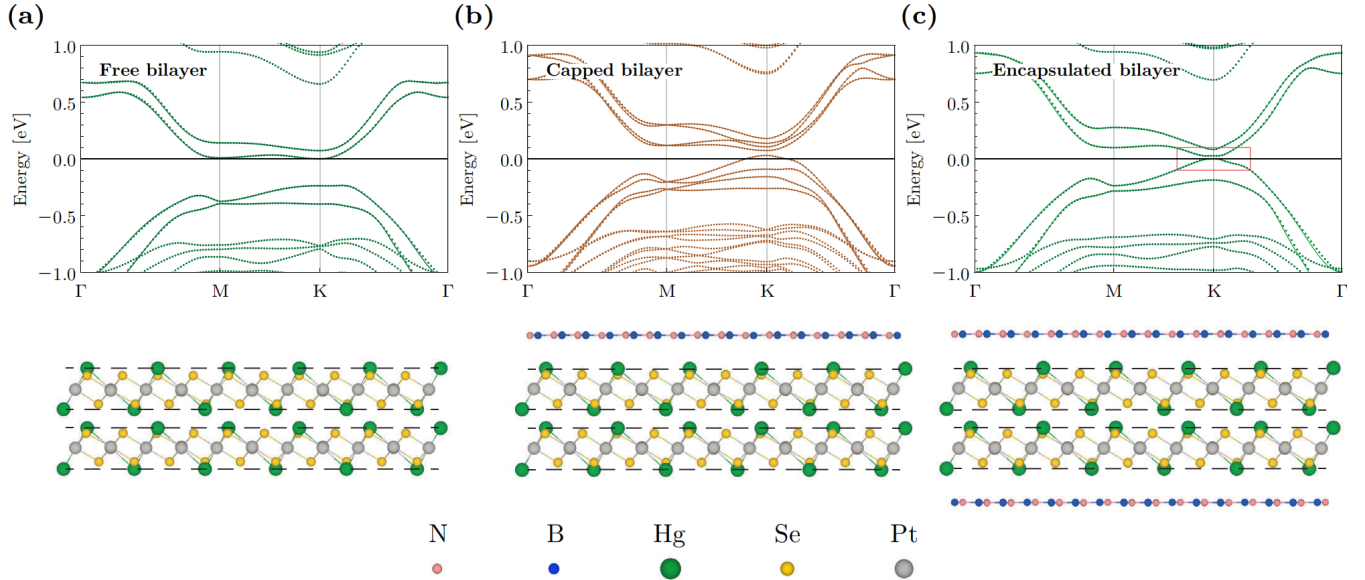


FIG. 10. Side and top views of bilayer Pt_2HgSe_3 in three configurations: (a) freestanding, (b) capped h-BN, and (c) encapsulated h-BN. Top panels show band structure along the path Γ -M-K- Γ , with dots from first-principles calculations and lines from Wannier interpolation. Sublattice asymmetry is reduced by h-BN capping and nearly eliminated by full encapsulation. (Adapted from Ref. [76].)

considering electron doping using DFT with SOC and the virtual crystal approximation (VCA) as implemented in FPLO. The pristine compound exhibited a SOC induced bulk band gap of about 29 meV. Increasing electron concentration on the Te sublattice of compound $\text{Pt}_2\text{Hg}(\text{Te}_{1-x}\text{I}_x)_3$, the Fermi level shifted toward the conduction region. Topological analyses showed that the undoped Pt_2HgTe_3 is a weak TI with a few Dirac-like features near E_F ; at 5% doping, the material showed a topological metal, this character persisted for $< 15\%$ doping, and at $\geq 15\%$ it transformed into a trivial metal as illustrated in Fig. 12 [77].

C. Chemical functionalization for QAH effect

Luo *et al.* [78] demonstrated a transition from the QSH to the QAH phase in 2D Pt_2HgSe_3 through chemical surface functionalization by combining DFT and TB modeling. They

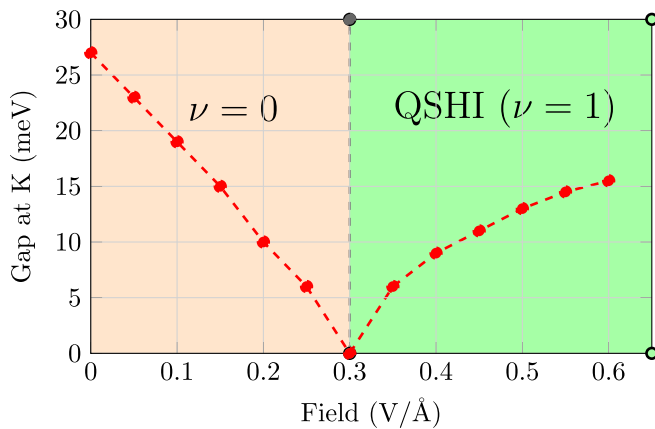


FIG. 11. Evolution of direct gap at K point versus external electric field, indicating transition to a QSH insulator ($\nu = 1$) near $E_{\text{ext}} \approx 0.30 \text{ V}\text{\AA}^{-1}$.

considered the functionalization of Pt_2HgSe_3 by adsorption of S, Se, and Te. Figure 13(a) illustrates the ground state of $\text{Pt}_2\text{HgSe}_3\text{-X}$ ($X = \text{S}, \text{Se}, \text{Te}$) with the chalcogen adsorbed on top of the Hg atom. Unlike pristine Pt_2HgSe_3 , which is nonmagnetic, $\text{Pt}_2\text{HgSe}_3\text{-X}$ develops a spontaneous magnetic moment $1 \mu_B$ on each chalcogen atom. This magnetic moment comes from an unpaired electron. Each chalcogen has two electrons available: one forms the Hg-X bond, and the other remains unpaired, giving a magnetic moment. The localized spin is visible in the real space spin density map [Fig. 13(b)]. They further compared total energies for the ferromagnetic (FM) state and several antiferromagnetic (AFM) patterns which shows $\text{Pt}_2\text{HgSe}_3\text{-X}$ has an FM ground state. The underlying electronic structure is well described by a four-band model involving chalcogen p_x/p_y orbitals on a hexagonal lattice. When SOC and magnetization are introduced, it enters a topologically nontrivial QAH phase, characterized by chiral edge states which was further supported by a nonzero Chern number and a quantized Hall conductance. Importantly, the size of the SOC-induced gap increases with the atomic

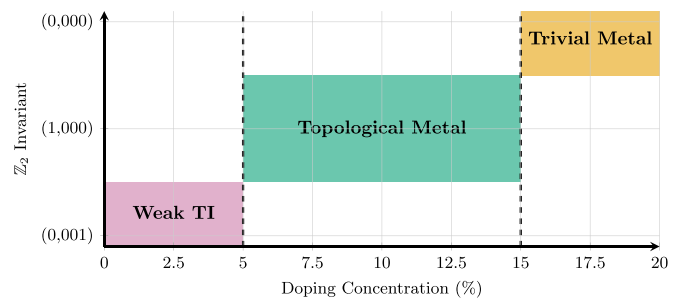


FIG. 12. Topological phase diagram for Pt_2HgTe_3 as a function of the electron doping. Vertical dashed lines at 5% and 15% mark phase boundaries between weak TI, topological metal, and trivial metal.

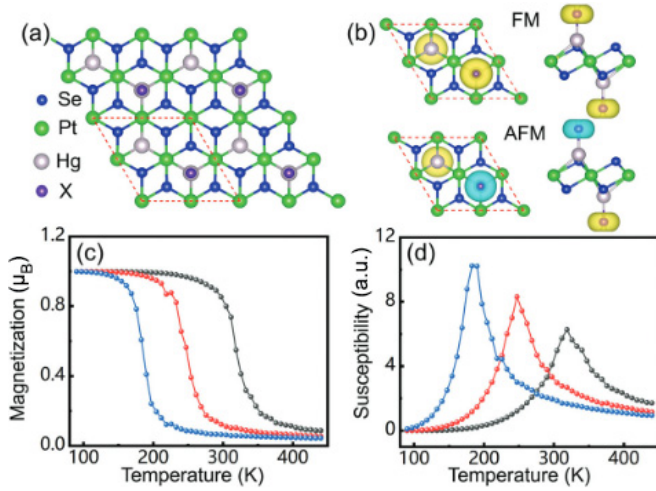


FIG. 13. (a) Optimized structure of chalcogen-functionalized jatacingaite (Pt₂HgSe₃-X, X = S, Se, Te); blue, green, grey, and purple spheres represent Se, Pt, Hg, and chalcogen atoms. (b) Spin density plots of Pt₂HgSe₃-S in FM and AFM states. (c), (d) MC-simulated magnetization, and susceptibility vs temperature, estimating Curie temperatures of 196 K (S), 245 K (Se), and 316 K (Te). (Adapted from Ref. [78].)

number of the functionalizing chalcogen atom, reaching up to 0.28 eV for tellurium substitution. To evaluate the thermal stability of adsorption induced ferromagnetism in functionalized Pt₂HgSe₃, they used Monte Carlo simulations based on the Ising model to estimate Curie temperatures. They reported exchange interaction parameter of 7.9 meV for Pt₂HgSe₃-S, 13.8 meV for Pt₂HgSe₃-Se, and 10.4 meV for Pt₂HgSe₃-Te. The temperature-dependent magnetization and susceptibility curves show clear ferromagnetic to paramagnetic transitions, giving Curie temperatures of 196 K, 246 K, and 316 K for S, Se, and Te functionalization, respectively [see Figs. 13(c) and 13(d)]. These results suggest a viable path toward engineering large gap QAH phases in realistic materials, with potential applications in low dissipation electronic and spintronic devices.

Vargiamidis *et al.* [79] explored the topological phase of monolayer Pt₂HgSe₃ by considering the combined effects of intrinsic SOC, a staggered sublattice potential V arising from an applied perpendicular electric field, and unequal magnetic exchange fields m_b and m_t on the bottom and top Hg sublattices respectively. Two regimes: (i) $m_b < \lambda_{SO}$ and (ii) $m_b > \lambda_{SO}$, where λ_{SO} is the intrinsic SOC. In regime (i) with $V = 0$, the system remains a (TRS-broken) QSH insulator. As V increases, it transitions first to a valley polarized metal (VPM) and then to a quantum valley Hall (QVH) phase, passing through a single Dirac cone (SDC) semimetal at each boundary. To identify these phases, they computed Chern numbers and spin/valley resolved Hall conductivities and showed that the quantization persists up to 90 K. In regime (ii) ($m_b > \lambda_{SO}$), with Rashba SOC included, spin bands overlap and spin along z direction is no longer conserved; with $V = 0$, the system becomes a valley polarized quantum anomalous Hall (VP-QAH) state characterized by total Chern number $C = 1$ and valley Chern number $C_v = -1$. Increasing V drives the system through VP-QAH $\rightarrow$ VPM $\rightarrow$ QVH; reversing the sign of

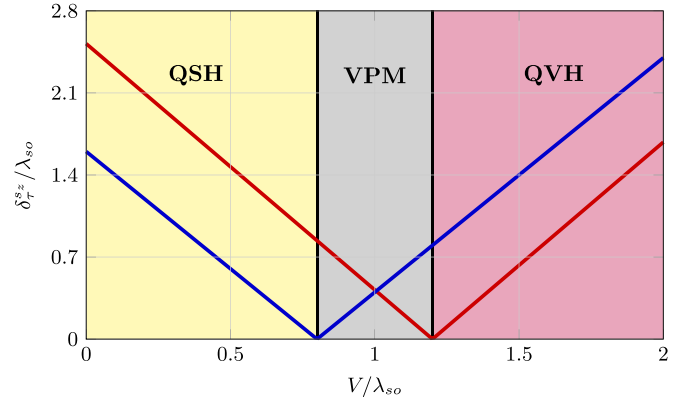


FIG. 14. Phase diagram with QSH, VPM, and QVH regions. Red and blue lines use the specified functional forms and meet the black boundaries at $V/\lambda_{SO} = 0.8$ and 1.2 , respectively.

the exchange flips C from $+1$ to -1 . According to their phase diagram: for $0 < V < V_1 \approx 0.78\lambda_{SO}$, the system is in a QSH phase (spin Hall conductivity $2e^2/h$); for $V_1 < V < V_2 \approx 1.22\lambda_{SO}$, it is in a VPM phase; and for $V_2 < V < 2\lambda_{SO}$, it enters the QVH phase (quantized valley Hall conductivity $2e^2/h$) (see Fig. 14). This tunability demonstrates the potential for external control of topological phases in realistic 2D materials.

Hajati *et al.* [80] studied the anomalous Nernst effect (ANE) in monolayer of Pt₂HgSe₃ under a vertical electric field, off-resonant circularly polarized light (OCPL), and an antiferromagnetic exchange field. They showed, within a low-energy framework, that OCPL can induce a perfectly spin-polarized ANE, whereas an antiferromagnetic exchange field results in a perfectly VP ANE. Leveraging Pt₂HgSe₃'s strong SOC, they showed that any pairwise combination of these controls yields perfectly spin/valley polarized Nernst currents over a wide Fermi energy level. For experimental feasibility, they mapped a Floquet driving regime with OCPL photon energies less than 0.25 eV and a short laser pulse intensities of $0.3\text{--}130 \times 10^{10} \text{ W cm}^{-2}$ corresponding to eA from $0.01\text{--}0.2 \text{ \AA}^{-1}$ and VP used off-resonance light up to 2.33 eV energies. They found that when the monolayer is exposed to pairs of electric, magnetic, and optical fields, it can produce perfect spin and valley polarized Nernst currents.

D. Ordered and random alloys

Lima *et al.* [81] studied QSH phase by introducing Hg_{Se} impurities into a PtSe₂ monolayer. By substituting Hg_{Se} atoms into the PtSe₂ structure, they created both ordered and randomly distributed Pt(Hg_xSe_{1-x})₂ alloys. They explored a series of ordered Pt(Hg_xSe_{1-x})₂ ($x = 0, 0.25, 0.5, 0.75, 1.0$) alloys by gradually adding mercury into the PtSe₂ structure. They found that alloy stability decreases with increasing Hg content: PtSe₂ ($x = 0$) is stable with $E^{\text{for}} = -0.38 \text{ eV/atom}$ and Pt₂HgSe₃ ($x = 0.25$) also has $E^{\text{for}} < 0$, while PtHgSe ($x = 0.50$) shows the verge of positive value. In terms of electronic behavior, PtSe₂ is a semiconducting with a bandgap of 1.2 eV, while PtHg₂ ($x = 1$) behaves as a metal. For intermediate compositions ($x = 0.25, 0.5$, and 0.75), SOC plays a crucial role. It opens band gaps of 0.14, 0.11 and 0.20 V

TABLE II. Transferred charge ΔQ (e), the vdW gap d (Å), and the magnetic moments (μ_B) for $\text{Pt}_2\text{AX}_3/\text{MY}_2$ heterostructures [83].

Structure	ΔQ (e)	d (Å)	M_{jac} (μ_B)	M_{tot} (μ_B)	M_{A1} (μ_B)	M_{A2} (μ_B)
$\text{Pt}_2\text{HgS}_3/\text{CoBr}_2$	-0.17	2.51	0.330	11.525	0.005	0.056
$\text{Pt}_2\text{HgSe}_3/\text{CoBr}_2$	-0.20	2.74	0.061	11.530	-0.009	0.016
$\text{Pt}_2\text{HgTe}_3/\text{CoBr}_2$	-0.09	2.90	0.068	11.490	-0.005	0.007
$\text{Pt}_2\text{ZnS}_3/\text{CoBr}_2$	-0.32	2.70	0.050	11.503	-0.014	0.024
$\text{Pt}_2\text{HgS}_3/\text{NiBr}_2$	-0.03	2.28	0.219	7.453	-0.016	0.067
$\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$	-0.11	2.46	0.204	7.446	-0.021	0.045
$\text{Pt}_2\text{CdS}_3/\text{NiBr}_2$	-0.18	2.18	0.276	7.392	-0.020	0.104
$\text{Pt}_2\text{ZnSe}_3/\text{NiBr}_2$	-0.17	2.51	0.167	7.420	0.009	0.027

for $x = 0.25, 0.5$, and 0.75 , respectively, indicating potential QSH phases. To confirm topological nature of $\text{Pt}(\text{Hg}_x\text{Se}_{1-x})_2$ alloys, they further calculated the Z_2 topological invariant using a Wannier-based approach. They observed that every composition other than pure PtSe_2 ($x = 0$) shows nontrivial topological character.

Using the special quasirandom structure method [82], they modeled random $\text{Pt}(\text{Hg}_x\text{Se}_{1-x})_2$ alloys for x between 0.25 and 0.75 . By accounting for configurational entropy $S = k_B \ln(\Omega)$, where Ω represents the number of equivalent ways the atoms can be arranged, they calculated free energy ($F = U - TS$) which shows a clear temperature dependent stability sequence. At low temperatures with the $k_B T < 15$ meV, pure PtSe_2 ($x = 0$) is energetically preferred, while the random form of the jacutingaite ($x = 0.25$) becomes more stable relative to the ordered phase for $k_B T > 6$ meV and remains energetically preferred up to the $k_B T < 32$ meV. Beyond that threshold, the random PtHgSe alloy becomes the lowest free energy. Topological analysis using the spin Bott-index shows that, despite some trivial band gaps near E_F caused by randomness, nontrivial topological gaps remain present within ± 0.5 eV around E_F for alloy concentrations between 0.25 and 0.75 . This indicates the system retains its QSH phase regardless of whether HgSe impurities are ordered or randomly distributed. Since PtSe_2 ($x = 0$) is the trivial insulator and Pt_2HgSe_3 ($x = 0.25$) is the TI, a topological phase transition is expected between $x = 0$ and $x = 0.25$. In addition, they estimated a threshold concentration of approximately 9% for the transition between the topologically nontrivial and trivial phases in random alloys [81].

VI. VAN DER WAALS HETEROSTRUCTURES WITH FERROMAGNETIC SUBSTRATE

Zhu *et al.* [83] showed that monolayer materials in the jacutingaite family provide a platform for achieving the VP and realizing the VP QAHE. Using first-principles calculations, they explored over 100 types of Pt_2AX_3 ($A = \text{Cd}, \text{Hg}, \text{Zn}$; $X = \text{Se}, \text{S}, \text{Te}$)/ferromagnetic substrate, i.e., MY_2 ($M = \text{Co}, \text{Fe}, \text{Ni}$; $Y = \text{Br}, \text{Cl}, \text{I}$) vdW heterostructures. Based on specific criteria such as lattice mismatch, the stacking configuration, and the band alignment, they identified 44 well-matched candidates that show distinct Berry curvature features near the K and K' valleys. Among these, four heterostructures like $\text{Pt}_2\text{HgSe}_3/\text{CoBr}_2$, $\text{Pt}_2\text{HgS}_3/\text{NiBr}_2$, $\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$, and $\text{Pt}_2\text{ZnS}_3/\text{CoBr}_2$ were identified as nontrivial topology with Chern numbers $C = \pm 1$. They observed

a strong valley splitting of 134.2 meV in $\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$ heterostructures and a notable topological band gap of 58.8 meV in $\text{Pt}_2\text{HgS}_3/\text{NiBr}_2$. Both the jacutingaite monolayers and the 2D ferromagnetic substrates were confirmed to be energetically and dynamically stable. Their band alignment analysis classified the $\text{Pt}_2\text{AX}_3/\text{MY}_2$ stacking into type I (straddling), type II (staggered), and type III (broken gap) configurations: $\text{Pt}_2\text{HgS}_3/\text{NiBr}_2$ is type I, $\text{Pt}_2\text{HgS}_3/\text{FeBr}_2$ is type II, while $\text{Pt}_2\text{HgS}_3/\text{NiCl}_2$ corresponds to a type III alignment and is excluded due to its broken gap. Interfacial charge transfer was analyzed using the charge-density difference and planar-averaged electrostatic potential. Table II presents transferred charge (ΔQ), vdW gap (d), and the magnetic moments for eight $\text{Pt}_2\text{AX}_3/\text{MY}_2$ heterostructures. After structural relaxation, all interlayer gaps shrink. Due to smaller atomic radius of sulfur, Pt_2HgS_3 moves closer to substrate than the Pt_2HgSe_3 for the same interface. In general, $\text{Pt}_2\text{AX}_3/\text{NiBr}_2$ have a smaller d compared to $\text{Pt}_2\text{AX}_3/\text{CoBr}_2$, resulting in a stronger magnetic proximity effect and greater induced magnetization in the jacutingaite layer. This proximity also leads to distinct magnetic moments (M_{A1} and M_{A2}) due to their different distances from the substrate. The ferromagnetic layer breaks both the inversion symmetry and the TRS, producing unequal exchange fields on A_1 and A_2 , which lifts the spin degeneracy and leads to the valley-dependent band gaps. Among 44 well-matched $\text{Pt}_2\text{AX}_3/\text{MY}_2$ vdWs heterostructures, only four were identified as topological nontrivial. To analyze the topology of the band structures, they calculated Berry curvature for all occupied bands in each system using the MLWFs. Further, they computed Chern numbers by integrating Berry curvature throughout entire first Brillouin zone. These values, shown in Table III, tell us important information about the material's electronic properties. $\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$ and $\text{Pt}_2\text{ZnS}_3/\text{CoBr}_2$ show a quantized conductance of $-e^2/h$, while $\text{Pt}_2\text{HgS}_3/\text{NiBr}_2$ and $\text{Pt}_2\text{HgSe}_3/\text{CoBr}_2$ show $+e^2/h$, confirming the QAHE [83].

Additionally, Liu *et al.* [84] proposed a vdW heterostructure design to realize second-order topological insulating states (SOTIs) in Pt_2HgSe_3 -based materials. A SOTI is a topological phase that hosts lower dimensional boundary modes. Materials like 2D structures can host localized 0D corner states, while 3D possess 1D hinge states. By sandwiching a Pt_2HgSe_3 monolayer between two ferromagnetic layers, Liu *et al.* [84] constructed the proposed vdW heterostructure. From first-principles calculations, they observed that in the absence of SOC, magnetic proximity induces strong spin splitting exceeding 200 meV at the K and K' valleys, and

TABLE III. The valley splitting Δ , the global band gap E_g , the local gaps Δ_K and $\Delta_{K'}$ at the K and the K' valleys, and the Chern number C for the jacutingaite monolayer/ferromagnetic substrate vdW heterostructures. The valley splitting is the difference between the valence band maxima at K' and the K , $\Delta = E_V(K') - E_V(K)$ [83].

Nontrivial vdW Heterostructures	Δ (meV)	E_g (meV)	Δ_K (meV)	$\Delta_{K'}$ (meV)	C
Pt ₂ HgSe ₃ /NiBr ₂	134.2	6.3	182.8	73.5	-1
Pt ₂ ZnS ₃ /CoBr ₂	36.3	7.8	185.9	59.9	-1
Pt ₂ HgS ₃ /NiBr ₂	15.4	58.8	74.2	78.8	1
Pt ₂ HgSe ₃ /CoBr ₂	3.5	19.3	22.8	124.0	1

upon including SOC, band gaps of about 79.7 meV (bulk) and 72.8 meV (nanoribbon) are opened. In nanoflakes, a topological corner state appears whose eigenenergy lies within the edge state gap that can be understood by the 1D Jackiw–Rebbi model and probed by measuring the LDOS around the corner, and remain stable even with edge irregularities and Anderson disorder up to $W = 80$ meV. They showed that this SOTI can also be realized in other materials such as $MZ_2/Pt_2XS_3/MZ_2$ ($M = \text{Ni}$ and Co ; $Z = \text{Cl}$ and Br ; $X = \text{Hg}$ and Zn).

Rehman *et al.* [85] integrated vdW ferromagnetic insulators (CrGeTe₃ and CrI₃) with Kane–Mele-type TIs (Pt₂HgSe₃ and Pd₂HgSe₃) as heterobilayers. The schematic and mechanism of Pt₂HgSe₃-based material is illustrated in Fig. 15.

Figures 15(a) and 15(b) show the atomic configuration of freestanding Pt₂HgSe₃, where including SOC opens a band gap as evident in the band structures of Figs. 15(c) and 15(d). Figures 15(e)–15(h) describe the crystal and band structures of the monolayer CrGeTe₃, a vdW ferromagnetic insulator that exhibits in-plane magnetic anisotropy ($\parallel a$) and long-range magnetic order. When these layers are combined into the heterobilayer [see Figs. 15(i) and 15(j)], interfacial coupling between Pt₂HgSe₃ and CrGeTe₃ reorients the magnetic anisotropy to the out-of-plane direction ($\parallel c$) and induces exchange splitting in the topological layer. The resulting spin-resolved band structures in Figs. 15(k)–15(l) clearly show SOC-induced valley asymmetry hints to realize a VP QAHE. In comparison, Pd₂HgSe₃ based heterostructures display similar magnetic valley asymmetry but with smaller nontrivial gaps shown in Table IV. To induce magnetic order and break TRS in Pt₂HgSe₃ and Pd₂HgSe₃, these materials are interfaced with vdW ferromagnetic layers like CrGeTe₃ or CrI₃, which have stable magnetic order. The interlayer distances are about 2.51/2.50 Å for (Pt/Pd)₂HgSe₃/CrGeTe₃ and 2.67 Å for Pd₂HgSe₃/CrI₃, indicating moderate coupling. Charge transfers from CrGeTe₃ or CrI₃ to the (Pt/Pd)₂HgSe₃ layers are approximately 0.12, 0.16, and 0.005 e for Pt₂HgSe₃/CrGeTe₃, Pd₂HgSe₃/CrGeTe₃, and Pd₂HgSe₃/CrI₃, respectively. This causes potential drops of about 6.4 eV, 7.86 eV, and 5.62 eV at the interfaces. These findings establish (Pt/Pd)₂HgSe₃ heterostructures as promising platforms for topological spintronic and valleytronic applications.

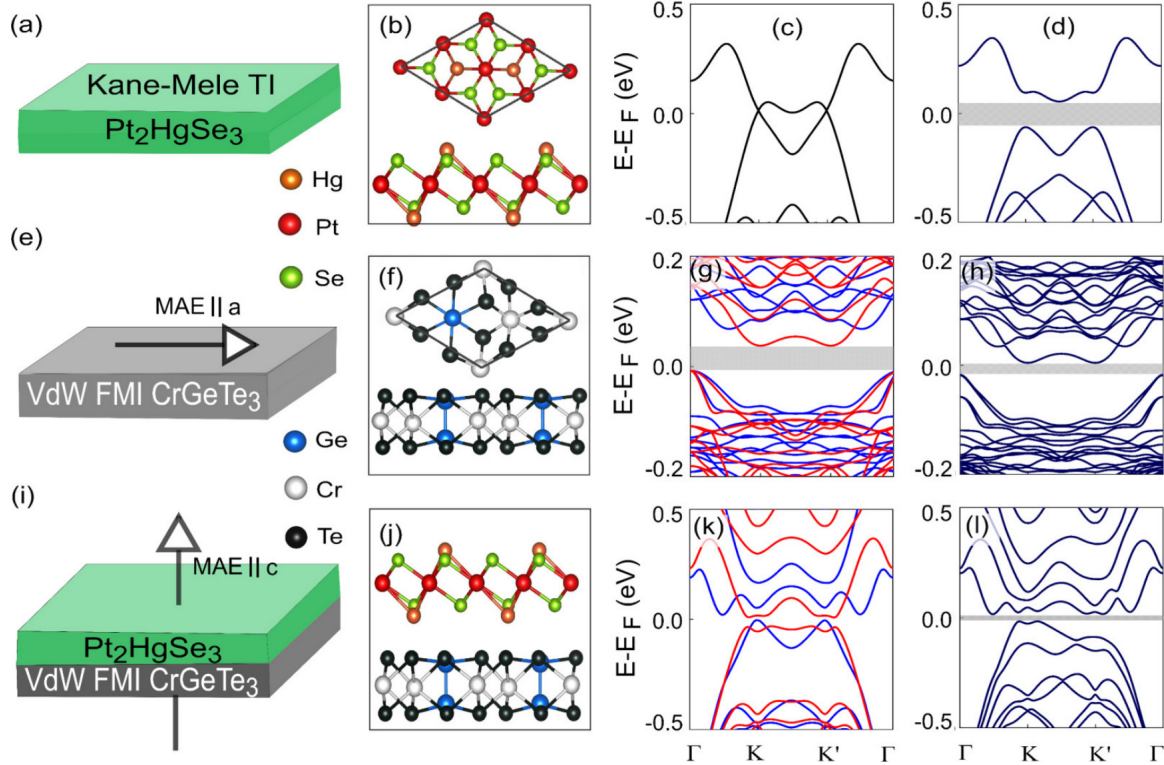


FIG. 15. (a) Schematic illustration of freestanding Pt₂HgSe₃. (b) Top and side views of the atomic structure for Pt₂HgSe₃. Electronic band structures of Pt₂HgSe₃ without SOC and (d) with SOC; (e) Schematic of freestanding CrGeTe₃. (f) Top and side views of CrGeTe₃ atomic structure. Band structures of CrGeTe₃ (g) without SOC, and (h) with SOC. (i) Schematic diagram of the Pt₂HgSe₃/CrGeTe₃ heterobilayer. (j) Side view of the heterobilayer configuration. (k), (l) Band structures of Pt₂HgSe₃/CrGeTe₃ heterobilayer (k) without SOC, and (l) with SOC. Spin-up and the spin-down components are represented by the blue and red curves, respectively (adapted from Ref. [85]).

TABLE IV. Summary of valley-resolved band gaps ($\Delta_K/\Delta_{K'}$), spin splitting ($\delta_K^{\text{vv}}/\delta_{K'}^{\text{vv}}$) between the two topmost valence bands at the valleys (K/K'), the valley splitting ($\Delta_{K-K'} \equiv \varepsilon_{\text{max}}(K) - \varepsilon_{\text{max}}(K')$), global nontrivial band gap (E_g), and the corresponding Chern number for the listed heterobilayer systems [85].

Property	Pt ₂ HgSe ₃ /CrGeTe ₃	Pd ₂ HgSe ₃ /CrGeTe ₃	Pd ₂ HgSe ₃ /CrI ₃
Δ_K (meV)	74	27	28.5
$\Delta_{K'}$ (meV)	113	69	71.0
δ_K^{vv} (meV)	95.0	22.5	29.0
$\delta_{K'}^{\text{vv}}$ (meV)	63.0	52.0	70.0
$\Delta_{K-K'}$ (meV)	67.0	24.0	16.2
E_g (meV)	32	17	16
Chern number	+1	+1	-1

VII. EMERGENT SUPERCONDUCTIVITY AND CORRELATED STATES

A. Unconventional superconductivity via doping

Unconventional superconductors are materials whose superconducting behavior cannot be fully explained by the standard BCS theory or its extension, the Eliashberg theory [86]. In these systems, electron pairing may arise from mechanisms other than conventional electron-phonon interactions. A common way to identify them is through the symmetry of the superconducting order parameter: if it transforms under a non-trivial irreducible representation of the crystal's point or space group, the superconductor is considered unconventional. More broadly, if the superconducting state breaks additional symmetries beyond the usual $U(1)$ gauge symmetry, it falls into this category. Conventional superconductors typically exhibit s -wave symmetry, resulting in an isotropic energy gap. In contrast, unconventional superconductors often display d -, p -, or f -wave symmetries, which can lead to nodal gaps points/lines on the Fermi surface where, gap vanishes. These features give rise to anisotropic and direction-dependent behavior, particularly at low temperatures [87].

Wu *et al.* [88] proposed that a monolayer of Pt₂HgSe₃ not only hosts a QSH insulating phase at its pristine state but also exhibits various forms of unconventional superconductivity when doped with holes or electrons. This dual behavior arises from its unique long-range hybridization, linked to the extended Wannier orbitals of jacutingaite. The combination of its multi-orbital character and buckled honeycomb structure results in a TB model with a large topological band gap and nearby van Hove singularities (vHs): type-I for hole doping and type-II represents electron doping. In type-I, the saddle points appear at time-reversal invariant M points of the Brillouin zone, while in type-II, they lie along the K - M path and do not coincide with TRIMs [89]. These vHs enhance the DOS near E_F , encouraging unconventional superconductivity. Using random phase approximation (RPA) and the functional renormalization group analysis, they showed that type-I vHs leads to chiral d -wave superconductivity with spontaneous TRS breaking. Meanwhile, type-II vHs favors strong ferromagnetic fluctuations, giving rise to an odd-parity f -wave pairing state.

To reach the type-I vHs in jacutingaite, about 9.8% hole doping is required, which corresponds to approximately 0.39 holes per unit cell. In contrast, the type-II vHs can be accessed with only 4.0% electron doping (around 0.16 electrons), a

level that might even be achievable through electrolytic gating rather than chemical doping. This low doping threshold, combined with the material's exotic electronic behavior, makes monolayer jacutingaite especially attractive. For comparison, several attempts have been made to dope the graphene to vHs using calcium and the potassium adsorbates [90], but no superconductivity has been observed. In contrast, the relatively small amount of doping needed for jacutingaite makes it a realistic and promising candidate for exploring unconventional superconductivity in a doped QSHI [88].

B. Pressure-induced superconductivity

In some of the topological compounds, superconductivity has been successfully induced by applying external pressure [91]. Superconductivity is a remarkable property of certain materials that, when cooled below a critical temperature, completely loses electrical resistance and pushes out magnetic fields. Unlike typical metals that slowly become better conductors as they cool, superconductors make a sharp transition into this zero-resistance state [92]. Pei *et al.* [93] explored how bulk Pt₂HgSe₃ responds to high pressure. Pt₂HgSe₃ is a layered material that reacts noticeably to pressure. They measured its electrical resistance up to very high pressures (88.8 GPa) and found it stays metallic throughout. Initially, increasing pressure lowers the resistance until about 12 GPa, after which it slowly rises again. At 54.9 GPa, a small drop in resistance near 1.9 K was obtained, hinting at the start of superconductivity. As pressure went higher, this drop became more obvious, with the superconducting temperature reaching 4.4 K at the highest pressure 88.8 GPa.

TABLE V. Lattice parameters of Pt₂HgSe₃ under different pressures [93].

Pressure	1 atm	82.7 GPa	82.7 GPa
Phase	Phase I	Phase I	Phase II
Crystal system	Trigonal	Trigonal	Monoclinic
Space group	$P\bar{3}m1$ (164)	$P\bar{3}m1$ (164)	Pc (7)
a (Å)	7.341132(2)	6.781756(4)	7.166096(1)
b (Å)	7.341132(2)	6.781856(4)	6.045144(3)
c (Å)	5.275207(3)	4.004362(2)	12.129331(3)
α (deg)	90	90	90
β (deg)	90	90	146.262
γ (deg)	120	120	90

They repeated measurements on different samples and got consistent results, confirming that superconductivity really happens under pressure in this material. They predicted an alternative stable monoclinic phase (phase II, space group Pc) at 68 GPa. Enthalpy calculations show that phase II becomes more stable than the ambient trigonal phase (phase I, $P\bar{3}m1$) above 45 GPa, consistent with experimental phase transition observations. They verified the dynamical stability of phase II through phonon dispersion calculations, which revealed no imaginary frequencies [93]. The structural parameters of Pt_2HgSe_3 at various pressures are presented in Table V.

VIII. ADVANCED CHARACTERIZATION

Mauro *et al.* [94] studied Pt_2HgSe_3 crystals, which are found stable in air during fabrication. They observed metallic behavior and a decrease in resistivity upon cooling, which

then saturated at low temperature. Residual-resistivity ratios confirmed good crystal quality. Under magnetic field, the material exhibited strong and nearly linear magnetoresistance. Shubnikov–de Haas oscillations implied electron mobility of around $10^3 \text{ cm}^2/\text{Vs}$, with small electron pockets of light cyclotron masses; hole oscillations were absent due to heavier masses. A refined Lifshitz–Kosevich fit agreed with DFT (including SOC), which linked these pockets to gapped nodal lines. This study provided a platform for studying transport in 2D QSHI.

Santos-Castro *et al.* [95] developed a TB model for Pt-based jacutingaite monolayers (Pt_2NX_3 , $N = \text{Zn, Cd, Hg}$; $X = \text{S, Se, Te}$) that captured conduction and valence bands near the SOC gaps. By including Pt $5D_{5/2}$ and $N 5s_{1/2}$ orbitals, the model formed interpenetrating kagome (Pt) and honeycomb (N) sublattices with next-nearest-neighbor hoppings, reproducing quasiflat bands absent in Kane–Mele models, and the states along $K(K')\text{--}M$.

TABLE VI. Summary of energy band gaps, Z_2 , critical electric fields, valley splittings, Chern numbers (C), Curie temperatures (T_C) and superconducting (T_c) of jacutingaite (Pt_2HgSe_3) family. Quantities labeled as th represent results obtained from theory and those with exp represent experimentally measured.

Physical quantity	Values	System	Reference
Band gaps			
Bulk gap (GGA+SOC)	~ 0 (semimetallic)	Bulk Pt_2HgSe_3	[54]
Monolayer QSH gap (DFT)	0.15 eV	Monolayer Pt_2HgSe_3	[53]
Monolayer QSH gap (G_0W_0)	0.53 eV	Monolayer Pt_2HgSe_3	[53]
Monolayer gap (expt, STM)	0.11 ± 0.03 eV	Monolayer Pt_2HgSe_3	[63]
Monolayer gap (SOC, DFT)	~ 160 meV	Monolayer Pt_2HgSe_3	[71]
Bilayer gap (free-standing)	290 meV	Bilayer Pt_2HgSe_3	[76]
Bilayer gap (BN/BL/BN)	27 meV	Encapsulated bilayer	[76]
QAH gap (Te functionalization)	0.28 eV	$\text{Pt}_2\text{HgSe}_3\text{--Te}$	[78]
Z_2 topological indices			
Bulk Z_2 invariant	(0; 001) – weak TI	Bulk Pt_2HgSe_3	[54]
Mirror Chern number	-2 (all mirror planes)	Bulk Pt_2HgSe_3	[54]
Monolayer Z_2	$\nu = 1$ (QSHI)	Monolayer Pt_2HgSe_3	[53]
Bilayer Z_2	$\nu = 0$ (trivial)	Bilayer Pt_2HgSe_3	[76]
Critical electric fields			
Field for band closure (bilayer/BN)	$\approx 0.30 \text{ V}/\text{\AA}$	Encapsulated bilayer	[76]
Field for gap closure (monolayer)	$\approx 0.50 \text{ V}/\text{\AA}$	Monolayer Pt_2HgSe_3	[71]
Splittings			
Valley splitting	134.2 meV	$\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$	[83]
Valley splitting	67.0 meV	$\text{Pt}_2\text{HgSe}_3/\text{CrGeTe}_3$	[85]
Chern numbers			
Chern number C	-1	$\text{Pt}_2\text{HgSe}_3/\text{NiBr}_2$	[83]
Chern number C	$+1$	$\text{Pt}_2\text{HgSe}_3/\text{CoBr}_2$	[83]
Chern number C	$+1$	$\text{Pt}_2\text{HgSe}_3/\text{CrGeTe}_3$	[85]
Curie temperatures (functionalized)			
T_C (S functionalization)	196 K	$\text{Pt}_2\text{HgSe}_3\text{--S}$ (th, MC)	[78]
T_C (Se functionalization)	246 K	$\text{Pt}_2\text{HgSe}_3\text{--Se}$ (th, MC)	[78]
T_C (Te functionalization)	316 K	$\text{Pt}_2\text{HgSe}_3\text{--Te}$ (th, MC)	[78]
Superconducting critical temperature			
T_c (expt, at 88.8 GPa)	4.4 K	Bulk Pt_2HgSe_3	[93]
T_c onset (expt, 54.9 GPa)	~ 1.9 K	Bulk Pt_2HgSe_3	[93]

Yarmohammadi *et al.* [96] employed a perturbed Kane-Mele model and applied linear response theory to evaluate the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction between magnetic impurities. They studied perturbations such as gate fields, magnetic exchange (e.g., proximity to a 2D ferromagnet), and off-resonant circularly polarized light that drive phase transitions among QSHI, band insulator (BI), quantum Hall insulator (QHI), and semimetal phases and showed these perturbations can flip RKKY couplings. They explored how symmetric (Heisenberg) and asymmetric (Dzyaloshinskii–Moriya) exchange components reveal topological phases: same-sublattice impurities (Hg–Hg or Pt–Pt) show maxima/minima near semimetallic phases, while different-sublattice pairs (Hg–Pt) show sharp peaks or vanishing responses, providing a magnetic fingerprint for identifying and controlling the topological states.

Pt₂HgSe₃ nanoribbons are reported to be a robust platform for topological transports. Freire *et al.* [97] combined DFT with nonequilibrium Green’s functions to study ballistic transport in pristine and defective ribbons. Monolayer Pt₂HgSe₃ has a Dirac cone at *K* that opens to 0.13 eV with SOC, primarily due to hybridization between Hg-6s and Pt-4d orbitals. Hybrid-functional and *GW* calculations predict a band gap of 0.2–0.5 eV, while STM finds 0.08 ± 0.03 eV. The Hg vacancies and Se $\leftrightarrow$ Hg antistructure defects affect the transport properties significantly. Narrow ribbons ($W = 34\text{--}60$ Å) show enhanced gaps; wider ribbons ($W = 99$ Å) restore the Dirac cone. Short penetration depth ensures their robust edge channels. Defect reduces the conductance but backscattering was suppressed by TRS. These results confirm defect-tolerant transport and large band gaps with robust edge channels.

Shah and Anwar [98] studied monolayer Pt₂HgSe₃ under a staggered sublattice potential and off-resonant circularly polarized light, mapping a rich spin/valley phase diagram via Berry curvature and Chern numbers. They observed a QSHI $\rightarrow$ BI/quantum valley Hall insulator transition driven by the staggered potential and, at fixed electric field, a QSHI $\rightarrow$ spin-polarized semimetal $\rightarrow$ photo-induced QHI. In addition, Bau *et al.* [99] reported the topological transitions through Edelstein responses: The orbital Edelstein susceptibility vanishes at the critical point, while the spin Edelstein conductivity exhibits a sharp discontinuity. These transport signature remains robust under finite scattering and scale consistently across the phase boundaries, establishing Edelstein measurements as reliable probes for mapping and controlling photo-induced topological phases.

Furthermore, Shah *et al.* [100] showed that quantum magnetotransport in monolayer Pt₂HgSe₃ can be tuned by electric fields and off-resonant circularly polarized light, inducing sequence of topological phase transitions with spin- and valley-polarized splitting, and magneto-optical responses. When reversing the electric field or flipping the light helicity, the Berry curvature and hence the magnetic moment reverses. Fachin *et al.* [101] demonstrated that infrared-active phonons are precise markers of topological phase transitions in 2D materials like germanene and jacutingaite. These transitions involve large jumps in Born effective charges (up to ~ 2), producing distinct changes in the IR spectrum such as the disappearance of the in-plane *E* mode in germanene’s QSHI

phase which remain robust even under dynamical effects near the gap-closing point ($\Delta_0 \sim \omega_{\text{ph}}$).

Additionally, Phong *et al.* [102] used the KM model together with the Boltzmann method to study how quantum capacitance (QC) changes in gated and irradiated monolayer Pt₂HgSe₃. Their result shows that an applied electric field can drive a topological phase transition from a QSHI to a semimetal increasing QC, whereas a transition to a QSHI phase reduces QC. Further, they established heat capacity and Pauli spin susceptibility as indicators of topological states at low temperatures [103]. Likewise, Tho *et al.* [104] found that both static and dynamic electric field suppresses electrical conductivity in monolayer Pt₂HgSe₃, with static fields having the stronger effect due to more persistent band structure variation. However, thermal conductivity is barely modified, suggesting phonon-dominated heat transport indicating that charge conduction can be engineered by external fields with negligible affect on the heat flow. Most recently, Hoi and Tho [105] studied the frequency-dependent optical conductivity of gapped monolayer Pt₂HgSe₃, finding a Drude-like intraband decay and a sharp interband onset at the band gap, with negligible Hall response in the pristine, symmetry-preserving phase. By tuning the gap with static and dynamic electric fields, they shift the interband threshold, induce topological phase transitions, and generate a finite Hall conductivity over specific photon-energy ranges.

IX. APPLICATIONS AND CHALLENGES

The strong SOC and nontrivial band topology of jacutingaite-based materials create promising prospects for spintronic applications, where spin currents are manipulated without relying on external magnetic fields. Notably, the sizable intrinsic QSH gap predicted for monolayer Pt₂HgSe₃ sets it apart from many proposed 2D TIs that rely on fine structural tuning or extreme experimental conditions. The resulting topological edge states are protected against nonmagnetic backscattering, offering a pathway toward low-dissipation electronic transport that could surpass conventional semiconductor technologies. In addition to spin transport, the presence of inequivalent valleys in the Brillouin zone introduces a valley degree of freedom, providing a basis for valleytronics. By using valley polarization and the valley Hall effect, information processing schemes can move beyond purely charge- or spin-based approaches.

The electronic structure of Pt₂HgSe₃ can be further tailored through heterostructure design, magnetic proximity coupling, and external stimuli such as gating, strain, or circularly polarized light, enabling controllable spin-valley responses. Its van der Waals character also facilitates stacking with other layered materials, minimizing lattice-mismatch constraints and broadening device design possibilities. Engineered interfaces between TIs and superconductors are widely considered promising platforms for realizing non-Abelian quasiparticles, including Majorana-bound states and parafermions. Pt₂HgSe₃ and its family of compounds, with their large intrinsic band gaps and tunability via doping or strain, are attractive candidates for realizing such exotic states. The interplay between TRS edge states and induced superconducting pairing

provides a platform for fault-tolerant topological qubits for quantum information applications. Although clear experimental demonstrations remain pending, integration of Pt_2HgSe_3 monolayers with superconducting or magnetic substrates represents a realistic and scientifically compelling direction.

Despite rapid progress, several obstacles must be overcome before device-level implementation becomes feasible. The controlled synthesis of high-quality monolayer and few-layer Pt_2HgSe_3 remains challenging, limiting large-scale device integration. Growth methods such as molecular beam epitaxy and chemical vapor deposition require further refinement to ensure thickness uniformity, low defect densities, and accurate stoichiometry. Precise control of the Fermi level is equally critical, since intrinsic doping or surface-related electronic reconstruction can displace the chemical potential from the topological gap and obscure edge-state transport signatures. Additional concerns include environmental stability, mechanical robustness under strain, interface-induced band modifications in heterostructures, and scalability to wafer-sized samples. Addressing these limitations will be essential for converting the fundamental topological properties of jacutingaite-based materials into viable technological platforms. To facilitate comparison across different theoretical and experimental studies, Table VI collects the principal benchmark quantities discussed throughout this review.

X. CONCLUSIONS AND PERSPECTIVES

The discovery of jacutingaite (Pt_2HgSe_3) highlights how a rare mineral from Brazil can provide a naturally occurring platform for studying quantum materials and topological phenomena. Jacutingaite material connects mineralogy with condensed-matter physics through topological features. In bulk, it exhibits dual topological character, associated with weak TI and a mirror-protected crystalline insulator, while calculations indicate that its monolayer can host a Kane-Mele-type quantum spin Hall state with a sizable band gap. Its layered structure, consisting of buckled Pt-Se planes with Hg atoms between them, is associated with strong intrinsic spin-orbit coupling and suggests the potential for monolayer or few-layer forms through exfoliation.

The electronic phases of jacutingaite are tunable. Bilayers, initially topologically trivial due to inversion asymmetry, can regain nontrivial topology when encapsulated in hexagonal boron nitride and exposed to an out-of-plane electric field. Chemical functionalization with chalcogen atoms can induce ferromagnetism, enabling a transition from a quantum spin Hall to a quantum anomalous Hall phase. Under high pressure, bulk Pt_2HgSe_3 becomes superconducting, with a critical temperature of 4.4 K at 88.8 GPa.

These features make jacutingaite an attractive platform for investigating spin-dependent and topological phenomena, with potential relevance to emerging areas such as spintronics and valleytronics. Its topological edge states and tunable electronic phases motivate further investigation of whether such properties can be exploited in quantum devices. Further progress toward device-oriented applications will require advances in the controlled preparation of monolayers and few-layer structures, interface engineering, and long-term materials stability. In this sense, jacutingaite represents not only as a material of fundamental research interest but also a promising platform for design and engineering of next-generation topological quantum materials.

ACKNOWLEDGMENTS

M.P.G. thanks Research Directorate, Office of Rector, Tribhuvan University for supporting through National Priority Collaborative Research Project (EF80/81/Col-9). All authors thank U. Nitzsche for her skillful technical assistance.

P.B. analyzed the literature and prepared the first draft of the research updates along with M.P.G. (principal investigator). M.P.G. planned the project, supervised, provided critical feedback, and wrote the revised version of the manuscript. Both authors discussed and proofread the manuscript.

The authors declare no competing interests.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

-
- [1] X.-G. Wen, Choreographed entanglement dances: Topological states of quantum matter, *Science* **363**, eaal3099 (2019).
 - [2] L. D. Landau, *Collected Papers of L. D. Landau* (Pergamon Press, Oxford, 1965).
 - [3] V. Kalmeyer and R. B. Laughlin, Equivalence of the resonating-valence-bond and fractional quantum Hall states, *Phys. Rev. Lett.* **59**, 2095 (1987).
 - [4] X.-G. Wen, F. Wilczek, and A. Zee, Chiral spin states and superconductivity, *Phys. Rev. B* **39**, 11413 (1989).
 - [5] A. Bednorz, K. Franke, and W. Belzig, Noninvasiveness and time symmetry of weak measurements, *New J. Phys.* **15**, 023043 (2013).
 - [6] J. Timmer, 25 years on, the search for higher-temp superconductors continues, *Ars Technica* (2011), <https://arstechnica.com/science/2011/04/25-years-on-the-search-for-higher-temp-superconductors-continues/>.
 - [7] X. G. Wen, Topological orders in rigid states, *Int. J. Mod. Phys. B* **04**, 239 (1990).
 - [8] The Nobel Foundation, The Nobel prize in physics 2016, <https://www.nobelprize.org/prizes/physics/2016/summary/>.
 - [9] M. Z. Hasan and C. L. Kane, *Colloquium*: Topological insulators, *Rev. Mod. Phys.* **82**, 3045 (2010).
 - [10] X.-L. Qi and S.-C. Zhang, Topological insulators and superconductors, *Rev. Mod. Phys.* **83**, 1057 (2011).
 - [11] M. Mandal, N. C. Drucker, P. Siriviboon, T. Nguyen, T. Boonkird, T. N. Lamichhane, R. Okabe, A. Chottrattanapituk, and M. Li, Topological superconductors from a materials perspective, *Chem. Mater.* **35**, 6184 (2023).

- [12] F. H. Croom, *Principles of Topology* (Courier Dover Publications, Mineola, NY, 2016).
- [13] A. Pressley, in *Elementary Differential Geometry*, Springer Undergraduate Mathematics Series (Springer, London, 2010), pp. 335–377.
- [14] D. Bhattarai, D. B. Shahi, and M. P. Ghimire, in *Contemporary Advancements in Materials Technology: Novel Solutions to Complex Problems*, edited by S. Kulkarni, V. Srivastava, and P. William (Apple Academic Press, New York, 2025), pp. 177–197.
- [15] J. H. Cullen and D. Culcer, Spin-Hall effect due to the bulk states of topological insulators: Extrinsic contribution to the proper spin current, *Phys. Rev. B* **108**, 245418 (2023).
- [16] E. H. Hall, On a new action of the magnet on electric currents, *Am. J. Math.* **2**, 287 (1879).
- [17] K. v. Klitzing, G. Dorda, and M. Pepper, New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance, *Phys. Rev. Lett.* **45**, 494 (1980).
- [18] J. E. Hirsch, Spin Hall effect, *Phys. Rev. Lett.* **83**, 1834 (1999).
- [19] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, Anomalous Hall effect, *Rev. Mod. Phys.* **82**, 1539 (2010).
- [20] B. A. Bernevig, T. L. Hughes, and S.-C. Zhang, Quantum spin Hall effect and topological phase transition in HgTe quantum wells, *Science* **314**, 1757 (2006).
- [21] C.-Z. Chang, J. Zhang, X. Feng, J. Shen, Z. Zhang, M. Guo, K. Li, Y. Ou, P. Wei, L.-L. Wang, Z.-Q. Ji, Y. Feng, S. Ji, X. Chen, J. Jia, X. Dai, Z. Fang, S.-C. Zhang, K. He, Y. Wang, *et al.*, Experimental observation of the quantum anomalous Hall effect in a magnetic topological insulator, *Science* **340**, 167 (2013).
- [22] P. Narang, C. A. C. Garcia, and C. Felser, The topology of electronic band structures, *Nat. Mater.* **20**, 293 (2021).
- [23] B. A. Bernevig, *Topological Insulators and Topological Superconductors* (Princeton University Press, Princeton, NJ, 2013).
- [24] L. Fu and C. L. Kane, Topological insulators with inversion symmetry, *Phys. Rev. B* **76**, 045302 (2007).
- [25] H. Obuse, S. Ryu, A. Furusaki, and C. Mudry, Spin-directed network model for the surface states of weak three-dimensional $\mathbb{Z}_2$ topological insulators, *Phys. Rev. B* **89**, 155315 (2014).
- [26] Z. Ringel, Y. E. Kraus, and A. Stern, Strong side of weak topological insulators, *Phys. Rev. B* **86**, 045102 (2012).
- [27] B. A. Bernevig and S.-C. Zhang, Quantum spin Hall effect, *Phys. Rev. Lett.* **96**, 106802 (2006).
- [28] C. Liu, T. L. Hughes, X.-L. Qi, K. Wang, and S.-C. Zhang, Quantum spin Hall effect in inverted type-II semiconductors, *Phys. Rev. Lett.* **100**, 236601 (2008).
- [29] C. L. Kane and E. J. Mele, Quantum spin Hall effect in graphene, *Phys. Rev. Lett.* **95**, 226801 (2005).
- [30] C. L. Kane and E. J. Mele, $\mathbb{Z}_2$ topological order and the quantum spin Hall effect, *Phys. Rev. Lett.* **95**, 146802 (2005).
- [31] S.-C. Ho, C.-H. Chang, Y.-C. Hsieh, S.-T. Lo, B. Huang, T.-H.-Y. Vu, C. Ortix, and T.-M. Chen, Hall effects in artificially corrugated bilayer graphene without breaking time-reversal symmetry, *Nat. Electron.* **4**, 116 (2021).
- [32] F. Reis, G. Li, L. Dudy, M. Bauernfeind, S. Glass, W. Hanke, R. Thomale, J. Schäfer, and R. Claessen, Bismuthene on a SiC substrate: A candidate for a high-temperature quantum spin Hall material, *Science* **357**, 287 (2017).
- [33] B. Rasche, A. Isaeva, A. Gerisch, M. Kaiser, W. Van den Broek, C. T. Koch, U. Kaiser, and M. Ruck, Crystal growth and real structure effects of the first weak 3D stacked topological insulator $\text{Bi}_4\text{Rh}_3\text{I}_9$, *Chem. Mater.* **25**, 2359 (2013).
- [34] M. P. Ghimire and M. Richter, Chemical gating of a weak topological insulator: $\text{Bi}_4\text{Rh}_3\text{I}_9$, *Nano Lett.* **17**, 6303 (2017).
- [35] M. Lê Anh, M. Kaiser, M. P. Ghimire, M. Richter, K. Koepnik, M. Gruschwitz, C. Tegenkamp, T. Doert, and M. Ruck, Cover feature: The weak 3D topological insulator $\text{Bi}_2\text{Rh}_3\text{Sn}_3\text{I}_9$ (Chem. Eur. J. 67/2020), *Chem. A Eur. J.* **26**, 15342 (2020).
- [36] M. Lê Anh, M. Kaiser, M. P. Ghimire, M. Richter, K. Koepnik, M. Gruschwitz, C. Tegenkamp, T. Doert, and M. Ruck, The weak 3D topological insulator $\text{Bi}_2\text{Rh}_3\text{Sn}_3\text{I}_9$, *Chem. A Eur. J.* **26**, 15549 (2020).
- [37] D. Bhattarai, D. B. Shahi, S. Lawaju, C. Mitra, and M. P. Ghimire, Magnetic doping-induced topological phase transition in Bi_2TeI : A density functional study, *J. Phys. Chem. C* **129**, 8764 (2025).
- [38] X. Feng, Y. Feng, J. Wang, Y. Ou, Z. Hao, C. Liu, Z. Zhang, L. Zhang, C. Lin, J. Liao, Y. Li, L.-L. Wang, S.-H. Ji, X. Chen, X. Ma, S.-C. Zhang, Y. Wang, K. He, and Q.-K. Xue, Thickness dependence of the quantum anomalous Hall effect in magnetic topological insulator films, *Adv. Mater.* **28**, 6386 (2016).
- [39] J.-M. Zhang, W. Zhu, Y. Zhang, D. Xiao, and Y. Yao, Tailoring magnetic doping in the topological insulator Bi_2Se_3 , *Phys. Rev. Lett.* **109**, 266405 (2012).
- [40] J.-M. Zhang, W. Ming, Z. Huang, G.-B. Liu, X. Kou, Y. Fan, K. L. Wang, and Y. Yao, Stability, electronic, and magnetic properties of the magnetically doped topological insulators Bi_2Se_3 , Bi_2Te_3 , and Sb_2Te_3 , *Phys. Rev. B* **88**, 235131 (2013).
- [41] B. P. Belbase, L. Ye, B. Karki, J. I. Facio, J.-S. You, J. G. Checkelsky, J. van den Brink, and M. P. Ghimire, Large anomalous Hall effect in single crystals of the kagome Weyl ferromagnet Fe_3Sn , *Phys. Rev. B* **108**, 075164 (2023).
- [42] G. B. Acharya, S. K. Barik, S. R. Mishra, B. Karki, P. K. Muduli, B. Srinivasan, and M. P. Ghimire, Berry curvature-driven anomalous Hall effect in polycrystalline ferromagnet Fe_5Sn_3 , *Chem. Mater.* **37**, 7419 (2025).
- [43] D. C. Jones, S. Das, H. Bhandari, X. Liu, P. Siegfried, M. P. Ghimire, S. S. Tsirkin, I. I. Mazin, and N. J. Ghimire, Origin of spin reorientation and intrinsic anomalous Hall effect in the kagome ferrimagnet TbMn_6Sn_6 , *Phys. Rev. B* **110**, 115134 (2024).
- [44] M. P. Ghimire, J. I. Facio, J.-S. You, L. Ye, J. G. Checkelsky, S. Fang, E. Kaxiras, M. Richter, and J. van den Brink, Creating Weyl nodes and controlling their energy by magnetization rotation, *Phys. Rev. Res.* **1**, 032044(R) (2019).
- [45] G. B. Acharya, B. Karki, M. P. Ghimire, and B. Srinivasan, Weyl characteristics induced an anomalous Hall effect in double half-Heusler alloy $\text{Cr}_2\text{FeCoAs}_2$: A density-functional study, *ACS Appl. Electron. Mater.* **6**, 8260 (2024).
- [46] M. B. Neupane, R. Ghimire, G. B. Acharya, R. J. Yadav, and M. P. Ghimire, PtNiO_2 : A magnetic Weyl semimetal with large anomalous Hall conductivity, *J. Chem. Phys.* **164**, 034702 (2026).
- [47] L. Ye, J. I. Facio, M. P. Ghimire, M. K. Chan, J.-S. You, D. C. Bell, M. Richter, J. van den Brink, and J. G. Checkelsky, Magnetization orientation-dependent Shubnikov-de Haas

- oscillations in ferromagnetic Weyl semimetal $\text{Co}_3\text{Sn}_2\text{S}_2$, *npj Quantum Mater.* **11**, 14 (2026).
- [48] B. Sharma, M. P. Ghimire, D. B. Shahi, D. Bhattarai, Y. Sun, J.-S. You, J. van den Brink, and S. Singh, Large Berry curvature dipole and enhanced nonlinear Hall effects in monolayer $\text{W}_{0.5}\text{Mo}_{0.5}\text{Te}_2$, *Phys. Rev. B* **112**, 235433 (2025).
- [49] A. Nayak, S. Jamaluddin, F. Wu, E. Rapp, R. B. Regmi, M. E. Gazzah, B. G. Márkus, L. Forró, M. P. Ghimire, A. Oliver, K. Foyevtsova, I. I. Mazin, and N. J. Ghimire, Crystal growth and physical properties of orthorhombic kagome lattice magnets RFe_6Ge_6 ($R = \text{Y, Tb, Dy}$), [arXiv:2511.17398](https://arxiv.org/abs/2511.17398).
- [50] A. Vymazalova, F. Laufek, M. Drabek, A. R. Cabral, J. Haloda, T. Sidorinova, B. Lehmann, H. F. Galbiatti, and J. Drahokoupil, Jacutingaite, Pt_2HgSe_3 , a new platinum-group mineral species from the Caue iron-ore deposit, Itabira district, Minas Gerais, Brazil, *Can. Mineral.* **50**, 431 (2012).
- [51] M. Drabek, A. Vymazalova, and A. R. Cabral, The system Hg-Pt-Se at 400 C: Phase relations involving jacutingaite, *Can. Mineral.* **50**, 441 (2012).
- [52] A. R. Cabral, H. F. Galbiatti, R. Kwitko-Ribeiro, and B. Lehmann, Platinum enrichment at low temperatures and related microstructures, with examples of hongshiite (PtCu) and empirical Pt_2HgSe_3 from Itabira, Minas Gerais, Brazil, *Terra Nova* **20**, 32 (2008).
- [53] A. Marrazzo, M. Gibertini, D. Campi, N. Mounet, and N. Marzari, Prediction of a large-gap and switchable Kane-Mele quantum spin Hall insulator, *Phys. Rev. Lett.* **120**, 117701 (2018).
- [54] J. I. Facio, S. K. Das, Y. Zhang, K. Koepnik, J. van den Brink, and I. C. Fulga, Dual topology in jacutingaite Pt_2HgSe_3 , *Phys. Rev. Mater.* **3**, 074202 (2019).
- [55] B. Ghosh, S. Mardanya, B. Singh, X. Zhou, B. Wang, T.-R. Chang, C. Su, H. Lin, A. Agarwal, and A. Bansil, Saddle-point van Hove singularity and dual topological state in Pt_2HgSe_3 , *Phys. Rev. B* **100**, 235101 (2019).
- [56] A. Marrazzo, N. Marzari, and M. Gibertini, Emergent dual topology in the three-dimensional Kane-Mele Pt_2HgSe_3 , *Phys. Rev. Res.* **2**, 012063(R) (2020).
- [57] Z. Yue, B. Cai, L. Wang, X. Wang, and M. Gu, Intrinsically core-shell plasmonic dielectric nanostructures with ultrahigh refractive index, *Sci. Adv.* **2**, e1501536 (2016).
- [58] G. Kullerud, in *Research Techniques for High Pressure and High Temperature*, edited by G. C. Ulmer (Springer, Berlin, Heidelberg, 1971), pp. 289–315.
- [59] T. Björkman, A. Gulans, A. V. Krashenninnikov, and R. M. Nieminen, van der Waals bonding in layered compounds from advanced density-functional first-principles calculations, *Phys. Rev. Lett.* **108**, 235502 (2012).
- [60] N. Mounet, M. Gibertini, P. Schwaller, D. Campi, A. Merkys, A. Marrazzo, T. Sohier, I. E. Castelli, A. Cepellotti, G. Pizzi, and N. Marzari, Two-dimensional materials from high-throughput computational exfoliation of experimentally known compounds, *Nat. Nanotechnol.* **13**, 246 (2018).
- [61] J. Zeisner, A. Alfonsov, S. Selzer, S. Aswartham, M. P. Ghimire, M. Richter, J. van den Brink, B. Büchner, and V. Kataev, Magnetic anisotropy and spin-polarized two-dimensional electron gas in the van der Waals ferromagnet $\text{Cr}_2\text{Ge}_2\text{Te}_6$, *Phys. Rev. B* **99**, 165109 (2019).
- [62] F. C. de Lima, R. H. Miwa, and A. Fazzio, Jacutingaite-family: A class of topological materials, *Phys. Rev. B* **102**, 235153 (2020).
- [63] K. Kandrai, P. Vancsó, G. Kukucska, J. Koltai, G. Baranka, A. Hoffmann, A. Pekker, K. Kamarás, Z. E. Horváth, A. Vymazalová, L. Tapasztó, and P. Nemes-Incze, Signature of large-gap quantum spin Hall state in the layered mineral jacutingaite, *Nano Lett.* **20**, 5207 (2020).
- [64] R. Longuinhos, A. Vymazalová, A. R. Cabral, S. S. Alexandre, R. W. Nunes, and J. Ribeiro-Soares, Raman spectrum of layered jacutingaite (Pt_2HgSe_3) crystals—Experimental and theoretical study, *J. Raman Spectrosc.* **51**, 357 (2020).
- [65] W. Wang, S. Dai, X. Li, J. Yang, D. J. Srolovitz, and Q. Zheng, Measurement of the cleavage energy of graphite, *Nat. Commun.* **6**, 7853 (2015).
- [66] K. Koepnik and H. Eschrig, Full-potential nonorthogonal local-orbital minimum-basis band-structure scheme, *Phys. Rev. B* **59**, 1743 (1999).
- [67] J. P. Perdew, K. Burke, and M. Ernzerhof, Generalized gradient approximation made simple, *Phys. Rev. Lett.* **77**, 3865 (1996).
- [68] L. Fu and C. L. Kane, Time reversal polarization and a Z_2 adiabatic spin pump, *Phys. Rev. B* **74**, 195312 (2006).
- [69] D. B. Shahi, D. Bhattarai, and M. P. Ghimire, Exploring topological phase transition in $\text{Pt}_2\text{Hg}_{1-x}\text{Ti}_x\text{Se}_3$, *BIBICHANA* **20**, 309 (2023).
- [70] I. Cucchi, A. Marrazzo, E. Cappelli, S. Riccò, F.Y. Bruno, S. Lisi, M. Hoesch, T.K. Kim, C. Cacho, C. Besnard, E. Giannini, N. Marzari, M. Gibertini, F. Baumberger, and A. Tamai, Bulk and surface electronic structure of the dual-topology semimetal Pt_2HgSe_3 , *Phys. Rev. Lett.* **124**, 106402 (2020).
- [71] A. Bafekry, C. Stampfl, C. Nguyen, M. Ghergherehchi, and B. Mortazavi, Tunable electronic properties of the dynamically stable layered mineral Pt_2HgSe_3 (jacutingaite), *Phys. Chem. Chem. Phys.* **22**, 24471 (2020).
- [72] N. Marzari and D. Vanderbilt, Maximally localized generalized Wannier functions for composite energy bands, *Phys. Rev. B* **56**, 12847 (1997).
- [73] N. Marzari, A. A. Mostofi, J. R. Yates, I. Souza, and D. Vanderbilt, Maximally localized Wannier functions: Theory and applications, *Rev. Mod. Phys.* **84**, 1419 (2012).
- [74] X. Chen, Y. Wu, Z. Wu, Y. Han, S. Xu, L. Wang, W. Ye, T. Han, Y. He, Y. Cai, and N. Wang, High-quality sandwiched black phosphorus heterostructure and its quantum oscillations, *Nat. Commun.* **6**, 7315 (2015).
- [75] K. Kang, K.-H. Lee, Y. Han, H. Gao, S. Xie, D. A. Muller, and J. Park, Layer-by-layer assembly of two-dimensional materials into wafer-scale heterostructures, *Nature (London)* **550**, 229 (2017).
- [76] L. Rademaker and M. Gibertini, Gate-tunable imbalanced Kane-Mele model in encapsulated bilayer jacutingaite, *Phys. Rev. Mater.* **5**, 044201 (2021).
- [77] D. B. Shahi, D. Bhattarai, P. Basnet, and M. P. Ghimire, Topological phase transition in Pt_2HgTe_3 caused by chemical doping: A density functional study, *Comput. Mater. Sci.* **260**, 114225 (2025).
- [78] F. Luo, X. Hao, Y. Jia, J. Yao, Q. Meng, S. Zhai, J. Wu, W. Dou, and M. Zhou, Functionalization induced quantum spin Hall to quantum anomalous Hall phase transition in monolayer jacutingaite, *Nanoscale* **13**, 2527 (2021).

- [79] V. Vargiamidis, P. Vasilopoulos, and N. Neophytou, Tunable topological phases in monolayer Pt_2HgSe_3 with exchange fields, *Phys. Rev. B* **106**, 205416 (2022).
- [80] Y. Hajati, M. Alipourzadeh, I. Makhfudz, and J. Berakdar, Electromagnetically tunable spin-valley-polarized current via anomalous Nernst effect in monolayer of jacutingaite, *J. Phys.: Condens. Matter* **37**, 065802 (2025).
- [81] F. Crasto de Lima, B. Focassio, R. H. Miwa, and A. Fazzio, Topological insulating phase arising in transition metal dichalcogenide alloy, *2D Mater.* **10**, 035001 (2023).
- [82] A. Zunger, S.-H. Wei, L. G. Ferreira, and J. E. Bernard, Special quasirandom structures, *Phys. Rev. Lett.* **65**, 353 (1990).
- [83] X. Zhu, Y. Chen, Z. Liu, Y. Han, and Z. Qiao, Valley-polarized quantum anomalous Hall effect in van der Waals heterostructures based on monolayer jacutingaite family materials, *Front. Phys.* **18**, 23302 (2023).
- [84] Z. Liu, Y. Ren, Y. Han, Q. Niu, and Z. Qiao, Second-order topological insulator in van der Waals heterostructures of $\text{CoBr}_2/\text{Pt}_2\text{HgSe}_3/\text{CoBr}_2$, *Phys. Rev. B* **106**, 195303 (2022).
- [85] M. U. Rehman, Z. Qiao, and J. Wang, Valley-symmetry-broken magnetic topological responses in $(\text{Pt}/\text{Pd})_2\text{HgSe}_3/\text{CrGeTe}_3$ and $\text{Pd}_2\text{HgSe}_3/\text{CrI}_3$ through interfacial coupling, *Phys. Rev. B* **105**, 165417 (2022).
- [86] J. E. Hirsch, M. B. Maple, and F. Marsiglio, Superconducting materials classes: Introduction and overview, *Physica C* **514**, 1 (2015).
- [87] M. Sigrist and K. Ueda, Phenomenological theory of unconventional superconductivity, *Rev. Mod. Phys.* **63**, 239 (1991).
- [88] X. Wu, M. Fink, W. Hanke, R. Thomale, and D. Di Sante, Unconventional superconductivity in a doped quantum spin Hall insulator, *Phys. Rev. B* **100**, 041117(R) (2019).
- [89] H. Yao and F. Yang, Topological odd-parity superconductivity at type-II two-dimensional van Hove singularities, *Phys. Rev. B* **92**, 035132 (2015).
- [90] J. L. McChesney, A. Bostwick, T. Ohta, T. Seyller, K. Horn, J. González, and E. Rotenberg, Extended van Hove singularity and superconducting instability in doped graphene, *Phys. Rev. Lett.* **104**, 136803 (2010).
- [91] Y. Qi, P. G. Naumov, M. N. Ali, C. R. Rajamathi, W. Schnelle, O. Barkalov, M. Hanfland, S.-C. Wu, C. Shekhar, Y. Sun, V. Süß, M. Schmidt, U. Schwarz, E. Pippel, P. Werner, R. Hillebrand, T. Förster, E. Kampert, S. Parkin, R. J. Cava, *et al.*, Superconductivity in Weyl semimetal candidate MoTe_2 , *Nat. Commun.* **7**, 11038 (2016).
- [92] K. Fossheim and A. Sudbø, *Superconductivity: Physics and Applications* (John Wiley & Sons, Chichester, UK, 2004).
- [93] C. Pei, S. Jin, P. Huang, A. Vymazalova, L. Gao, Y. Zhao, W. Cao, C. Li, P. Nemes-Incze, Y. Chen, H. Liu, G. Li, and Y. Qi, Pressure-induced superconductivity and structure phase transition in Pt_2HgSe_3 , *npj Quantum Mater.* **6**, 98 (2021).
- [94] D. Mauro, H. Henck, M. Gibertini, M. Filippone, E. Giannini, I. Gutiérrez-Lezama, and A. F. Morpurgo, Multi-frequency Shubnikov-de Haas oscillations in topological semimetal Pt_2HgSe_3 , *2D Mater.* **7**, 025042 (2020).
- [95] G. Santos-Castro, L. K. Teles, I. Guilhon Mitoso, and J. M. Pereira Jr, Tight-binding model of Pt-based jacutingaites as combination of the honeycomb and kagome lattices, *J. Phys.: Condens. Matter* **37**, 035502 (2025).
- [96] M. Yarmohammadi, S. R. Koshkaki, J. Berakdar, M. Bukov, and M. H. Kolodrubetz, Probing topological phases in a perturbed Kane-Mele model via RKKY interaction: Application to monolayer jacutingaite Pt_2HgSe_3 , *Phys. Rev. B* **111**, 014440 (2025).
- [97] Rafael L. H. Freire, F. C. de Lima, R. H. Miwa, and A. Fazzio, Exploring topological transport in Pt_2HgSe_3 nanoribbons: Insights for spintronic device integration, *Phys. Rev. B* **110**, 035111 (2024).
- [98] M. Shah and M. S. Anwar, Topological transport in monolayer jacutingaite, *arXiv:2412.16965*.
- [99] N. Q. Bau, T. T. Tho, Le T. T. Phuong, and B. D. Hoi, Edelstein effect in optically driven monolayer jacutingaite Pt_2HgSe_3 , *Phys. Rev. B* **112**, 035428 (2025).
- [100] M. Shah, I. Khan, K. Sabeeh, M. S. Anwar, and R. Asgari, Quantum magnetotransport in monolayer Pt_2HgSe_3 , *Phys. Rev. B* **112**, 195415 (2025).
- [101] P. Fachin, F. Macheda, P. Barone, and F. Mauri, Infrared markers of topological phase transitions in quantum spin Hall insulators, *npj Comput. Mater.* **11**, 307 (2025).
- [102] T. C. Phong, T. T. Tho, N. T. Nam, and L. T. T. Phuong, Quantum capacitance of dressed monolayer jacutingaite Pt_2HgSe_3 , *Physica B* **716**, 417731 (2025).
- [103] T. C. Phong, T. T. Tho, and L. T. T. Phuong, Detecting topological phase transition in monolayer jacutingaite Pt_2HgSe_3 via thermal and magnetic properties, *Phys. E: Low-Dimens. Syst. Nanostructures* **175**, 116395 (2025).
- [104] T. T. Tho, N. D. Nam, and B. D. Hoi, Electrical and thermal conductivity of gated and irradiated jacutingaite Pt_2HgSe_3 , *Phys. Lett. A* **562**, 131012 (2025).
- [105] B. D. Hoi and T. T. Tho, Quantized optical conductivity of gated and irradiated monolayer Pt_2HgSe_3 , *Phys. Chem. Chem. Phys.* **27**, 18511 (2025).