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Rashba spin–orbit driven topological phase transitions in heterogeneous armchair honeycomb nanoribbons

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E-mail: jhihshihyou@ntnu.edu.tw, yrchen@phy.ntnu.edu.tw and hongyi@ntnu.edu.tw**Keywords:** topological phase transition, Rashba spin–orbit coupling, nanoribbon, winding number, lattice geometry

Abstract

We investigate the emergence of nontrivial topological phases in heterogeneous armchair honeycomb nanoribbons arising from the interplay between structural geometry and Rashba spin–orbit coupling (RSOC). The system consists of a central RSOC-active region sandwiched between two pristine segments, forming interfaces between topologically distinct phases. As the RSOC strength increases, interface states emerge and become localized at the junctions. These states remain unchanged despite variations in edge configurations and ribbon widths. For finite ribbon widths, the RSOC induces a closing and subsequent reopening of the bulk energy gap, signaling a topological phase transition without altering the underlying lattice geometry. These findings reveal a route to engineering tunable topological states through the cooperative effects of interfacial structure and spin–orbit interactions.

Symmetry and topology jointly govern the emergence of protected boundary states through the bulk–edge correspondence [1–3], establishing a fundamental connection between electronic structure and wave-function geometry in quantum systems. Subsequently, a general topological invariant has been proposed to extend bulk–edge correspondence to asymmetric systems [4–6]. In low-dimensional lattices, topological phases are conventionally realized through structural modifications such as lattice deformation [7], width variation [8, 9], edge reconstruction [10–15], or hopping geometry [16] to induce nontrivial band topology. While these approaches have enabled symmetry-protected edge modes in graphene nanoribbons and related systems, they typically require permanent geometric alternations to lattice structure, thereby limiting *in situ* tunability of topological properties. Therefore, we aim to explore the mechanism of tuning topological phases without relying on geometric modification.

Spin–orbit coupling provides a natural candidate mechanism to generate and control topological phases without modifying lattice geometry. In particular, Rashba spin–orbit coupling (RSOC), originating from inversion-symmetry breaking induced by substrates [17] or external electric fields [18], provides a highly tunable interaction widely exploited in spin transport and spintronic devices [19–22]. Notably, RSOC is commonly realized to destroy topological insulating phases in 2D honeycomb lattices [23, 24] and induce nontrivial topological phases in certain quasi-1D systems [25–27]. Nevertheless, the capability of RSOC to systematically drive topology in geometrically identical structures remains unexplored.

Here we show that the interplay between structural geometry and RSOC enables tunable topological phases without modifying lattice topology. We consider a heterogeneous armchair honeycomb nanoribbon in which a RSOC-active region (R) is embedded between pristine nanoribbons (P), forming a P–R–P junction. By continuously tuning the Rashba coupling strength, the system undergoes gap closing and reopening associated with distinct topological invariants, leading to symmetry-protected interface states localized at junction boundaries. These states remain unchanged against edge and ribbon width modifications, demonstrating that RSOC acts as an effective control parameter for inducing non-trivial topological phases. Different from previous approaches, our mechanism relies on an externally induced interaction instead of any modification of underlying lattice geometry.

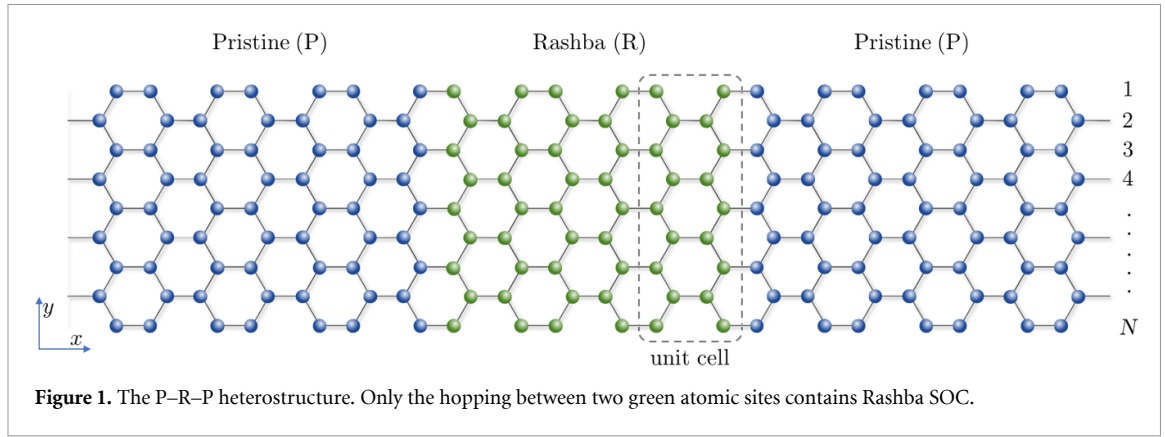


Figure 1. The P–R–P heterostructure. Only the hopping between two green atomic sites contains Rashba SOC.

Our mechanism can be extended to photonic crystals [28–30] and other synthetic lattices [31–33], where honeycomb lattice structures can be effectively engineered and Rashba-type spin–orbit interactions, together with nanoribbon geometries, have recently been realized. Our results therefore identify spin–orbit interaction as a general mechanism for generating dynamically tunable topological states across a broad class of wave-based platforms.

We consider a heterojunction of three armchair honeycomb nanoribbons of the width N as illustrated in figure 1. The Hamiltonian of the P–R–P heterostructure is

$$\hat{H} = \sum_{\langle i, j \rangle} \sum_{\alpha} t_0 \hat{c}_{i\alpha}^{\dagger} \hat{c}_{j\alpha} + \sum_{\langle i, j \rangle \in \text{RGNR}} \sum_{\alpha\beta} i t_R \hat{c}_{i\alpha}^{\dagger} \mathbf{z} \cdot (\boldsymbol{\sigma}_{\alpha\beta} \times \boldsymbol{\delta}_{ij}) c_{j\beta} + h.c.,$$

where $\langle i, j \rangle$ includes all configurations of the nearest-neighbor sites, α and β are the spin indices, $c_{i\alpha}^{\dagger}$ ($c_{i\alpha}$) is the creation (annihilation) operator with spin α at site i , t_0 is the nearest-neighbor hopping strength, t_R is the RSOC strength, $\boldsymbol{\sigma}$ are the Pauli matrices, and $\boldsymbol{\delta}_{ij}$ is the unit vector pointing in the direction from site i to site j . Hereafter, we set the nearest-neighbor hopping strength as the unit of energy, $t_0 = 1$. Also, the two ends of the pristine armchair nanoribbon are connected to eliminate possible edge states associated with the zigzag terminations.

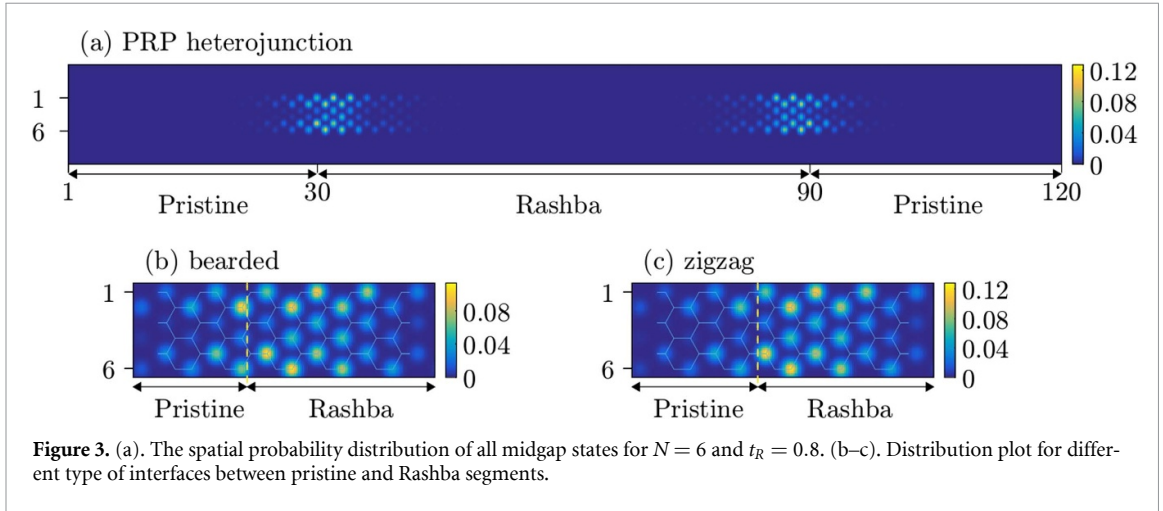
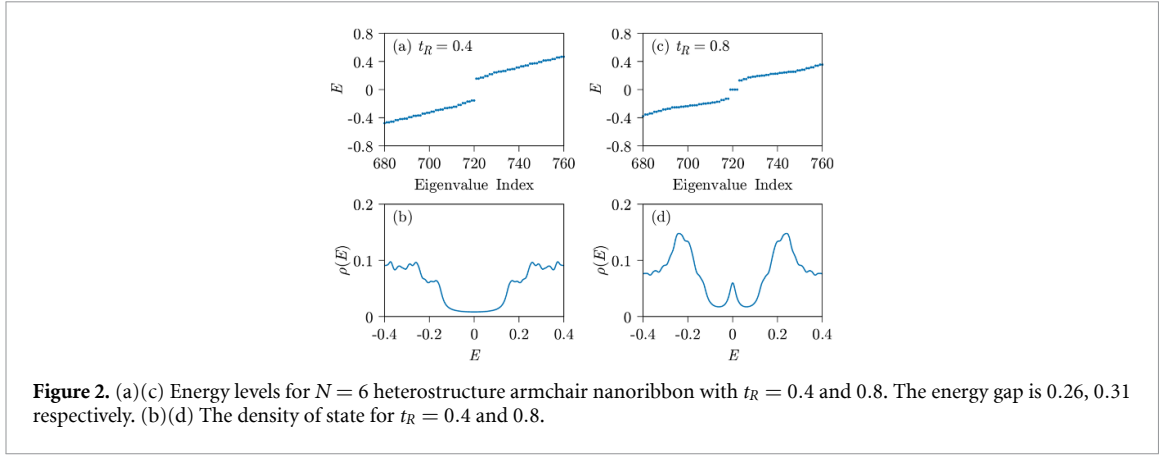
For $t_R = 0$, the PRP heterostructure reduces to a pristine armchair nanoribbon. The pristine armchair nanoribbon is gapped unless the width N of the armchair nanoribbon satisfy the condition $N = 3M - 1$ with an integer $M > 0$ [34]. Previous studies have shown analytically that the band gap closes every three ribbon widths [35, 36]. For armchair nanoribbon, the edge boundary condition discretizes the wavenumber in the y -direction. When the allowed wavenumber hit the Dirac points, which corresponds to the width $N = 3M - 1$, then the nanoribbon becomes metallic [36]. Hence, for $N = 2, 5, 8, 11$, and so on, the armchair nanoribbon is gapless.

Notably, the additional midgap states emerge within the gap as t_R exceeds a certain number. Figure 2 shows the energy spectrum and the density of states for the case $N = 6$, for different values of t_R . In stark contrast to figure 2(a) for $t_R = 0.4$, figure 2(c) for $t_R = 0.8$ clearly shows the existence of four midgap states. This leads to the pronounced peak at the vicinity of $E = 0$ in the density of state shown in figure 2(d).

We further explore the local density map for the heterostructure in figure 3(a), obtained by integrating the distribution of all mid-gap states. The local density at each point is given by summing the spin-up and spin-down probabilities. We found that these mid-gap states are exponentially localized at the interface between pristine and Rashba regions. In addition, as the size of the RSOC–pristine interfaces geometry, such as the zigzag figure 3(b) and bearded figure 3(c) interfaces, the four midgap edge states remain observable.

We further investigate the effect due to different ribbon widths. For example, for $N = 9$, four midgap states localized at the interfaces are found throughout the range $0.499 < t_R < 0.786$. Moreover, the presence of these states is not sensitive to small variations in the Rashba strength, nor to changes in the interface geometry. These observations suggest a topological origin rather than conventional band-offset confinement in the semi-conductor.

Motivated by the boundary states emerging in the P–R–P structure, we study the topological properties of an armchair nanoribbon uniformly covered by RSOC. We consider an infinite RSOC armchair nanoribbon with width N , whose unit cell contains $2N$ atomic sites, as shown in figure 1. Due to the



translational symmetry along the direction parallel to the edges, the Bloch momentum k is a good quantum number and the Hamiltonian of the quasi-1-D system can be written in a fully block-off-diagonal matrix

$$\mathcal{H} = \begin{pmatrix} 0 & h_k^\dagger \\ h_k & 0 \end{pmatrix}$$

in the basis $\{|A_1^\uparrow, \dots, |A_N^\downarrow, |B_1^\uparrow, \dots, |B_N^\downarrow\}$, where A and B denote the sublattice and h_k is a $2N \times 2N$ matrix. For chiral (sublattice) symmetric system, its 1-D topological properties can be characterized by the winding number [37]

$$W = \int_{-\pi}^{\pi} \frac{dk}{2\pi i} \text{Tr} [h_k^{-1} \partial_k h_k] = \int_{-\pi}^{\pi} \frac{dk}{2\pi i} \partial_k \log [\text{Det}(h_k)].$$

The winding number equals to the number of times the trajectory of $\det(h_k)$ winds around the origin in the complex plane.

For $N = 6$, in the absence of RSOC, the bulk armchair nanoribbon exhibits a finite energy gap (figure 4(a)). The trajectory of $\text{Det}(h_k)$ in the complex plane encircles the origin twice, corresponding to a winding number $W = 2$ (figure 4(d)).

As the RSOC strength t_R increases, the energy bands split and smaller band gaps appear, away from the $k = 0$ point. Unlike in two-dimensional graphene, where the Rashba contribution vanishes at the Γ point, RSOC modifies the energy band at $k = 0$ point of an armchair nanoribbon. This discrepancy emerges from the dangling bonds of the ribbon's edge atoms, where the Rashba contributions cannot cancel completely, as they do in graphene.

At $t_R = 0.624$, the gap closes (figure 4(b)), and the trajectory of $\text{Det}(h_k)$ touches the origin, rendering the winding number ill-defined (figure 4(e)). Upon further increasing t_R , the gap reopens (figure 4(c)), and the trajectory of $\text{Det}(h_k)$ encloses the origin four times, yielding a winding number

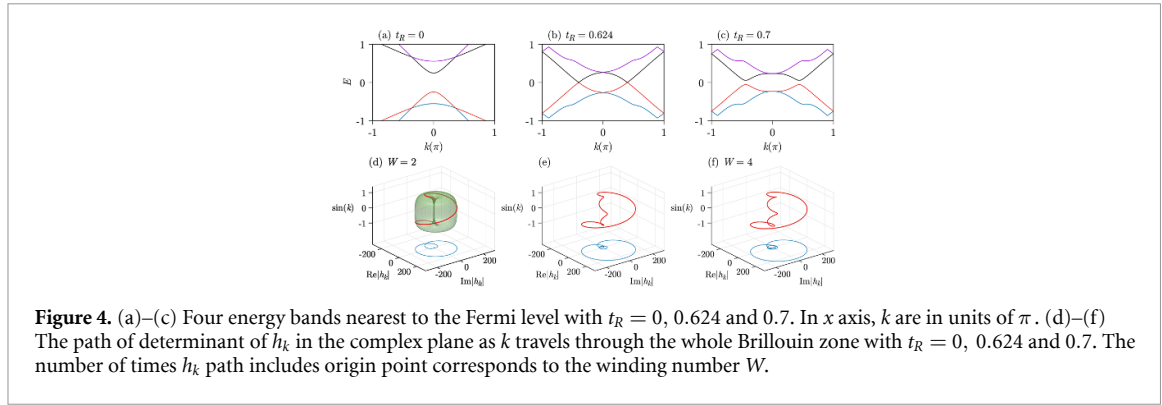


Figure 4. (a)–(c) Four energy bands nearest to the Fermi level with $t_R = 0, 0.624$ and 0.7 . In x axis, k are in units of π . (d)–(f) The path of determinant of h_k in the complex plane as k travels through the whole Brillouin zone with $t_R = 0, 0.624$ and 0.7 . The number of times h_k path includes origin point corresponds to the winding number W .

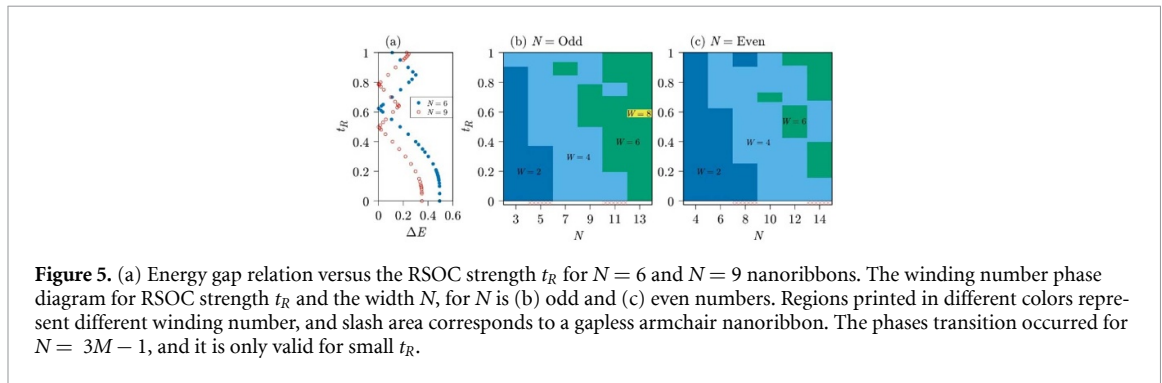


Figure 5. (a) Energy gap relation versus the RSOC strength t_R for $N = 6$ and $N = 9$ nanoribbons. The winding number phase diagram for RSOC strength t_R and the width N , for N is (b) odd and (c) even numbers. Regions printed in different colors represent different winding number, and slash area corresponds to a gapless armchair nanoribbon. The phases transition occurred for $N = 3M - 1$, and it is only valid for small t_R .

$W = 4$ (figure 4(f)). These results demonstrate that Rashba SOC drives a topological phase transition in armchair nanoribbon, characterized by a change in winding number from $W = 2$ to $W = 4$.

We note that when the z -axis values are obtained from the periodic function $\sin(k)$, the winding number can be interpreted as a two-dimensional projection of a three-dimensional unknot trajectory, represented by the red curves in figures 4(d)–(f). For $t_R = 0$, the corresponding three-dimensional curve forms a torus knot $\mathcal{T}(3, 1)$, where the trajectory winds three times around the torus hole and once around the tube.

In figure 5(a), we show the energy gap versus the RSOC strength t_R for $N \neq 3M - 1$ nanoribbons. When increasing the RSOC strength, the energy gap quadratically decreases at small t_R . For $t_R \neq 0$, new Dirac points appear at the vicinity of the original Dirac points with the distances $\sim t_R^2$ for small strength of t_R [38]. As increase t_R , the allowed wavenumbers in the y -direction moves close to the new Dirac points, the size of gap decreases quadratically. As a consequence, we obtain a quadratically relation of the gap versus the Rashba strength.

Figures 5(b) and (c) show the topological phase diagram as a function of the armchair nanoribbon width N and RSOC strength t_R . When $t_R = 0$, our winding number calculations are consistent with the result reported in [8, 9], where armchair graphene nanoribbons (AGNRs) with odd and even widths are classified using different topological categories because the corresponding unit cells exhibit different spatial symmetries [8]. Upon turning on RSOC, the originally gapless nanoribbons with $N = 2, 5, 8, 11, 14$ become gapped and possess a nontrivial winding number. Moreover, when increasing t_R , the winding number changes only by two at each transition. For instance, the winding number for $N = 6$ is equal to 2 when $t_R = 0.4$ and becomes 4 when $t_R = 0.8$.

In the PRP heterostructure, the pristine and Rashba regions share the same width but are characterized by different winding numbers due to the presence or absence of RSOC. For example, as $N = 6$, the winding number in the pristine region is $W = 2$. By tuning the strength of RSOC t_R on the embedded region, the winding number can change from $W = 2$ to $W = 4$. Thus, the difference of winding number between two regions gives rise to the boundary states localized at the interface (shown in figure 2). According to bulk-edge correspondences, this winding number difference leads to the emergence of four symmetry-protected edge states (shown in figure 3).

In this work, we have demonstrated that RSOC can serve as an effective and tunable mechanism for generating topological phases in geometrically identical nanoribbon systems. By studying a P–R–P heterostructure, we show that increasing RSOC drives gap closing and reopening associated with

changes in the winding number, leading to symmetry-protected interface states consistent with bulk-edge correspondence. The resulting edge modes emerge solely from the contrast in topological invariants between regions with and without RSOC, without requiring modifications of lattice geometry or ribbon width.

This mechanism fundamentally differs from previously explored routes to nanoribbon topology, where edge states arise from junctions between structurally distinct ribbons. Instead, our results establish that spin-orbit interaction alone can induce topological phase transitions within a single geometric platform, providing a dynamically controllable route toward interface topology.

Notably, the topological role of RSOC in our system differs from its previously understood role in honeycomb-lattice systems. In the periodic 2D system of graphene, the intrinsic spin-orbit coupling opens a topological mass gap that is characterized by Z_2 invariant, as described in the Kane-Mele model, while RSOC alone does not generate such a gap. As we turn to quasi-1D systems, however, RSOC causes gap closing and gap reopening. The finite width of the ribbon discretizes the momentum in the y -direction, resulting in a set of one-dimensional subbands. The Rashba-induced displacement of the Dirac points therefore causes the gap among the subbands to close or reopen, leading to topological phase transitions. This mechanism provides a possible route for designing quasi-one-dimensional topological devices, peculiarly.

Consider the smallest Rashba strength required in our results to induce a topological phase transition, which is $t_R = 0.157t_0$ for an $N = 14$ nanoribbon. In practice, by putting graphene on top of an appropriate substrate, the RSOC can be induced via the proximity effect. Current experiments have reported Rashba-related energy scales of up to approximately $t_R \sim 0.1t_0$ [39, 40], which may be further enhanced by manipulating the distance of proximity [41]. In other honeycomb-lattice materials, due to the intrinsic field therein, RSOC strength of approximately $t_R \sim 0.1t_0$ have also been reported [42], and still stronger RSOC may be attained by joining an external electric field from similar substrate proximity method, with the existing intrinsic field.

Another possible route is to reduce the hopping strength, which can be achieved by adjusting the spacing between neighboring microcavity pillars in photonic lattice systems. In such systems, the polarization of the light modes can serve as an effective spin degree of freedom. The effective hopping strength in photonic honeycomb lattices is typically on the order of 0.1–1 meV [43, 44]. In addition, electrically tunable synthetic RSOC with an energy scale of several meV has been demonstrated in liquid-crystal optical cavities [45, 46]. Although further experimental developments are required to realize such an implementation, these advances suggest that photonic systems may provide promising platforms for observing the topological phases discussed in the present work.

Because the proposed mechanism relies only on bipartite lattice structure and tunable spin-orbit interaction, it is broadly applicable beyond honeycomb nanoribbons and may be realized in electronic, photonic, and synthetic lattice systems. Our findings therefore identify RSOC as a general tool for engineering geometrically preserving yet topologically tunable low-dimensional quantum systems.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

- [1] Chiu C-K, Teo J C Y, Schnyder A P and Ryu S 2016 Classification of topological quantum matter with symmetries *Rev. Mod. Phys.* **88** 035005
- [2] Kitaev A 2009 Periodic table for topological insulators and superconductors (arXiv:0901.2686)
- [3] Ryu S, Schnyder A P, Furusaki A and Ludwig A W W 2010 Topological insulators and superconductors: tenfold way and dimensional hierarchy *New J. Phys.* **12** 065010
- [4] Zhong J, Wang H, Poddubny A N and Fan S 2025 Topological nature of edge states for one-dimensional systems without symmetry protection *Phys. Rev. Lett.* **135** 016601
- [5] Wu H C and Jin L 2025 Topological zero modes from the interplay of PT symmetry and anti-PT symmetry *Phys. Rev. B* **112** 125146
- [6] Yunlin L, Liu Y, Wang X, Zhang H and Jiang X, Nontrivial topology in one- and two-dimensional asymmetric systems with chiral boundary states (arXiv:2509.20834)
- [7] Huang A, Shasha K, Guan J-H, Jun L and Lou W-K 2024 Strain-induced topological phase transition in graphene nanoribbons *Phys. Rev. B* **109** 045408
- [8] Cao T, Zhao F and Louie S G 2017 Topological phases in graphene nanoribbons: junction states, spin centers, and quantum spin chains *Phys. Rev. Lett.* **119** 076401
- [9] Jiang J and Louie S G 2021 Topology classification using chiral symmetry and spin correlations in graphene nanoribbons *Nano Lett.* **21** 197–202
- [10] Song S *et al* 2025 Janus graphene nanoribbons with localized states on a single zigzag edge *Nature* **637** 580–6
- [11] Lin K-S and Chou M-Y 2018 Topological properties of gapped graphene nanoribbons with spatial symmetries *Nano Lett.* **18** 7254–60
- [12] Lee Y-L, Zhao F, Cao T, Ihm J and Louie S G 2018 Topological phases in cove-edged and chevron graphene nanoribbons: geometric structures, z_2 invariants, and junction states *Nano Lett.* **18** 7247–53
- [13] Wang J, Chen W, Wang Z, Meng J, Yin R, Chen M, Tan S, Chuanxu M, Qunxiang L and Wang B 2024 Designer topological flat bands in one-dimensional armchair graphene antidot lattices *Phys. Rev. B* **110** 115138
- [14] Zhao F, Cao T and Louie S G 2021 Topological phases in graphene nanoribbons tuned by electric fields *Phys. Rev. Lett.* **127** 166401
- [15] Kuo D M T 2025 Topological states in finite graphene nanoribbons tuned by electric fields *J. Phys.: Condens. Matter* **37** 085304
- [16] Xiao Y-X, Guancong M, Zhang Z-Q and Chan C 2017 Topological subspace-induced bound state in the continuum *Phys. Rev. Lett.* **118** 166803
- [17] Varykhalov A, Sánchez-barriga J, Shikin A M, Biswas C, Vescovo E, Rybkin A, Marchenko D and Rader O 2008 Electronic and magnetic properties of quasifreestanding graphene on Ni *Phys. Rev. Lett.* **101** 157601
- [18] Bychkov Y A and Rashba E I 1984 Properties of a 2D electron gas with lifted spectral degeneracy, *JETP Lett.* **39** 78–83
- [19] Yang B, Lohmann M, Barroso D, Liao I, Lin Z, Liu Y, Bartels L, Watanabe K, Taniguchi T and Shi J 2017 Strong electron-hole symmetric Rashba spin-orbit coupling in graphene/monolayer transition metal dichalcogenide heterostructures *Phys. Rev. B* **96** 041409(R)
- [20] Ingot M, Dugaev V K, Dyrdał A and Barnaś J 2021 Graphene with Rashba spin-orbit interaction and coupling to a magnetic layer: electron states localized at the domain wall *Phys. Rev. B* **104** 214408
- [21] Poszwa A 2024 Spin orbit coupling effect on coherent transport properties of graphene nanoscopic rings in external magnetic field *Sci. Rep.* **14** 31554
- [22] Zhang H, Zhongshui M and Liu J-F 2014 Equilibrium spin current in graphene with Rashba spin-orbit coupling *Sci. Rep.* **4** 6464
- [23] Kane C L and Mele E J 2005 Quantum spin hall effect in graphene *Phys. Rev. Lett.* **95** 226801
- [24] Kane C L and Mele E J 2005 Z₂ topological order and the quantum spin hall effect *Phys. Rev. Lett.* **95** 146802
- [25] Yan Z and Wan S 2014 Topological phases, topological flat bands, and topological excitations in a one-dimensional dimerized lattice with spin-orbit coupling *Europhys. Lett.* **107** 47007
- [26] Bahari M and Hosseini M V 2016 Zeeman-field-induced nontrivial topological phases in a one-dimensional spin-orbit-coupled dimerized lattice *Phys. Rev. B* **94** 125119
- [27] Liu Z-H, Entin-wohlman O, Aharony A, You J Q and Xu H Q 2021 Topological states and interplay between spin-orbit and Zeeman interactions in a spinful Su-Schrieffer-Heeger nanowire *Phys. Rev. B* **104** 085302
- [28] Tripathi A, Zalogina A, Liao J, Wurdack M, Estrecho E, Zhou J, Jin D, Kruk S S and Kivshar Y 2023 Metasurface-controlled photonic rashba effect for upconversion photoluminescence *Nano Lett.* **23** 2228–32
- [29] Tian J, Adamo G, Liu H, Klein M, Han S, Liu H and Soci C 2022 Optical rashba effect in a light-emitting perovskite metasurface *Adv. Mater.* **34** 2109157
- [30] Shitrit N, Yulevich I, Maguid E, Ozeri D, Veksler D, Kleiner V and Hasman E 2013 Spin-Optical metamaterial route to spin-controlled photonics *Science* **340** 724–6
- [31] Rong K, Wang B, Reuven A, Maguid E, Cohn B, Kleiner V, Katznelson S, Koren E and Hasman E 2020 Photonic Rashba effect from quantum emitters mediated by a Berry-phase defective photonic crystal *Nat. Nanotechnol.* **15** 927–33
- [32] Zhong Q, Liang Y, Xia S, Song D and Chen Z 2025 Observation of topological armchair edge states in photonic biphenylene network *Adv. Opt. Mater.* **13** 2500152
- [33] Xia S, Liang Y, Tang L, Song D, Jingjun X and Chen Z 2023 Photonic realization of a generic type of graphene edge states exhibiting topological flat band *Phys. Rev. Lett.* **131** 013804
- [34] Nakada K, Fujita M, Dresselhaus G and Dresselhaus M S 1996 Edge state in graphene ribbons: nanometer size effect and edge shape dependence *Phys. Rev. B* **54** 17954
- [35] Brey L and Fertig H A 2006 Electronic states of graphene nanoribbons studied with the Dirac equation *Phys. Rev. B* **73** 235411

- [36] Wakabayashi K, Sasaki K-I, Nakanishi T and Enoki T 2010 Electronic states of graphene nanoribbons and analytical solutions *Sci. Technol. Adv. Mater.* **11** 054504
- [37] Maffei M, Dauphin A, Cardano F, Lewenstein M and Massignan P 2018 Topological characterization of chiral models through their long-time dynamics *New J. Phys.* **20** 013023
- [38] Zarea M and Sandler N 2009 Rashba spin-orbit interaction in graphene and zigzag nanoribbons *Phys. Rev. B* **79** 165442
- [39] Dedkov Y S, Fonin M, Rüdiger U and Laubschat C 2008 Rashba effect in the graphene/Ni (111) system *Phys. Rev. Lett.* **100** 107602
- [40] Rybkina A A, Gogina A A, Tarasov A V, Xin Y, Voroshnin V Y, Pudikov D A and Rybkin A G 2023 Origin of giant rashba effect in graphene on Pt/SiC *Symmetry* **15** 2052
- [41] Fülöp B, Márffy A, Zihlmann S, Gmitra M, Tóvári E, Szentpéteri B and Csonka S 2021 Boosting proximity spin-orbit coupling in graphene/WSe₂ heterostructures via hydrostatic pressure *npj 2D Mater. Appl.* **5** 82
- [42] Yu S B, Zhou M, Zhang D and Chang K 2021 Spin Hall effect in the monolayer Janus compound MoSSe enhanced by Rashba spin-orbit coupling *Phys. Rev. B* **104** 075435
- [43] Milićević M, Ozawa T, Andreakou P, Carusotto I, Jacqmin T, Galopin E and Amo A 2015 Edge states in polariton honeycomb lattices *2D Mater.* **2** 034012
- [44] Galbiati M, Ferrier L, Solnyshkov D D, Tanese D, Wertz E, Amo A and Bloch J 2012 Polariton condensation in photonic molecules *Phys. Rev. Lett.* **108** 126403
- [45] Rechcińska K, Król M, Mazur R, Morawiak P, Mirek R, Łempicka K and Szczytko J 2019 Engineering spin-orbit synthetic Hamiltonians in liquid-crystal optical cavities *Science* **366** 727–30
- [46] Li Y, Ma X, Zhai X, Gao M, Dai H, Schumacher S and Gao T 2022 Manipulating polariton condensates by Rashba-Dresselhaus coupling at room temperature *Nat. Commun.* **13** 3785