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View & perspective

Advances on topological materials

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Topological materials refer to solid structures with topologically protected electronic states or other degrees of freedom. A prime example is a Chern insulator in which the occupied bands of states are organized with a nontrivial topology as characterized by a nonzero Chern integer, exhibiting gapless chiral excitations on the boundaries, which are robust against scatterings. In the presence of certain discrete symmetries, such as time reversal or mirror reflection, one can have more general topological classes of insulators exhibiting helical or spin-momentum locked boundary excitations, with a lesser degree of robustness against scatterings [1].

These boundary states are usually modeled as massless particles like those in the Dirac or Weyl theory in one or two dimensions. However, nature also offers a class of materials known as topological semimetals with massless excitations in the three-dimensional bulk. These are characterized by divergent Berry curvatures surrounding the band crossing points, with topological charges (given by the net Berry curvature flux) known as Weyl points in the momentum space. These states cannot be gapped out unless a pair of opposite Weyl points is brought together and mixed. In the presence of additional crystal symmetries, mixing is prohibited so that even a degenerate pair of opposite Weyl points (as in a Dirac semimetal) can coexist without being annihilated [2].

Excellent reviews exist on the search and classifications of topological materials [2–6], and one can also consult [7–9] on reviews of activities beyond solid state context. This collection brings together a group of practitioners to provide timely reports of some advances of this rapidly evolving field. The topics include the modeling and exploration of various topological materials, and the study of transport and other material properties associated with the spin-momentum structure and Berry curvature of the low energy states.

Tang and Wan [10] provided a survey of relatively simple Dirac semimetals of various crystal symmetries, with desired properties such as proximity of the Dirac points to the Fermi energy, and with other material properties suited for experimental studies. They also provided realistic effective models, in terms of Dirac matrices and restricted by symmetry considerations, that will be useful for further investigations of such materials. These models also provide a convenient starting point for a perturbative description of Weyl semimetals, if additional terms are added to reflect the breaking of time reversal or spatial inversion symmetry, which split a Dirac point into two Weyl points.

Li *et al.* [11] reviewed progress on topological metals consisting of pairs of electron and hole Fermi pockets that touch at a point, line, or surface in the momentum space. These result from tipped-over Dirac cones or other type of band crossings, with the upper branch partially submerged below the Fermi level while the lower branch partially emerges above the Fermi level. Shan and Gao [12] considered another variant of Dirac semimetals that simulate exotic fermions of higher spin, and introduced a new candidate for a non-symmorphic crystal with a stable sixfold degenerate point of band touching.

The notion of topological materials is not limited to electronic systems, and this review provides some further exploration beyond the solid state context. Xu [13] summarized analogous investigations of cold atomic gases in optical lattices, in which key features of band dispersions of topological materials can be readily replicated. Zhao [14] explored the notion of PT-symmetric real Chern insulators that may be realized in artificial structures such as photonic crystals and mechanical arrays.

Chiral edge modes of two dimensional Chern insulators are robust because opposite-moving states are physically separated in different edges by the bulk. These are in sharp contrast with those symmetry protected topological insulators, where opposite-moving modes share the same edge, which are robust only against a limited class of scatterings, such as elastic processes with time reversal symmetry. Qi *et al.* [15] discussed the role of spin dephasing in the back scattering of these states in inelastic processes which are inevitable at finite temperatures. For surface states of three dimensional topological insulators, there is no protection against general-angle scattering even in time-reversal-symmetric elastic processes, but those near a Dirac point can be long lived because of phase space limitations of elastic scattering.

There has been a tremendous interest in Weyl semime-

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*Special Topic: Recent Advances in Topological Materials (Eds. Yugui Yao, Xiangang Wan, Shengyuan A. Yang & Hua Chen).

tals because of possible experimental observation of the chiral anomaly in magneto-transport. It was suggested that negative magneto resistance shown in experiments may be due to field induced non-conservation of particle numbers in individual valleys of non-zero topological charges. Sun and Lu [16] reviewed transport studies on topological semimetals in magnetic fields from the weak to strong limit, revealing the ubiquitous effect of Berry curvatures which compete with and even mask the chiral anomaly. Further complications occur because of skew scattering and side jump processes, which compete with intrinsic Berry curvature and other geometric effects. Sorting out various mechanisms in magneto-transport studies of topological materials remains challenging.

Side jumps refer to a coordinate shift during the scattering process due to spin–orbit coupling, and occurs most dramatically at an interface in analogy with the Goos–Hänchen and Imbert–Fedorov effects in optics. Yu *et al.* [17] described how spin-momentum locked electronic states show anomalous spatial shifts in scattering by a normal-superconductor interface, and how an unconventional superconducting order parameter can reveal its imprint in such a process. This would serve as a useful probe of topological superconductors, which are invariably based on unconventional pairing mechanisms.

Magneto-transport may be regarded as a nonlinear current response to electromagnetic fields, and a variety of other nonlinear transport in topological materials are also being actively pursued. Much intuition on Berry curvature effects in such studies are based on semiclassical dynamics, which was initially formulated with accuracy only up to first order in electromagnetic fields. Gao [18] outlined a second order semiclassical framework, which also includes additional geometric effects such as a field induced positional shift, with applications to various nonlinear responses including magneto-transport in topological materials.

There is much to be done on topological materials before they can be well controlled and useful. Topology of a phase is rigorously defined only at zero temperature, and its associated properties degrade with temperature on a scale that in practice is typically much lower than room temperature. Symmetry protected topology is as strong as the symmetry that one can maintain, and complexity of band structures also makes it easy to mix in unsought responses that are not associated with the topologically protected states. Finding a material system that overcomes these shortcomings will be much desired.

Due to their lower dimensionality or lower density of states, the low energy electronic states in topological materials can be easily tuned by external means and gapped under symmetry breaking fields. Hybridizing these states with collective modes including dynamical order parameters may offer very interesting material properties. Engineering topological band structures for various bosonic particles has mainly been pursued in artificial structures. It would be interesting to see if dressing the collective modes in solid materials by the electronic states can endow them with nontrivial topology and useful properties.

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References

1. M. Konig, S. Wiedmann, C. Brune, A. Roth, H. Buhmann, L. W. Molenkamp, X. L. Qi, and S. C. Zhang, Quantum spin Hall insulator state in HgTe quantum wells, *Science* 318(5851), 766 (2007)
2. N. P. Armitage, E. J. Mele, and A. Vishwanath, Weyl and Dirac semimetals in three-dimensional solids, *Rev. Mod. Phys.* 90(1), 015001 (2018)
3. M. Z. Hasan and C. L. Kane, Topologicalinsulators, *Rev. Mod. Phys.* 82(4), 3045 (2010)
4. X. L. Qi and S. C. Zhang, Topological insulators and superconductors, *Rev. Mod. Phys.* 83(4), 1057 (2011)
5. C. K. Chiu, J. C. Y. Teo, A. P. Schnyder, and S. Ryu, Classification of topological quantum matter with symmetries, *Rev. Mod. Phys.* 88(3), 035005 (2016)
6. A. Bansil, H. Lin, and T. Das, Topological band theory, *Rev. Mod. Phys.* 88(2), 021004 (2016)
7. L. Lu, J. D. Joannopoulos, and M. Soljacic, Topological photonics, *Nat. Photonics* 8(11), 821 (2014)
8. Y. Liu, X. Chen, and Y. Xu, Topological phononics: From fundamnetal models to real materials, *Adv. Funct. Mater.* 30(8), 1904784 (2020)
9. S. D. Huber, Topological mechanics, *Nat. Phys.* 12(7), 621 (2016)
10. F. Tang and X. Wan, Effective models for nearly ideal Dirac semimetals, *Front. Phys.* 14(4), 43603 (2019)
11. S. Li, Z. M. Yu, Y. Yao, and S. A. Yang, Type-II topological metals, *Front. Phys.* 15(4), 43201 (2020)
12. G. Shan and H. B. Gao, New topological semimetal candidate of nonsymmorphic PdSb$_2$ with unique six-fold degenerate point, *Front. Phys.* 14(4), 43201 (2019)
13. Y. Xu, Topological gapless matters in three-dimensional ultracold atomic gases, *Front. Phys.* 14(4), 43402 (2019)
14. Y. X. Zhao, Equivariant PT-symmetric real Chern insulators, *Front. Phys.* 15(1), 13603 (2020)
15. J. Qi, H. Liu, H. Jiang, and X. C. Xie, Dephasing effects in topological insulators, *Front. Phys.* 14(4), 43403 (2019)
16. H. P. Sun and H. Z. Lu, Quantum transport in topological semimetals under magnetic fields (II), *Front. Phys.* 14(3), 33405 (2019)
17. Z. M. Yu, Y. Liu, and S. A. Yang, Anomalous spatial shifts in interface electronic scattering, *Front. Phys.* 14(3), 33402 (2019)
18. Y. Gao, Semiclassical dynamics and nonlinear charge current, *Front. Phys.* 14(3), 33404 (2019)