Two-dimensional spin-gapless semiconductors: A mini-review

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In the past decade, two-dimensional (2D) materials and spintronic materials have been rapidly developing in recent years. 2D spin-gapless semiconductors (SGSs) are a novel class of ferromagnetic 2D spintronic materials with possible high Curie temperature, 100% spin-polarization, possible one-dimensional or zero-dimensional topological signatures, and other exciting spin transport properties. In this mini-review, we summarize a series of ideal 2D SGSs in the last 3 years, including 2D oxalate-based metal-organic frameworks, 2D single-layer Fe$_2$I$_2$, 2D Cr$_2$X$_3$ (X = S, Se, and Te) monolayer with the honeycomb kagome (HK) lattice, 2D CrGa$_2$Se$_4$ monolayer, 2D HK Mn–cyanogen lattice, 2D MnNF monolayer, and 2D Fe$_3$N$_2$ pentagon crystal. The mini-review also discusses the unique magnetic, electronic, topological, and spin-transport properties and the possible application of these 2D SGSs. The mini-review can be regarded as an improved understanding of the current state of 2D SGSs in recent 3 years.

KEYWORDS
two-dimensional material systems, spin-gapless materials, Dirac point, nodal line, spin transport properties

1 Introduction

Due to their unique physical and chemical characteristics induced by low-dimensionality and electronic constraints, as well as their potential applications in spintronics, high-temperature ferromagnetic two-dimensional (2D) materials (Lee et al., 2010; Li and Yang, 2014; Wang et al., 2016a; Zhou et al., 2016; Ashton et al., 2017; Benmansour et al., 2017; Gong and Zhang, 2019; Kim et al., 2019; Zhou et al., 2019; Chen et al., 2020; Torelli et al., 2020; Xu et al., 2020; Zhang et al., 2021a; Tang et al., 2021; Miao and Sun, 2022) have attracted a great deal of attention in recent years. Nevertheless, the majority of prepared 2D materials that resemble graphene are not magnetic (Wang et al., 2012; Liu and Zhou, 2019), magnetic ordering has not been observed in the 2D material family for more than 10 years since the discovery of graphene (Hashimoto et al., 2004; Novoselov et al., 2004; Huang et al., 2017) in 2004. Recently, only some intriguing 2D magnetic materials, such as CrI$_3$ (Huang et al., 2017), CrGeTe$_3$ (Gong et al., 2017; Wang et al., 2018a), Fe$_2$GeTe$_2$ (Deng et al., 2018a; Fei et al., 2018), VSe$_2$ (Bonilla et al., 2018) and CrTe$_2$ (Sun et al., 2020a), have been experimentally realized. Furthermore, it should be noticed that, the 2D magnetic material is far from the actual spintronic application at room temperature due to the low Curie temperature $T_C$ and low spin polarization. Thus, it is significant and urgent...
to develop ferromagnetic 2D materials with high spin-polarization and $T_c$ via theory and experiment.

Among different types of 2D ferromagnetic materials, 2D spin-gapless semiconductors (SGSs) (Li et al., 2009; Zhang et al., 2015; Gao et al., 2016; Zhu and Li, 2016; Wang et al., 2017a; He et al., 2017; Lei et al., 2017; Wang, 2017; Deng et al., 2018b; Wang et al., 2018b; Wu et al., 2020a; Yang et al., 2020a; Wu et al., 2020b; Deng et al., 2020; Feng et al., 2020; Li et al., 2020; Nadeem et al., 2020; Rani et al., 2020; Wang et al., 2020; Yue et al., 2020; Şaşıoğlu et al., 2020; Feng et al., 2021; Phong and Nguyen, 2022) are ideal candidates for high-efficient spintronic devices. Wang (Wang, 2008) first proposed the concept of SGSs in 2008, and the SGSs can be viewed as a bridge to connect the magnetic semiconductors (Haas, 1970; Dietl, 2010; Sato et al., 2010) and half-metals (Wang et al., 2016b; Wang et al., 2017b; Wang et al., 2017c; Liu et al., 2017; Wang et al., 2018c; Han et al., 2019; Wang et al., 2019; Yang et al., 2020b; Tang et al., 2021; Yang et al., 2021). It is well known that the SGSs (Wang et al., 2018b) can host parabolic and linear dispersion between energy and momentum (see Figure 1A–H). Moreover, SGSs (Wang, 2017) can be categorized into four different types depending on the touching types of the valence band maximum (VBM) and the conduction band minimum (CBM) in both spin directions. We take the SGSs with parabolic dispersion as examples to introduce the above four types (see Figure 1A–D). In Figure 1A, one finds the CBM and VBM touch each other at the Fermi level (FL) in the spin-up (SU) channel, whereas a semiconducting gap appears in the spin-down (SD) channel. The VBM in the SU channel...
touched the CBM in the SD channel, forming an indirect zero-gap state. The case of Figure 1C is similar to that of Figure 1B. However, the CBM touches the FL in the SD channel. Figure 1D is the standard form of SGSs with parabolic dispersion: a zero-gap in the SU channel and a semiconducting gap in the SD channel. Similarly, the cases of SGSs with linear dispersion are listed in Figure 1E–H. Note that, for cases I, III and IV (see Figures 1A, C, D, E, G, F), depending on how the VBM and CBM touch each other, the zero-gap in one spin channel can be direct (VBM and CBM touch each other at the same \( k \) point) or indirect (they touch each other at different \( k \) points) (Wang et al., 2020).

SGSs may host the following advantages: 1) the excitation of electrons from the valence band to the conduction band requires only a tiny amount of energy. 2) the excited carriers (electrons and holes) can be fully spin-polarized (S-P) simultaneously. 3) one can use the Hall effect to separate the 100% S-P electrons and holes. 4) for the case II SGSs (See Figure 1B and Figure 1F), one can control the gate voltage to manipulate the SU and SD electrons and holes. 5) researchers proposed nodal point SGSs and nodal line SGSs in 2D and 3D materials, which can be excellent candidates for studying the relationship between topological and spintronics. For example, Dirac SGSs may induce low energy consumption and ultrafast transport because of their unique linear band dispersion. Hence, Dirac SGSs can cohost 100% spin-polarization and linear Dirac point at the FL.

Although there were several reviews on the research topic of SGSs, these articles (Wang, 2017; Wang et al., 2020; Yue et al., 2020) all focused on SGSs from 2008 to 2020. To our best knowledge, other researchers have not reviewed the recent advances in 2D SGSs from 2020 to 2022. From 2020 to 2022, a series of ideal 2D SGSs are proposed via first-principles calculations, and the related novel properties are also investigated. Therefore, for spintronics and topology, a mini-review of 2D SGSs seems necessary. It is noteworthy that Dirac SGSs and nodal line SGSs are new cross concepts in spintronics and topology. Although in almost all the reported 2D (2D) materials, the twofold degenerate nodal points in their band structures are misused as “Dirac points” due to a historical issue (Yang, 2016). The correct naming of these nodal points should be “Weyl”, and then each twofold degenerate point is described by the Weyl model in 2D. This review follows the common practice of using “Dirac point” SGSs in 2D materials.

In this review, we divided 2D SGSs into four classes: 2D SGSs with direct band crossing points at high-symmetry (H-S) points and along the H-S paths, 2D SGSs with indirect zero-gap states, and 2D SGSs with zero-gap nodal ring states. Note that this is the first time to review SGSs based on classification as mentioned above.

Herein, we will review the most recent investigations of 2D SGSs from 2020 to 2022. Section 2 introduces the proposed 2D SGSs with band crossing points at the H-S point. Section 3 introduces the proposed 2D SGSs with band crossing points along the H-S paths and their unique behaviors. Section 3 reviews 2D SGSs with indirect zero-gap states and their possible application. Section 4 introduces the case of 2D SGSs with zero-gap nodal ring states. Section 5 is the conclusion.

### 2 2D SGSs with band crossing points at H-S points

In 2022, Xing et al. (Xing et al., 2022) proposed a family of 2D oxalate-based metal-organic frameworks (MOFs) that possessed the SGS characteristics. Figures 1I, J show the structure and reciprocal lattice of a 2D MOF TM₂(C₂O₄)₃ with a honeycomb-kagome (HK) lattice. Figure 1K–R show the electronic BSs of Ni₂(C₂O₄)₃ and Re₂(C₂O₄)₃ calculated by different methods along the \( \Gamma-M-K-\Gamma \) high symmetry paths. Without SOC, the valence band and conduction band in one spin channel touch the FL at the K point, and the other spin channel has a semiconducting band gap of 1 eV (see Figure 1K, O). Meanwhile, spin-gapless Dirac points with linear dispersion appear at the FL in one spin channel, which is beneficial for dissipationless spin transport. The influence of SOC on the Dirac point at the K H-S point is considered, and the results are shown in Figure 1L, P. One finds that the SOC triggers a band gap of about 7.6 meV in Ni₂(C₂O₄)₃ and 143 meV in Re₂(C₂O₄)₃, respectively. Compared with Ni₂(C₂O₄)₃, the SOC-induced gap of Re₂(C₂O₄)₃ is more significant than that of Ni₂(C₂O₄)₃ because the relative atomic mass of the Re atom is heavier than that of the Ni atom, and the Dirac point of Re₂(C₂O₄)₃ only contributes the d orbital of Re atom. Figure 1M, Q show the BSs calculated by the HSE06 method, and Figure 1N, R show the BSs calculated by the GGA + U method. One finds that the spin-gapless Dirac point is still maintained at the K point under both HSE06 and GGA + U methods.

With the PBE functional, the calculated Fermi velocity (\( v_F \)) values (Xing et al., 2022) are up to 2.0 × 10⁷ m s⁻¹ and 1.86 × 10⁷ m s⁻¹ for Ni₂(C₂O₄)₃ and Re₂(C₂O₄)₃, respectively. When using the HSE06 functional, the obtained \( v_F \) values are relatively higher, up to 2.78 × 10⁷ m s⁻¹ and 2.58 × 10⁷ m s⁻¹ for Ni₂(C₂O₄)₃ and Re₂(C₂O₄)₃, respectively. As seen in Figure 1S, T, M and Cm exhibit a sudden change at a temperature of 208 K for Ni₂(C₂O₄)₃ and 34 K for Re₂(C₂O₄)₃, respectively. Note that the ultimate goals of spintronics or electronic devices in the future are ultra-fast transmission and extremely low energy consumption. The massless charge should ideally be fully S-P, and the (effective) mass of electrons or holes should be eliminated. Therefore, a class of magnetic materials called 2D SGSs with Dirac points at high symmetry points can be considered ideal for the use of next-generation spintronics (Wang et al., 2018b).
FIGURE 2

(A) The relationship between the MAE and strain. (B–D) BS of the Cr$_2$X$_3$ monolayers calculated with different methods. (E) The Cr$_2$S$_3$ device model. (F) The spin-resolved current-voltage curves for the PC and the APC of the device. (A–F) Reproduced from (Feng et al., 2021) with permission from AIP publishing. (G) Schematics for the FM and AFM states of the CrGa$_2$Se$_4$ monolayer. (H) Energy difference with respect to the ground state for T-I, T-II and T-III configurations. (I) The simulated Curie temperature. (J) The calculated BSs by the HSE06 method. (G–J) Reproduced from (Chen et al., 2021) with permission from RSC publishing. (K) The schematic diagram of NRSGSs. Reproduced from (Zhang et al., 2020b) with permission from APS. (L–N) Structures of 2D HK Mn-cyanogen lattice, 2D MnNF monolayer, and 2D Fe$_4$N$_2$ pentagon crystal, respectively. (O–Q) 3D plot of the gapless NR states in 2D HK Mn–cyanogen lattice, 2D MnNF monolayer, and 2D Fe$_4$N$_2$ pentagon crystal, respectively. (L–Q) Reproduced from (Zhang et al., 2018; Hu et al., 2019; Zhang et al., 2021b) with permission from RSC and ACS publishing.
3 2D SGSs with band crossing points along the H-S paths

3.1 Example 1: 2D single-layer Fe\(_2\)I\(_2\)

In 2020, Sun, Ma, and Kioussis (Sun et al., 2020b) proposed single-layer Fe\(_2\)I\(_2\), with space group \textit{P}4/\textit{mmm} (nop. 129) and calculated lattice constants \(a = b = 3.81\ \text{Å}\), is a 2D SGS. The calculated BSS for single-layer Fe\(_2\)I\(_2\) without SOC and with GGA + U are shown in Figure 1U. One finds that the SU bands show a semiconducting behavior, whereas the SD bands show a zero-gap behavior. Two gapless band crossing points appear at the FL in the SD channel. Unlike the gapless point at the H-S point in Cr\(_2\)S\(_3\) and Cr\(_2\)Se\(_3\), the gapless points in Fe\(_2\)I\(_2\) are along the H-S paths. As shown in Figure 1U, the gapless points appear along the Y-\(\Gamma\)-X H-S paths. The 3D plot of these gapless points (named as Dirac points in Ref. (Sun et al., 2020b)) is shown in Figure 1V. The obtained \(v_F\) with the help of GGA + U and HSE06 is 4.66 \(\times\) \(10^3\) m s\(^{-1}\) and 6.39 \(\times\) \(10^3\) m s\(^{-1}\), respectively. As we all know, the massless Dirac fermions will lead to low effective masses and high carrier mobility. Further, as shown in Figure 1W, single-layer Fe\(_2\)I\(_2\) undergoes a spin reorientation transition to an in-plane magnetization orientation beyond -4\% compressive strain. As shown in Figure 1X, one can see from Figure 2I that the Curie temperature of the CrGa\(_2\)Se\(_4\) monolayer with HSE06 functional. The results are collected in Figure 2J. At first glance, one finds that the CrGa\(_2\)Se\(_4\) monolayer is a ferromagnetic semiconductor. The bands in SU and SD channels host semiconducting gaps of 0.36 eV and 1.36 eV, respectively. Interestingly, the lowest conduction band state in the SD channel touches the FL, and the highest valence band states in the SU channel touch the FL, forming an indirect zero-gap state. Hence, the CrGa\(_2\)Se\(_4\) monolayer can also be seen as an SGS with an indirect spin-gapless semiconductor state.

We would like to point out that the indirect zero gap states occur because the two spin components at different \(k\) points accidentally have their extreme values at the FL. Therefore, in general, they are not protected from the symmetry of systems due to the indirect band touching. However, the SGSs with indirect band touching usually host bipolar magnetic behavior. That is, by changing the sign of the applied gate voltage, one can achieve the electrical manipulation of spin-polarization orientation in SGSs (with indirect band touching).

3.2 Example 2: 2D Cr\(_2\)X\(_3\) monolayer with the HK lattice

In 2021, Feng, Liu, and Gao (Feng et al., 2021) proposed the spin-gapless semiconducting states in 2D Cr\(_2\)X\(_3\) monolayers (X = S, Se, and Te) via first-principle calculations. The estimated Curie temperatures for these three monolayers are about 420, 480, and 510 K, respectively. The S-P BSSs and the calculated MAE for these three monolayers are collected in Figures 2B–D. One finds these three monolayers belong to 2D SGSs with zero-gap Dirac points along the H-S paths, i.e., K-\(\Gamma\)-M. As shown in Figure 2A one finds that the MAEs for these three monolayers increase with the increasing tensile strains from 1% to 5%. Unfortunately, the SGS behaviors in Cr\(_2\)Te\(_3\) at the FL are destroyed within HSE06. For the Cr\(_2\)S\(_3\) and Cr\(_2\)Se\(_3\), the Dirac points along the K-\(\Gamma\)-M paths are still maintained within PBE and HSE06. The effect of SOC to the Dirac points is also examined by Feng, Liu, and Gao (Feng et al., 2021); they stated that the SOC effect is weak for the proposed monolayers.

4 2D SGSs with indirect zero-gap states

In 2021, Chen et al. (Chen et al., 2021) also studied the nonequilibrium spin transport properties of monolayer Cr\(_2\)X\(_3\), and the device model is shown in Figure 2E. From Figure 2F, for the APC in both spin directions, one finds the values of spin-currents are extremely small. For the PC, one finds the spin-current of the PC-spin down can be neglected, whereas the spin-current of PC-spin up increased at first and then decreased with the increase of voltage form 0.0 V–1.0 V. The maximum value of spin current of PC-spin up appears at about+/-0.35 V. Hence, the device model in Figure 2E should host a perfect spin filtering effect (Chen et al., 2019; Zhang et al., 2020a; Han et al., 2022).

5 2D SGSs with zero-gap nodal ring states

Compared to the Dirac SGSs with single or multiple nodal point states, Zhang et al. (Zhang et al., 2018) proposed a new class of 2D SGSs with a gapless nodal ring (NR) in the momentum space and 100\% spin polarization. That is, the SGSs, with a one-dimensional topological signature, have zero-gap band crossing points that form a line in the momentum space. Typically, they are named as NRSGSs. The schematic diagram of NRSGSs is shown in Figure 2K. One finds that the SU channel shows a zero-gap NR state in the momentum space and the SD channel shows a semiconducting state.
To this date, 2D HK Mn–cyanogen lattice (Zhang et al., 2018), 2D MnNF monolayer (Hu et al., 2019), and 2D FeN₂ pentagon crystal (Zhang et al., 2021b) are proposed to be 2D NR SGSs. The structural model and the 3D plot of the gapless NR state in one spin channel are shown in Figure 2L. We would like to point out that the gapless NR state in one spin channel may suffer sizable SOC-induced gaps. Hence, searching for NRSGSs with light elements to reduce the value of SOC-induced gaps.

6 Conclusion and remarks

In this mini-review, we introduced a series of ideal 2D SGSs, including 2D SGSs with band-crossing points at H-S points or along the H-S paths, 2D SGSs with S-P NR states, and 2D SGSs with indirect zero-gap states.

The Dirac SGSs with band-crossing points at H-S points or along the H-S paths show massless fermions around the FL, ideal dissipation-less properties, and 100% spin-polarization. Furthermore, the band crossing points may form an NR in 2D SGSs. The NRSGSs will exhibit more intensive nonlinear electromagnetic responses than a single Dirac point. It should be noted that the 2D SGSs are hopped to host a high Curie temperature and a robust FM state at room temperature. Finally, a major challenge for 2D SGSs is that no 2D SGSs have been experimentally realized. The reason is that the 2D SGSs are monolayer materials, and they are hard to synthesize. Moreover, some monolayer materials are not stable in the ambient environment. Thus, new nanotechnology is needed for fabricating 2D monolayer SGSs.

References

Ashton, M., Ghuhoic, D., Sinnott, S. B., Guo, J., Stewart, D. A., and Hennig, R. G. (2017). Two-dimensional intrinsic half-metals with large spin gaps. Nano Lett. 17 (9), 5251–5257. doi:10.1021/acs.nanolett.7b01367

Benmoussa, S., Abbévrie, A., Gómez-Claramunt, P., Valls-García, C., and Gómez-García, C. I. (2017). Nanosheets of two-dimensional magnetic and conducting Fe(ll)/Fe(lll) mixed-valence metal-organic frameworks. ACS Appl. Mater. Interfaces 9 (31), 26210–26218. doi:10.1021/acsami.7b02352

Bonilla, M., Kolekar, S., Ma, Y., Diaz, H. C., Kalappattil, V., Das, R., et al. (2018). Strong room-temperature ferromagnetism in VSe₂ monolayers on van der Waals substrates. Nat. Nanotech 13 (4), 289–293. doi:10.1038/s41565-018-0063-9

Chen, Q., Wang, R., Huang, Z., Yuan, S., Wang, H., Ma, L., et al. (2021). Two dimensional CrGa2Se₄: A spin-gapsless ferromagnetic semiconductor with inclined uniaxial anisotropy. Nanoscale 13 (12), 6024–6029. doi:10.1039/D0NR08296a

Chen, Z., Fan, X., Shen, Z., Luo, Z., Yang, D., and Ma, S. (2020). Two-dimensional intrinsic ferromagnetic half-metals: Monolayers Mn₃X₄ (X = Te, Se, S). Nat. Mat. 19 (6), 1080–1084. doi:10.1038/s41563-020-04582-5

Chen, Z., Li, T., Yang, T., Xu, H., Khenata, R., Gao, Y., et al. (2019). Palladium (III) fluoride bulk and PdF₃/Ga₂O₃/PdF₃ magnetic tunnel junction: Multiple spin-gapsless semiconducting, perfect spin filtering, and high tunnel magnetoresistance. Nanomaterials 9 (9), 1342. doi:10.3390/ nanom9091342

Deng, Y. X., Chen, S. Z., Zeng, Y., Feng, Y., Zhou, W. X., Tang, L. M., et al. (2018). Spin gapsless semiconductor and half-metal properties in magnetic penta-hexa-graphene nanotubes. Org. Electron. 63, 310–317. doi:10.1016/j.orgel.2018.09.046

Deng, Y. X., Chen, S. Z., Zhang, Y., Yu, X., Xie, Z. X., Tang, L. M., et al. (2020). Penta-hexa-graphene nanoribbons: Intrinsic magnetism and edge effect induce spin-gapsless semiconducting and half-metallic properties. ACS Appl. Mater. Interfaces 12 (47), 53088–53095. doi:10.1021/acsami.0c04768

Deng, Y., Yu, Y., Song, Y., Zhang, J., Wang, N. Z., Sun, Z., et al. (2018). Gate-tunable room-temperature ferromagnetism in two-dimensional Fe₃GeTe₂. Nature 565 (7729), 94–99. doi:10.1038/s41586-018-0626-9

Dietl, T. (2010). A ten-year perspective on dilute magnetic semiconductors and oxides. Nat. Mater 9 (12), 965–974. doi:10.1038/nmat2898

Fei, Z., Huang, B., Malinowski, P., Wang, W., Song, T., Sanchez, J., et al. (2018). Two-dimensional itinerant ferromagnetism in atomically thin Fe₃GeTe₂. Nat. Mater 17 (9), 779–782. doi:10.1038/s41563-018-0149-7

Feng, Y., Liu, N., and Gao, G. (2021). Spin transport properties in Dirac spin gapless semiconductors GrX3 with high Curie temperature and large magnetic anisotropic energy. Appl. Phys. Lett. 118 (11), 112407. doi:10.1063/5.0045262

Feng, Y., Wu, X., and Gao, G. (2020). High tunnel magnetoresistance based on 2D Dirac spin gapless semiconductor VCl₃. Appl. Phys. Lett. 116 (2), 022402. doi:10.1063/5.00128204

Gao, G., Ding, G., Li, J., Yao, K., Wu, M., and Qian, M. (2016). Monolayer MXenes: Promising half-metals and spin gapless semiconductors. Nanoscale 8 (16), 8986–8994. doi:10.1039/c6nr01333c

Gong, C., Li, L., Li, Z., Ji, H., Stern, A., Xia, Y., et al. (2017). Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals. Nature 546 (7657), 265–269. doi:10.1038/nature22060

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Conflict of interest

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Wang, X., Cheng, Z., Huang, Y., Wang, X.L., and Liu, G. (2016). Dirac spin-gapless semiconductors. Nat. Rev. Mater. 1 (6), 99–105. doi:10.1038/s41578-016-0006-1

Wang, X., Ding, G., Cheng, Z., Yuan, H., Wang, X.L., Yang, T., Chen, H., He, J., Wang, Z., Zhang, T., Ding, M., et al. (2018). Dirac spin-gapless semiconductors: Promising platforms for massless and dissipationless spintronics and new (quantum) anomalous spin Hall effects. Nat. Sci. Rep. 4 (2), 252–257. doi:10.1038/s41598-020-62058-w

Wang, X., Li, T., Cheng, Z., Wang, X.L., and Chen, H. (2018). Recent advances in Dirac spin-gapless semiconductors. Appl. Phys. Rev. 5 (4), 041103. doi:10.1063/1.5042604

Wang, X. L. (2008). Proposal for a new class of materials: Spin gapless semiconductors. Phys. Rev. Lett. 100 (15), 156404. doi:10.1103/physrevlett.100.156404

Wang, Z., Zhang, T., Ding, M., Dong, B., Li, Y., Chen, M., et al. (2018). Electric-field control of magnetism in a few-layered van der Waals ferromagnetic semiconductor. Nat. Nanotechnol. 13 (7), 554–559. doi:10.1038/s41565-018-0186-x

Wu, X., Peng, Y., Yu, X., Liu, Z., Zhang, B., and Gao, G. (2020). 2D Mn2C6S12 and Mn2C6S8S6: Intrinsic room-temperature Dirac spin gapless semiconductors and perfect spin transport properties. J. Phys. Chem. C 124 (29), 16127–16135. doi:10.1021/acs.jpcc.0c04786

Wu, X., Feng, Y., Li, S., Zhang, B., and Gao, G. (2020). 2D Mn2C6S12 and Mn2C6S8S6: Intrinsic room-temperature Dirac spin gapless semiconductors and perfect spin transport properties.
Xing, J., Ji, Z., Xie, Z., Qian, Y., and Zhao, J. (2022). Robust Dirac spin gapless semiconductors in a two-dimensional oxalate based organic honeycomb-kagome lattice. *Nanoscale* 14 (5), 2023–2029. doi:10.1039/d1nr07076b

Xu, J., Li, W., and Hou, Y. (2020). Two-dimensional magnetic nanostructures. *Trends Chem.* 2 (2), 163–173. doi:10.1016/j.trechm.2019.11.007

Yang, Q., Hou, L., Hu, X., Wang, Y., Lin, C., Krasheninnikov, A. V., et al. (2020). Strain robust spin gapless semiconductors/half-metals in transition metal embedded MoSe2 monolayer. *J. Phys. Condens. Matter* 32 (36), 365305. doi:10.1088/1361-648x/ab9052

Yang, S. A. (2016). Dirac and Weyl materials: Fundamental aspects and some spintronics applications. *Spin*, 6. World Scientific Publishing Company, 1640003. doi:10.1142/s2010324716400038

Yang, T., Cheng, Z., Sarucu, G., and Wang, X. (2020). Coexistence of parabolic and linear band crossings and electron-doped spin-gapless properties in transition metal embedded MoSe2 monolayer. *Phys. Rev. Lett.* 124 (1), 016402. doi:10.1103/physrevlett.124.016402

Yang, T., Cheng, Z., Wang, X., and Wang, X. (2021). Nodal ring spin gapless semiconductor: New member of spintronic materials. *J. Adv. Res.* 28, 43–49. doi:10.1016/j.jare.2020.06.016

Ye, Z., Li, Z., Sang, L., and Wang, X. (2020). Spin-gapless semiconductors. *Small* 16 (31), 1905155. doi:10.1002/smll.201905155

Zhang, K., Chen, M., Wang, D., Lai, H., Wu, X., and Yang, J. (2021). Nodal-loop half-metallicity in a two-dimensional Fe3N2 pentagon crystal with room-temperature ferromagnetism. *Nanoscale* 13 (46), 19493–19499. doi:10.1039/d1nr06033c

Zhang, L., Li, T., Li, J., Jiang, Y., Yuan, J., and Li, H. (2020). Perfect spin filtering effect on Fe3GeTe2-based van der Waals magnetic tunnel junctions. *J. Phys. Chem. C* 124 (50), 27429–27435. doi:10.1021/acs.jpcc.0c09432

Zhang, L., Zhang, S. F., Ji, W. X., Zhang, C. W., Li, P., Wang, P. J., et al. (2018). Discovery of a novel spin-polarized nodal ring in a two-dimensional HK lattice. *Nanoscale* 10 (44), 20748–20753. doi:10.1039/c8nr05383a

Zhang, R. W., Zhang, Z., Liu, C. C., and Yao, Y. (2020). Nodal line spin-gapless semimetals and high-quality candidate materials. *Phys. Rev. Lett.* 124 (1), 016402. doi:10.1103/physrevlett.124.016402

Zhang, S., Xu, B., Luo, N., and Zou, X. (2021). Two-dimensional magnetic materials: Structures, properties and external controls. *Nanoscale* 13 (3), 1398–1424. doi:10.1039/d0nr06813f

Zhang, X., Wang, A., and Zhao, M. (2015). Spin-gapless semiconducting graphitic carbon nitrides: A theoretical design from first principles. *Carbon* 84, 1–8. doi:10.1016/j.carbon.2014.11.049

Zhou, X., Zhang, A. R., Wang, Z., Popov, I. A., Boldyrev, A. I., and Wang, H. T. (2016). Two-dimensional magnetic boron. *Phys. Rev. B* 93 (8), 085406. doi:10.1103/physrevb.93.085406

Zhou, X., Hang, Y., Liu, L., Zhang, Z., and Guo, W. (2019). A large family of synthetic two-dimensional metal hydrides. *J. Am. Chem. Soc.* 141 (19), 7899–7905. doi:10.1021/jacs.9b02279

Zhu, S., and Li, T. (2016). Strain-induced programmable half-metal and spin-gapless semiconductor in an edge-doped boron nitride nanoribbon. *Phys. Rev. B* 93 (11), 115401. doi:10.1103/physrevb.93.115401