Topological Dirac Spin-Gapless Valley-Filtered Chiral Edge States
“Topological Spin Field Effect Transistors without Spin-Orbit Interaction”

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The existence of chiral edge states, corresponding to the nontrivial bulk band topology characterized by a non-vanishing topological invariant, and the manipulation of topological transport via chiral edge states promise dissipationless topological electronics/spintronics. Here we predict the existence and the topological protection of spin-gapless valley-filtered chiral edge states, representing a novel topological Dirac spin-gapless/half-metal phase hosted by antiferromagnetic honeycomb structures terminated on zigzag edges. We demonstrate that this phenomenon is realizable if perpendicular (transverse) electric field, that is controlled by bulk (boundary) gates and induces staggered sublattice potentials in the bulk (on the boundary), is applied in zigzag nanoribbons with antiferromagnetic ordering on the boundary (in the bulk). While staggered potentials in the bulk are desired to induce bulk band topology characterized by valley or spin-valley Chern number, it is explicitly shown that the edge bands dispersion is controlled by staggered potentials on the boundary, and that their spin-polarization is practically tuned through an interplay between staggered potentials in the bulk and on the boundary. We discover that the existence of spin-gapless valley-filtered chiral edge states, their correspondence with nontrivial topological character in the bulk, and electric field driven switching of their spin-polarization that is accompanied by the switching of bulk band topology promise a new strategy for topological spintronics, even in the absence of spin-orbit coupling.

Keywords: Quantum valley Hall insulators, Quantum spin-valley Hall insulators, Dirac spin-gapless semiconductors, Dirac half-metals, Topological spintronics.

I. INTRODUCTION

The existence of topologically protected edge states along one-dimensional (1D) boundary, owning to the bulk band topology of a two-dimensional (2D) system, has brought about an interest in the Berry-phase supported dissipationless topological transport [1,3]. The nature of edge states in 2D topological insulating materials is characterized through a specific non-vanishing topological invariant in the bulk. For instance, integer quantum Hall (IQH) [4] and quantum anomalous Hall (QAH) [5,15], quantum spin Hall (QSH) [16,27], quantum valley Hall (QVH) [28,32], and quantum spin-valley Hall (QSVH) [33,35] with coupled spin and valley degrees of freedom [36,37] are well known examples of 2D topological insulators. These novel systems are distinct from conventional insulators; though the current cannot flow via bulk states as the empty bands are separated from fully occupied bands by an energy gap, however, a quantized conduction may still be allowed via edge states lying inside the energy gap. Such a nontrivial energy gap is characterized by Chern number ($C_s$) in IQH/QAH insulators [5,11,35] with chiral edge states (CES), spin Chern number ($C_s$) in QSH insulators [16,39,40] with spin-filtered (helical) chiral edge states (SF-CES), valley Chern number ($C_v$) in QVH insulators [11,24,30,41] with valley-filtered chiral edge states (VF-CES), and spin-valley Chern number ($C_{sv}$) in QSVH insulators [33,35] with spin-valley-filtered chiral edge states (SVF-CES). Such nontrivial bulk and dissipationless chiral edge states may provide promising platform for topological device applications [42,46].

Unlike QSH and QAH insulators where strong spin-orbit interaction (SOI) is desired to induce CES, VF-CES and SVF-CES can be realized through different physical mechanisms in QVH and QSVH insulators, for instance, by engineering topological domain walls [30,33,35,47,48], inducing ferromagnetic exchange interaction [11], and by applying perpendicular [49] or transverse electric field [30,50]. While electrical domain walls [30,47,48] and/or transverse electric fields [30,50] induce spin-degenerate VF-CES in nonmagnetic QVH insulators, magnetic domain walls in QSVH insulators [33] and an interface between QVH and QSH insulators [35] can induce SVF-CES. Unlike SF-CES in QSH insulators that are protected by time-reversal symmetry, topological robustness of QVH and QSVH insulators is guaranteed by large inter-valley separation in momentum space, and thus, suppressed inter-valley scattering [51,53].

Here we discover a new strategy that exploits interplay between inversion symmetry breaking perturbations in the bulk and on the boundaries (with unit cell length scale) of both QVH and QSVH insulators and leads to spin-gapless valley-filtered chiral edge states (SG-VF-CES): VF-CES displaying spin-gapless Dirac dispersion [53,55] where all the edge states lying inside the nontrivial energy gap carry same spin polarization, represent-
**FIG. 1.** Topological spin-gapless or half-metal phase with SG-VF-CES in ZNRs of 2D antiferromagnets. (a,b) ZNRs with antiferromagnetic ordering in the bulk (a) and on the boundary (b) connected with side gates and top/bottom gates respectively. (c,d) 1D band dispersion showing SG-VF-CES for ZNRs shown in (a) and (b). (e,f) Schematic representation of SG-VF-CES in real space. Here gray and red/cyan colours represent non-magnetic and magnetic atoms with spin up/down moments respectively.

By calculating tight binding band dispersion, density of states (DOS), and edge state wave functions for zigzag nanoribbons (ZNRs) of 2D antiferromagnets with honeycomb structure terminated on zigzag edges, it is explicitly demonstrated that inversion symmetry breaking perturbations such as staggered sublattice potentials (SSPs) in the bulk (on the boundary) induced by perpendicular (transverse) electric field and staggered magnetic potentials (SMPs) induced by antiferromagnetic ordering on the boundary (in the bulk) disperse energy-zero flat band bands into SG-VF-CES. The proposed mechanisms, studied for material-independent models here, are very generic and remain applicable for a wide variety of strongly correlated and weakly spin-orbit coupled 2D materials with honeycomb lattice structure terminated on zigzag edges. For instances, SG-VF-CES can be realized in graphene ZNRs with inter-edge antiferromagnetic ordering on the boundary [50, 51] and substrate induced SSPs in the bulk [61] and 2D antiferromagnets with intrinsic SMPs in the bulk and side-gate induced SSPs on the boundary.

Similar to VF-CES in QVH and SVF-CES in QSVH insulators, SG-VF-CES are characterized either by valley Chern number and valley-momentum locking or by spin-valley Chern number and spin-valley-momentum locking when the topologically nontrivial bulk energy gap is opened by SSPs or SMPs respectively. That is, if there is no inter-valley mixing, SG-VF-CES remain protected against backscattering. In both QVH and QSVH insulators, with SMPs on the boundaries and in the bulk respectively, spin-transport via SG-VF-CES can be switched by the perpendicular electric field controlled through top/bottom gates. Interestingly, electric field driven switching of spin-transport via SG-VF-CES is accompanied by the switching of bulk topological invariant, a blueprint for topological switching. For instance, in QVH insulators, reversal of perpendicular electric field switches spin-polarization of SG-VF-CES by switching the valley Chern number from $C_v = \pm 2$ to $C_v = \mp 2$. Similarly, in QSVH insulators, perpendicular electric field switches edge state spectrum from SG-VF-CES to VF-CES by switching bulk band topology characterized by $C_{sv} = -2$ to $C_{sv} = 2$. The existence of SG-VF-CES in nanometre-scale ZNRs, the topological origin of their spin-polarization corresponding to nontrivial bulk band topology, and electric field driven topological switching promise a new strategy for topological spintronics, even in the absence of SOI. It makes our proposals for topological spin field effect transistors (TSFETs) contrasting from the existing models in which SOI is a key ingredient for switching topological spin-transport [62–66]. In addition, owning to the edge state Dirac dispersion and topological protection, SG-VF-CES are well suited for steering the engineering of low-voltage device applications with high mobility and large signal-to-noise ratio.

**FIG. 2.** Bulk band topology and confinement effect. (a) Meron/anti-Meron pseudospin textures of filled bands for QVH and QSVH phases. (b) Electronic spectrum of pristine ZNRs (dashed lines) and gapped ZNRs in the presence of SPs on the boundaries (solid lines). Here $E_c$ is the energy of confined states on boundaries while $k_x = k'_x = k_{cx}$ are anti-crossing points in the edge state spectrum. (c) Confinement energy of boundary states and first bulk subband as a function of the ZNR width.
II. BULK/BOUNDARY GATING EFFECTS ON ZNRS OF 2D ANTIFERROMAGNETS

In ZNRs composed of N zigzag chains, with antiferromagnetic ordering in the bulk or on the boundary, perpendicular ($E_z$) or transverse ($E_y$) electric field induced SG-VF-CES traversing along x-axis can be characterized by a simple nearest-neighbour tight binding Hamiltonian

$$H_{UB}^{E_z} = t \sum_{\langle ij \rangle \alpha} c_{i \alpha}^\dagger c_{j \alpha} + \sum_{i \alpha} c_{i \alpha}^\dagger \left( v_i V_B \right) c_{i \alpha} + \sum_{i(=1\ldots N) \alpha} c_{i \alpha}^\dagger \left( s_z u_i U_B \right) c_{i \alpha} .$$

$$H_{UB}^{E_y} = t \sum_{\langle ij \rangle \alpha} c_{i \alpha}^\dagger c_{j \alpha} + \sum_{i \alpha} c_{i \alpha}^\dagger \left( s_z u_i U_B \right) c_{i \alpha} + \sum_{i(=1\ldots N) \alpha} c_{i \alpha}^\dagger \left( \tilde{v}_i V_E \right) c_{i \alpha} .$$

where $c_{i \alpha}^\dagger$ ($c_{i \alpha}$) is the creation (annihilation) electron operator with spin polarization $\alpha = \uparrow, \downarrow$ on site $i$ and $s_z$ represents the electron intrinsic spin. In the bulk, $V_B$ and $U_B$ represent SSP and SMPs respectively with $v_i = u_i = +1(-1)$ for sublattice A (B). On the boundary, $V_E$ and $U_E$ represent SSP and SMPs respectively with $v_{i(\ldots N)} = u_{i(\ldots N)} = +1(-1)$ for left(right) boundary terminated on sublattice A (B) while $v_i = u_i = 0$ for all other (bulk) sites.

As shown in figure 2(b), owning to the intrinsic band topology in the bulk [60,71] and associated with the electronic wave functions localized on the boundaries [50,72,74], nearest-neighbor hopping generates edge state spectrum that hosts fourfold spin-degenerate energy-zero flat bands in the nontrivial regime of the 1D Brillouin zone connecting Dirac pints, $k \in (2\pi/3a_0, 4\pi/3a_0)$. When the width of ZNRs is smaller than a critical limit, $W_z < W_z^c$, finite-size effects lead to confinement of both bulk and the boundary electronic states in the vicinity of Dirac points $K_x = K'/K'$. As shown in figure 2(c), obtained through tight binding model at Dirac point, we plot the confinement energy of boundary states and first bulk subband as a function of the ZNR width. The energy of these confined states increases with decreases in ZNR width. These tight binding results are consistent with the results obtained though low-energy effective Dirac theory for quantum confined ZNRs [75,76].

All the inversion symmetry breaking staggered potentials (SPs) induced by electric field and antiferromagnetic ordering, both in the bulk and on the boundary, open an energy gap in the edge state spectrum. For instance, SSPs and SMPs in the bulk open an energy gap of $2V_B$ and $2U_B$, respectively, in the whole Brillouin zone. Such topologically nontrivial gap in the bulk characterize QVH and QSVH states respectively, and transform spin-degenerate energy-zero flat bands into gapped flat bands on the boundaries. On the other hand, as depicted in the figure 2(b), both SSPs and SMPs on the boundary have no effect on the bulk subbands, and thus, leave bulk band topology nontrivial. However, unlike SPs in the bulk, SPs on the boundary disperse edge state flat bands through momentum-dependent energy splitting in the edge state spectrum: energy of confined boundary states associated with momentum across valleys remain insensitive to the strength of SPs on the boundary but the energy of confined boundary states associated with momentum across TRIM varies linearly with the strength of SPs on the boundary. Such momentum-dependent energy splitting leads to a confinement induced energy gap of $\delta = 2E_c$ at valleys.

Though, both SPs in the bulk and on the boundary open an energy gap in the edge state spectrum of quantum confined ZNRs, an interplay between SSPs in the bulk (on the boundary) and SMPs on the boundary (in the bulk) leads to SG-VF-CES. For instance, in ZNRs with boundary magnetism ($U_B = 0$ but $U_E \neq 0$), as shown in figure 1(d), perpendicular electric field induced SSPs in the bulk evolves edge state spectrum into SG-VF-CES. Similarly, in ZNRs with bulk magnetism ($U_B = 0$ but $U_E \neq 0$), as shown in figure 1(c), transverse electric field induced SSPs on the boundary evolves gapped flat bands into SG-VF-CES. To induce such SG-VF-CES at valleys and to ensure complete admixing of edge states with the bulk subbands at TRIM, SPs on the boundary are required to satisfy constraint $|U_E| > |t + V_B|$ for SG-VF-CES in ZNRs with boundary magnetism and $|V_E| > |t + U_B|$ for SG-VF-CES in ZNRs with bulk magnetism. In magnetic ZNRs, with antiferromagnetic ordering either in the bulk or on the boundary, spin-polarization of SG-VF-CES can be manipulated by controlling the polarity of gate electric fields.

Contrary to previously proposed perpendicular (transverse) electric field induced half-metallicity in condensed matter systems with antiferromagnetic ordering in the bulk (one the boundary) [59,77], we discover a new strategy that exploits transverse (perpendicular) to induce half-metallicity in condensed matter systems with antiferromagnetic ordering in the bulk (on the boundary). In addition, this new strategy allows topological protection of spin-transport via SG-VF-CES that correspond to the nontrivial bulk band topology, representing a novel topological Dirac spin-gapless or half-metal phase.
Since spin remains a good quantum number and thus spin textures remain trivial in the absence of Rashba SOI, the nontrivial bulk band topology in QVH and QSVH phases can be verified by examining the pseudospin textures of low energy bands. For a minimal four-band model, Chern, spin-Chern, valley Chern, and spin-valley Chern numbers are defined as

\[ C = C_{K_1} + C_{K_2} = \left( C_{K_1}^\uparrow + C_{K_2}^\uparrow \right) + \left( C_{K_1}^\downarrow + C_{K_2}^\downarrow \right), \]  
\[ 2C_s = C_\uparrow - C_\downarrow = \left( C_{K_1}^{K_1} + C_{K_2}^{K_2} \right) - \left( C_{K_1}^{K_1} + C_{K_2}^{K_2} \right), \]  
\[ C_v = C_{K_1} - C_{K_2} = \left( C_{K_1}^\uparrow + C_{K_2}^\uparrow \right) - \left( C_{K_2}^\downarrow - C_{K_2}^\downarrow \right), \]  
\[ C_{sv} = C_{K_1} - C_{K_2} = \left( C_{K_1}^\uparrow - C_{K_2}^\downarrow \right) - \left( C_{K_2}^\uparrow - C_{K_2}^\downarrow \right). \]

where spin Chern number is subject to modulo 2. As shown in figure 2(a), Meron and anti-Meron like pseudospin textures for filled/valence bands suggest that nonvanishing SSPs in the bulk lead to QVH state characterized by quartet \((C, C_s, C_v, C_{sv}) = (0, 0, 0, -2)\) while nonvanishing SMPs in the bulk lead to QSVH state characterized by quartet \((C, C_s, C_v, C_{sv}) = (0, 0, 0, -2)\).

Since SPs on the boundaries do not affect the bulk band spectrum, the band topology induced by SPs in the bulk remains intact even in the presence of SPs on the boundaries. Thus, similar to VF-CES and SVF-CES, SG-VF-CES are also characterized either by valley Chern number and valley-momentum locking or by spin-valley Chern number and spin-valley-momentum locking when the topologically nontrivial bulk energy gap is opened by SSPs or SMPs respectively. It is important to note that, owing to the combined effect of SPs in the bulk and on the boundary, \(C_s = \pm 1\) and \(C_{sv} = \pm 1\) correspond to two oppositely propagating chiral modes (one from each valley) on each edge.

Consistent with the tight binding picture of electronic dispersion, these results can be verified by studying real space distribution of edge state wave functions and calculation of DOS. Sinusoidal behaviour of edge state wave functions and vanishing DOS at zero-energy, show that SPs on the boundary open an energy gap in the edge state spectrum. However, in the presence of SSPs in the bulk along with SSPs on the boundary, edge state wave functions confined on boundaries and a non-vanishing energy-zero DOS represent the existence of gapless VF-CES. Similarly, in the presence of SSPs (SMPs) in the bulk along with SMPs (SSPs) on the boundaries, exponentially (sinusoidal) decaying wave functions for spin-down (spin-up) edge states and a no-vanishing (vanishing) energy-zero DOS for spin-down (spin-up) edge states confirm the existence of SG-VF-CES. That is, in the presence of SPs on the boundary, SPs in the bulk overcome confinement induced energy gap in the edge state spectrum and ensure gapless CES at valleys that stem from the nontrivial bulk band topology.

Since, confinement induced energy gap in the edge state spectrum remains independent of the strength of SPs on the boundaries, the minimal strength of bulk SPs desired for inducing gapless CES is purely a function of ZNRs width. However, on the other hand, the minimal strength of boundary SPs required for complete submergence of edge states with the bulk subbands at \(k_x = \pi\) is highly dependent on the strength of bulk SPs. The dependence of bulk SPs on the width of ZNRs and, in turn, dependence of boundary SPs on the bulk SPs can be understood as follows: Similar to the boundaries states, energies of confined bulk states associated with momentum around TRIM \(k_x = \pi\) remain independent of width. It implies that, in the absence of SSPs (SMPs) in the bulk, edge states at \(k_x = \pi\) completely submerges with the bulk states when \(U_E/t = 1 (V_E/t = 1)\). However, in the presence of SSPs (SMPs) in bulk that induce a linear shift in the energies of bulk and boundary states across the whole Brillouin zone, the minimum strength of boundary SMPs (SSPs) required to submerge edge states with bulk subbands at \(k_x = \pi\) increases to \(U_E/t \geq 1 + V_B/t (V_E/t \geq 1 + U_B/t)\).

On the other hand, since inter-edge hybridization between exponentially decaying edge state wave functions in the vicinity of valleys increases with decrease in the width, the strength of bulk SPs required to overcome confinement induced gap in the edge state spectrum also increases. In addition, for a fixed width of 6-ZNRs as shown in figure 3(i), unlike linear behaviour when the strength of bulk SPs exceeds the strength of SPs on the boundary, confinement induced gap in the edge state spectrum varies exponentially with the bulk SPs. In response, in gapped ZNRs where bandgap is induced by bulk SPs, strength of boundary SPs also increases to meet the constraint \(U_E \geq t + V_B\) (or \(V_E \geq t + U_B\)) for complete submerging of boundary and bulk states at \(k_x = \pi\).

The increasing strength of bulk SPs with decrease in width, and thus, the increasing strength of boundary SPs, demands finding some mechanisms to optimize the strengths of gate electric electric fields and magnetic properties for quantum confined ZNRs. Interestingly, the strength of boundary (bulk) magnetism can be optimized by applying transverse (perpendicular) electric field leading to SSPs on the boundary (in the bulk) of ZNRs. In antiferromagnets, it is customary to tune magnetic properties either by perpendicular electric field or by transverse electric field. However, the generation of SG-VF-CES by perpendicular (transverse) electric field open a new direction for tuning magnetic properties via electric fields: magnetic properties of ZNRs may be practically tuned by a new strategy that exploits both perpendicular and transverse electric fields simultaneously.
FIG. 3. Edge state wave functions, density of states, and bulk-boundary gating effects. (a-c) Edge state square wave functions in real space, at \( k_x = K \), obtained from 4-band model for 32-ZNRs. SPs on the boundaries evolve exponentially decaying edge states into sinusoidal wave functions that correspond to gapped edge state spectrum (a). In the presence of SSPs in the bulk and that on the boundaries, exponentially decaying edge states wave functions imply gapless VF-CES (b). In the presence of SSPs (SMPs) in the bulk and SMPs (SSPs) on the boundaries, exponentially (sinusoidal) decaying edge states wave functions in spin down (up) sector imply SG-VF-CES (c). (d-f) Partial DOS obtained from 4-band model for 6-ZNRs. Vanishing DOS (d), non-vanishing DOS in both spin sectors (e), and non-vanishing (vanishing) DOS in spin down (up) sectors at energy-zero level confirms the distribution of edge state wave functions in real space. (g-i) Bulk-boundary gating effects on DOS obtained from low-energy 2-band model for 6-ZNRs. With fixed SPs on the boundaries \( (U_E(V_E)) \), SPs in the bulk transform vanishing energy-zero DOS \( (V_B(U_B) < V_{c1}) \) into non-vanishing energy-zero DOS \( (V_{c1} < V_B(U_B) < V_{c2}) \), and to vanishing energy-zero DOS \( (V_B(U_B) > V_{c2}) \). Here \( V_{c1} \) is the critical potential at which gapped edge states transform to gapless chiral edge state while \( V_{c2} \) is the critical potential at which gapless chiral edge states transform to gapped edge state. While \( V_{c1} \) depends upon the width of ZNRs, and thus, the confinement energy \( E_c \), \( V_{c2} \) is equivalent to boundary SP, \( V_{c2} = U_E(V_E) \). The symbol | denotes ‘or’ here.

III. TOPOLOGICAL SPIN FETS

Honeycomb lattice structures terminated on zigzag nanoribbons are a special class of 2D material where topological transport on 1D boundaries promise dissipationless topological electronics and spintronics applications [46] with reduced subthreshold swing via Rashba effect [78] and negative capacitance [79] and may allow miniaturization owning to the intertwining of edge state transport with intrinsic band topology [76]. After demonstrating the existence and the topological protection of SG-VF-CES, here we propose two different models for TSFETs utilizing ZNRs with the boundary magnetism, figure 4(b), and ZNRs with the bulk magnetism, figure 4(c). Unlike Rashba SOI driven spin-precession, topological spin-transport via SG-VF-CES is enabled and manipulated through spin-valley locking with momentum, and that is implemented by the gate-controlled perpendicular electric field \( E_z \).

In ZNRs with gapped edge state spectrum due to non-vanishing boundary magnetism, \( E_z \) closes the energy gap and induces SG-VF-CES in one of the spin sectors while leaves other spin sector gapped. In ad-
dition, $E_z$ enhances bulk band gap such that topological SG-VF-CES are completely disentangled from bulk subbands at the valleys. For the SMPs on the boundary ($U_B$) with $u_{i(N)} = +1(-1)$ for left(right) boundary terminated on sublattice A (B) sites, spin-polarization of SG-VF-CES switches by switching the polarization of $E_z$-induced SSPs: spin down with $v_i = +1(-1)$ and spin up with $v = -1(+1)$ for A(B) sublattice sites. On the other hand, in ZNRs with gapped edge state spectrum due to SSPs on the boundary, bulk SSPs leads to spin-degenerate VF-CES while bulk SMPs leads to SG-VF-CES. If we consider ZNRs with bulk magnetism and thus SG-VF-CES, $E_z$ switches on-state with SG-VF-CES ($V_B < U_B$) to an off-state with spin-degenerate VF-CES ($V_B > U_B$). That is, $E_z$ leaves CES in one of the spin sector gapless while closes the energy gap and induces gapless CES in other spin sector such that gapless CES arise in both of the spin sectors and spin transport is prohibited.

The proposed mechanism for TSFETs without SOI suggest a new strategy for topological spintronics that may display several advantages over previously proposed models in which SOI is a key ingredient. For instance, proposed models for TSFETs are highly contrasting from conventional Datta-Dass model [80], as neither ferromagnetic contacts are desired for spin injection/detection at the source/drain nor Rashba SOI is required for the spin-precession. Furthermore, proposed models are also completely different from recently studied models for TSFETs based on topological insulators displaying large Rashba SOI [62–66]. Such intrinsic control over spin transport via spin-valley-momentum locking automatically overcomes the fundamental obstacles faced by conventional spin FETs such as conductivity mismatch resulting from electrical spin injection from a ferromagnetic metallic contacts into a diffusive semiconducting channel [81]. Moreover, the proposed strategy of TSFETs without SOI also resolves the conundrum originated from the interplay between spin-relaxation and spin-manipulation. That is, in the spin FETs based on conventional switching mechanisms, spin-relaxation and spin-manipulation are two critical aspects for the realization of fully polarized spin currents over long distance and their SOI-driven switching respectively. Since weak spin relaxation ascribes to weak intrinsic SOI, a property that makes the manipulation of spins in the same material challenging [82].

In addition, owning to the edge state Dirac dispersion and topological protection, SG-VF-CES are well suited for steering the engineering of low-voltage device applications with high mobility and large signal-to-noise ratio. For instance, perpendicular electric field driven topological switching of spin-transport via SG-VF-CES is also different from transverse electric field driven conventional switching in ZNRs of graphene, where spin-polarized flat bands are generated from combined action of SPs on the boundaries [59] and only one of the valleys contribute in the spin transport. On the other hand, SG-VF-CES generated through combined action of SPs in the bulk and on the boundary assures contribution from both valleys and thus promise large signal-to-noise ratio by doubling the traversing spin-polarized edge states in ZNRs. In addition, SG-VF-CES promise other advantages owning to their Dirac dispersion, such as large mobility, that are trademark of graphene.

![FIG. 4. Topological spin FET](image)
(a) Schematic representation for Datta-Dass spin FET based on a conventional semi-conducting transport. (b,c) Schematic representation for topological spin FET where spin-transport is enabled via SG-VF-CES and controlled via topological phase transition between different spin-orientation of SG-VF-CES (b) or between SG-VF-CES and VF-CES (c). In the lower panel, $\sigma_{++}$ and $\sigma_{+-}$ represent the quantized spin-resolved edge state conductivity in spin-up and spin-down sector respectively. Here, $V_G$ is the gate potential, $V_s$ is the critical potential in Datta-Dass model, and $U_B$ is the strength of intrinsic staggered magnetic potential. Here solid (dashed) arrows represent gapless/conducting (gapped/non-conducting) chiral modes.

### IV. CONCLUSION

We demonstrate that spin-gapless valley-filtered chiral edge states, representing a novel topological Dirac spin-gapless or half-metal phase, can be realized by a new strategy that exploits perpendicular (transverse) electric fields in ZNRs with antiferromagnetic ordering on the boundary (in the bulk). While staggered potentials on the boundaries, either intrinsically present staggered magnetic potentials or side gate induced staggered sub-lattice potentials, disperse the flat band edge states of pristine ZNRs, staggered potentials in the bulk are crucial for inducing and controlling topologically nontrivial bulk band gap, controlling energy gap in the edge state spectrum, and switching topological spin-transport via spin-gapless valley-filtered chiral edge states by switching the bulk band topology. The utilization of spin-gapless valley-filtered chiral edge states is explicitly demonstrated for two different models of topological spin FETs where, unlike SOI-driven switching, edge state topological spin-transport is enabled and manipulated via intrinsic spin-valley locking with momentum, and that is im-
plemented by the gate-controlled perpendicular electric field. Including high mobility and large signal-to-noise ratio, we pointed that proposed models for topological spin FETs may display several other advantages over previously proposed conventional/topological spin FETs and may guide a new strategy for engineering topological spintronic devices without spin-orbit interaction. The proposed mechanisms may be realized in a wide variety of weakly spin-orbit coupled but strongly interacting 2D materials, ranging from graphene to other 2D structures with honeycomb structure terminated on zigzag edges, and that their magnetic properties can be optimized by the gate-controlled electric fields.

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