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ABSTRACT

Low-symmetry 2D materials—such as ReS_2 and $ReSe_2$ monolayers, black phosphorus monolayers, group-IV monochalcogenide monolayers, borophene, among others—have more complex atomistic structures than the honeycomb lattices of graphene, hexagonal boron nitride, and transition metal dichalcogenides. The reduced symmetries of these emerging materials give rise to inhomogeneous electron, optical, valley, and spin responses, as well as entirely new properties such as ferroelasticity, ferroelectricity, magnetism, spin-wave phenomena, large nonlinear optical properties, photogalvanic effects, and superconductivity. Novel electronic topological properties, nonlinear elastic properties, and structural phase transformations can also take place due to low symmetry. The "Beyond Graphene: Low-Symmetry and Anisotropic 2D Materials" Special Topic was assembled to highlight recent experimental and theoretical research on these emerging materials.

I. INTRODUCTION

Graphene,[1–3] hexagonal boron nitride monolayers,[4,5] and transition-metal dichalcogenide monolayers (TMDCs) with a 2H symmetry (2H-TMDCs)[6] are all well-established two-dimensional (2D) materials. Graphene displays a sixfold rotational symmetry and also has three mirror planes, while hBN and hexagonal 2H-TMDCs have a sixfold roto-inversion symmetry with two mirror planes. The physical properties of these materials have been studied at length (see, e.g., Refs. 7–9). Along these lines, and appearing in the "Beyond Graphene: Low-Symmetry and Anisotropic 2D Materials" Special Topic, Yamasue and Cho use scanning nonlinear dielectric microscopy to visualize unintentional carrier doping of few-layer Nb-doped MoS_2.[10] They show that atomically thin layers exhibit a p- to n-type transition as the thickness decreases. This sensitive technique is applicable to arbitrary two-dimensional materials, and it will advance understanding of and the ability to predict device characteristics even at an early stage of the fabrication process.

But two-dimensional structural anisotropy implies that a given material displays different physical properties when probed along different spatial directions, and lowering the symmetry of graphene and of other two-dimensional materials by the application of strain leads to remarkable effects, not available in the highly symmetric phase. For example, graphene develops local gauge fields whereby electrons behave as if under an external magnetic field,[11–13] and its spin–orbit coupling strength can also be tuned by curvature.[14] Uniaxial strain, in turn, induces a piezoelectric response in binary materials such as hexagonal boron nitride[15,16] and 2H-TMDCs.[15,17] Local strain has also been proposed to tune the electronic bandgap in 2D semiconductors.[18] Another striking effect from a lowered local symmetry is the superconductivity observed in angularly mismatched (moiré) graphene bilayers.[19]

While previous examples point to an engineered anisotropy, new 2D materials with a spontaneous, *intrinsic* lower symmetry are being predicted and/or experimentally discovered.[20–25] Their structural anisotropy influences all possible (electric, magnetic, optical, or mechanical) material responses, and the Special Topic "Beyond Graphene: Low-Symmetry and Anisotropic 2D Materials" in the *Journal of Applied Physics* has been assembled to showcase recent research into a large number of 2D materials displaying an intrinsic structural anisotropy. As shown by the breadth of submissions,

anisotropic 2D materials represent an exciting and extremely active avenue of research in physics, chemistry, and engineering.

II. LAYERED AND 2D MATERIALS WITH AN IN-PLANE INTRINSIC STRUCTURAL ANISOTROPY

A. Transition metal dichalcogenides in the T and T′ phases

Metal atoms sit at prismatic positions in 2H-TMDCs, but they occupy the octahedral positions between two chalcogen layers in the trigonal (T) phase. Representing an early demonstration of permanent structural phase transitions onto a crystalline structure with a lower symmetry, a triclinic (T) phase was created at the surface of TMDC tantalum diselenide back in the mid-1990s.[26,27] TMDCs with trigonal symmetry have been shown to host superconductivity,[28] charge density waves,[29] quantum spin Hall semimetal behavior,[30–34] and ferroelectricity.[34,35]

Reporting their results in the "Beyond Graphene" Special Topic, Saha *et al.* undertook a systematic study of pressure induced lattice expansion and phonon softening in layered ReS_2, a TMDC with a trigonal structure. The techniques employed include *x*-ray diffraction and Raman spectroscopy. They observed all the eighteen active Raman modes in their experimental results under standard temperature and pressure conditions, and ascertained an isostructural transition onto the 1T′ phase (which is still trigonal but features an even more reduced symmetry) taking place above 6.1 GPa. The 1T′ phase remained stable up to a pressure of 42 GPa. The softening of Raman modes was assigned to vibrational modes predominantly created by rhenium atoms.[36]

In addition, the scanning tunneling microscopy/spectroscopy work by Plumadore *et al.* showcases the properties of a graphene/ReS_2 heterojunction, in which novel properties become enabled by a combination of proximity effects and moiré patterns.[37] They observe a striped superpattern created by interlayer interactions between graphene's hexagonal structure and the triclinic, low in-plane symmetry of ReS_2. They compared their experimental results with a theoretical model that estimates the shape and angle dependence of the moiré pattern between graphene and ReS_2. Their results shed light on the complex interface phenomena between van der Waals materials with different lattice symmetries.

Kipczak *et al.* studied the photoluminescence (PL) and Raman scattering properties of ultrathin $ReSe_2$—whose thicknesses ranged from nine to one monolayer—at 5 K and at room temperature,[38] paving the way for the identification of few-layer $ReSe_2$ samples by optical means. The PL spectra of $ReSe_2$ layers display two well-resolved emission lines, which blue shift by about 120 meV when the layer thickness decreases from nine monolayers to a monolayer, confirming a direct optical transition. More specifically, the two phonon modes of intralayer vibrations observed in Raman scattering spectra at about 120 cm^{-1} exhibit an opposite evolution as a function of layer thickness. Their energy difference can serve as a convenient and reliable tool to determine the thickness of $ReSe_2$ flakes in the few-layer limit.[38]

B. Ultrathin black phosphorus (including monolayers)

Black phosphorus (BP) is another layered material with in-plane anisotropy.[8,39–42] Phosphorus belongs to the nitrogen group, which is located to the right of the carbon group in the periodic table of elements. Phosphorus has five valence electrons, while carbon has four. As it turns out, a black phosphorus monolayer and graphene are both threefold coordinated, which means that they form three strong chemical bonds. In the case of graphene, the remaining (π) electron hovers out of plane. But a *lone pair* ensues in black phosphorus, leading to an out-of-plane buckling of the atoms in its unit cell, which turns rectangular and contains four atoms. This difference in the chemistry of carbon and phosphorus leads to a large number of anisotropic properties (elastic, electronic, and optical) observed on this material.[8,43,44]

Publishing their results in the "Beyond Graphene" Special Topic, Doha *et al.* created an anti-reflection cavity that optimizes absorption in a BP layer, which was characterized using scanning photocurrent microscopy. They also modeled the devices by solving Maxwell's equations and the drift–diffusion equation to obtain the optical absorption and photocurrent density in response to pulsed laser excitation. They observed a strong absorption of 36% at 780 nm, which suggests a promising outlook for the THz performance of these devices.[45] Additionally, the computational work by Sibari *et al.* explores the relation among atomistic structure and electronic properties of few-layer black phosphorene,[46] while Betancur-Ocampo *et al.* employed a Green's function formalism on a tight-binding model of a black phosphorus monolayer pnp junction, as well as a continuum description, and determine that these junctions operate as electron waveguides.[47]

C. Multiferroic behavior in layered and 2D materials with low symmetry

Layered ferroelectrics—such as In_2Se_3,[48] $CuInP_2S_6$,[49] BA_2PbCl_4,[50] 1T′-$MoTe_2$,[35] and 1T′-WTe_2[34]—provide unprecedented freedom for the design and fabrication of functional (van der Waals) heterostructures. This Special Issue features four works in a subset of these materials, namely, ferroelectric and ferroelastic group-IV transition monochalcogenide monolayers (MX, with M being Ge, Sn, or Pb, while X could be S, Se, or Te).[43,51] MX monolayers are a family of novel two-dimensional (2D) materials whose atomistic structures closely resemble the black phosphorus lattice. Most MX monolayers exhibit a broken inversion symmetry and are ferroelectric with a reversible in-plane electric polarization. MX monolayers are promising materials for applications in nonlinear optics, photovoltaics, spintronics, and valleytronics.

The "Beyond Graphene" Special Topic features a Perspective Article by Chang and Parkin, in which a detailed exposition of the experimental creation and characterization of MX monolayers is provided.[52] Due to their relatively large exfoliation energy, the creation of MX monolayers is not an easy endeavor, which hinders the integration of these materials into the fast-developing field of 2D material heterostructures. They review recent developments in experimental routes to the creation of these materials, including molecular beam epitaxy and two-step etching methods. Other approaches that could be used to prepare MX monolayers, such as liquid phase exfoliation and solution-phase synthesis, were discussed as well. Quantitative comparisons between the material properties observed were also presented.[52]

In turn, Gomes and Carvalho provide a Tutorial of the electronic and optical properties of 2D group-IV monochalcogenides, including predictions from first-principles DFT calculations, and available experimental observations.[53] They discuss the variation of the bandgap from the bulk down to the monolayer, and the respective band structures, which are characterized by multiple valence and conduction band valleys, making these materials suitable for a variety of applications, including valleytronics. They also discuss the emergence of spin–orbit splitting, piezoelectricity, and ferroelectricity as a result of the polar character of the monolayers. Current predictions of carrier mobilities in monolayers and their potential application as thermoelectric materials were discussed as well. Ferroelectric and ferroelastic materials have thermally accessible elastic energy barriers separating degenerate structural ground states. Du *et al.* studied the effect of charge doping on the elastic energy barrier created by a $Pnm2_1 \rightarrow P4/nmm$ two-dimensional structural transformation of a black phosphorus monolayer and nine ferroelectric/ferroelastic group-IV monochalcogenide monolayers. Group-IV monochalcogenide monolayers show a tunable elastic energy barrier for small amounts of doping: a decrease (increase) in the energy barrier can be engineered under a modest hole (electron) doping of no more than one tenth of an electron or a hole per atom. These results provide further guidance concerning a possible tunability of the ferroelectric-to-paraelectric transition temperature of these compounds by charge doping.[54] Lastly, Seixas employed first-principles techniques to study the structural, electronic, and vibrational properties of 15 group-IV monochalcogenide monolayers based on Janus substitution. These Janus materials are potential candidates for similar applications but with additionally broken symmetry that can enrich their electronic and optical properties.[55]

D. Borophene

In the "Beyond Graphene" Special Topic, Sandoval-Santana *et al.* address the dynamics of charge carriers in borophene with an Pmmn symmetry obeying an anisotropic Dirac Hamiltonian, subjected to illumination by linearly polarized light of arbitrary intensity. To this end, they develop analytical methods, including a set of unitary transformations that enable the reduction of the matrix-differential equation into a scalar differential equation, the Floquet theorem, and a Fourier spectral decomposition. They show that the quasi-energy spectrum develops an anisotropic structure in the intense field regime.[56]

E. Silicene, silicane, germanene, and germanane

A number of 2D materials—such as silicene and germanene, as well as their hydrogenated silicane and germanane counterparts—lack an out-of-plane inversion symmetry. The "Beyond Graphene" Special Topic features work by Araidai *et al.*, in which hydrogen desorption from silicane (SiH) and germanane (GeH) is investigated by first-principles calculations and experiment. Their results indicate that SiH and GeH monolayers could become precursors of silicene and germanene monolayers.[57]

III. ADDITIONAL ANISOTROPIC LAYERED AND 2D MATERIALS IN THE HORIZON

Displaying the sheer vitality of this research field, Vannucci *et al.*[58] report a high-throughput search of anisotropic two-dimensional materials from the C2DB database,[20] which contains in excess of 1000 entries. They give special attention to the ternary orthorhombic compound prototype ABC-59-ab class, which combines three different atomic species in a low-symmetry structure leading to strongly anisotropic properties, including magnetism. Excitingly, one of such materials (CrSBr) has been recently isolated down to monolayers.[59]

In turn, Liu *et al.* propose a layered multiferroic ($MoCr_2S_6$) by alloying chromium into the ferroelectric 1T phase of the MoS_2 matrix. First-principles calculations disclose that a spontaneous symmetry breaking, depending on the Mo atom displacement, leads to a robust ferroelectricity, which coexists with a ferromagnetic order originated from two neighboring chromium atoms. Their findings shed new light on the fundamental understanding of multiferroics and display promising applications in spintronics and multistate data storage.[60]

Last but not least, an authoritative Tutorial contributed by May *et al.*[61] covers the technical aspects associated with the growth of layered (anisotropic) materials via melt-based techniques, vapor transport growth, and the characterization of crystal quality with an emphasis on structural and chemical homogeneities. Important for the development of this field, details on growth and characterization of many specific compounds were provided. The Tutorial's goal is to motivate more researchers to grow van der Waals crystals.

IV. CONCLUSIONS

In conclusion, this Special Issue showcases recent research in the rapidly evolving area of two-dimensional materials with low symmetry. The contributed works feature predictions of novel phases and detailed experimental discussions of growth and characterization of these phases—including the creation of van der Waals heterostructures. The variety of these published contributions is a testament to the vitality of this field.

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REFERENCES

[1]A. H. Castro Neto, F. Guinea, N. M. R. Peres, K. S. Novoselov, and A. K. Geim, "The electronic properties of graphene," Rev. Mod. Phys. **81**, 109–162 (2009).
[2]V. N. Kotov, B. Uchoa, V. M. Pereira, F. Guinea, and A. H. Castro Neto, "Electron-electron interactions in graphene: Current status and perspectives," Rev. Mod. Phys. **84**, 1067–1125 (2012).
[3]A. Avsar, H. Ochoa, F. Guinea, B. Özyilmaz, B. J. van Wees, and I. J. Vera-Marun, "Colloquium: Spintronics in graphene and other two-dimensional materials," Rev. Mod. Phys. **92**, 021003 (2020).
[4]C. Jin, F. Lin, K. Suenaga, and S. Iijima, "Fabrication of a freestanding boron nitride single layer and its defect assignments," Phys. Rev. Lett. **102**, 195505 (2009).

[5]L. H. Li and Y. Chen, "Atomically thin boron nitride: Unique properties and applications," Adv. Funct. Mater. **26**, 2594–2608 (2016).
[6]K. F. Mak, C. Lee, J. Hone, J. Shan, and T. F. Heinz, "Atomically thin mos$_2$: A new direct-gap semiconductor," Phys. Rev. Lett. **105**, 136805 (2010).
[7]M. I. Katsnelson, *Graphene: Carbon in Two Dimensions*, 1st ed. (Cambridge University Press, Cambdridge, 2012).
[8]P. Avouris, T. Heinz, and T. Low, *2D Materials*, 1st ed. (Cambridge University Press, Cambdridge, 2017).
[9]A. V. Kolobov and J. Tominaga, *Two-Dimensional Transition-Metal Dichalcogenides*, 1st ed. (Springer, Switzerland, 2016).
[10]K. Yamasue and Y. Cho, "Nanoscale characterization of unintentional doping of atomically thin layered semiconductors by scanning nonlinear dielectric microscopy," J. Appl. Phys. **128**, 074301 (2020).
[11]M. Vozmediano, M. Katsnelson, and F. Guinea, "Gauge fields in graphene," Phys. Rep. **496**, 109–148 (2010).
[12]B. Amorim, A. Cortijo, F. de Juan, A. Grushin, F. Guinea, A. Gutiérrez-Rubio, H. Ochoa, V. Parente, R. Roldán, P. San-Jose, J. Schiefele, M. Sturla, and M. Vozmediano, "Novel effects of strains in graphene and other two dimensional materials," Phys. Rep. **617**, 1–54 (2016).
[13]G. G. Naumis, S. Barraza-Lopez, M. Oliva-Leyva, and H. Terrones, "Electronic and optical properties of strained graphene and other strained 2D materials: A review," Rep. Prog. Phys. **80**, 096501 (2017).
[14]D. Huertas-Hernando, F. Guinea, and A. Brataas, "Spin-orbit coupling in curved graphene, fullerenes, nanotubes, and nanotube caps," Phys. Rev. B **74**, 155426 (2006).
[15]K.-A. N. Duerloo, M. T. Ong, and E. J. Reed, "Intrinsic piezoelectricity in two-dimensional materials," J. Phys. Chem. Lett. **3**, 2871–2876 (2012).
[16]P. Ares, T. Cea, M. Holwill, Y. B. Wang, R. Roldán, F. Guinea, D. V. Andreeva, L. Fumagalli, K. S. Novoselov, and C. R. Woods, "Piezoelectricity in monolayer hexagonal boron nitride," Adv. Mater. **32**, 1905504 (2020).
[17]W. Wu, L. Wang, Y. Li, F. Zhang, L. Lin, S. Niu, D. Chenet, X. Zhang, Y. Hao, T. F. Heinz, J. Hone, and Z. L. Wang, "Piezoelectricity of single-atomic-layer MoS_2 for energy conversion and piezotronics," Nature **514**, 470–474 (2014).
[18]J. Feng, X. Qian, C.-W. Huang, and J. Li, "Strain-engineered artificial atom as a broad-spectrum solar energy funnel," Nat. Photon. **6**, 866–872 (2012).
[19]Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, "Unconventional superconductivity in magic-angle graphene superlattices," Nature **556**, 43–50 (2018).
[20]S. Haastrup, M. Strange, M. Pandey, T. Deilmann, P. S. Schmidt, N. F. Hinsche, M. N. Gjerding, D. Torelli, P. M. Larsen, A. C. Riis-Jensen, J. Gath, K. W. Jacobsen, J. J. Mortensen, T. Olsen, and K. S. Thygesen, "The computational 2D materials database: High-throughput modeling and discovery of atomically thin crystals," 2D Mater. **5**, 042002 (2018).
[21]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**, 246–252 (2018).
[22]M. Ashton, J. Paul, S. B. Sinnott, and R. G. Hennig, "Topology-scaling identification of layered solids and stable exfoliated 2D materials," Phys. Rev. Lett. **118**, 106101 (2017).
[23]K. Choudhary, I. Kalish, R. Beams, and F. Tavazza, "High-throughput identification and characterization of two-dimensional materials using density functional theory," Sci. Rep. **7**, 5179 (2017).
[24]G. Cheon, K.-A. N. Duerloo, A. D. Sendek, C. Porter, Y. Chen, and E. J. Reed, "Data mining for new two- and one-dimensional weakly bonded solids and lattice-commensurate heterostructures," Nano Lett. **17**, 1915–1923 (2017).
[25]J. Zhou, L. Shen, M. Dias Costa, K. A. Persson, S. P. Ong, P. Huck, Y. Lu, X. Ma, Y. Chen, H. Tang, and Y. P. Feng, "2DMatPedia, an open computational database of two-dimensional materials from top-down and bottom-up approaches," Sci. Data **6**, 86 (2019).
[26]J.-J. Kim, C. Park, W. Yamaguchi, O. Shiino, K. Kitazawa, and T. Hasegawa, "Observation of a phase transition from the *T* phase to the *H* phase induced by a STM tip in 1*T*-TaS_2," Phys. Rev. B **56**, R15573–R15576 (1997).
[27]J. Zhang, J. Liu, J. L. Huang, P. Kim, and C. M. Lieber, "Creation of nanocrystals through a solid-solid phase transition induced by an STM tip," Science **274**, 757–760 (1996).
[28]Z. Chi, X. Chen, F. Yen, F. Peng, Y. Zhou, J. Zhu, Y. Zhang, X. Liu, C. Lin, S. Chu, Y. Li, J. Zhao, T. Kagayama, Y. Ma, and Z. Yang, "Superconductivity in pristine $2H_a-MoS_2$ at ultrahigh pressure," Phys. Rev. Lett. **120**, 037002 (2018).
[29]M. Calandra and F. Mauri, "Charge-density wave and superconducting dome in $TiSe_2$ from electron-phonon interaction," Phys. Rev. Lett. **106**, 196406 (2011).
[30]X. Qian, J. Liu, L. Fu, and J. Li, "Quantum spin Hall effect in two-dimensional transition metal dichalcogenides," Science **346**, 1344–1347 (2014).
[31]Z. Fei, T. Palomaki, S. Wu, W. Zhao, X. Cai, B. Sun, P. Nguyen, J. Finney, X. Xu, and D. H. Cobden, "Edge conduction in monolayer WTe_2," Nat. Phys. **13**, 677–682 (2017).
[32]S. Tang, C. Zhang, D. Wong, Z. Pedramrazi, H.-Z. Tsai, C. Jia, B. Moritz, M. Claassen, H. Ryu, S. Kahn, J. Jiang, H. Yan, M. Hashimoto, D. Lu, R. G. Moore, C.-C. Hwang, C. Hwang, Z. Hussain, Y. Chen, M. M. Ugeda, Z. Liu, X. Xie, T. P. Devereaux, M. F. Crommie, S.-K. Mo, and Z.-X. Shen, "Quantum spin Hall state in monolayer 1T′-WTe_2," Nat. Phys. **13**, 683–687 (2017).
[33]S. Wu, V. Fatemi, Q. D. Gibson, K. Watanabe, T. Taniguchi, R. J. Cava, and P. Jarillo-Herrero, "Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal," Science **359**, 76–79 (2018).
[34]Z. Fei, W. Zhao, T. A. Palomaki, B. Sun, M. K. Miller, Z. Zhao, J. Yan, X. Xu, and D. H. Cobden, "Ferroelectric switching of a two-dimensional metal," Nature **560**, 336–339 (2018).
[35]S. Yuan, X. Luo, H. L. Chan, C. Xiao, Y. Dai, M. Xie, and J. Hao, "Room-temperature ferroelectricity in $MoTe_2$ down to the atomic monolayer limit," Nat. Commun. **10**, 1775 (2019).
[36]P. Saha, B. Ghosh, A. Mazumder, K. Glazyrin, and G. Dev Mukherjee, "Pressure induced lattice expansion and phonon softening in layered ReS_2," J. Appl. Phys. **128**, 085904 (2020).
[37]R. Plumadore, M. M. Al Ezzi, S. Adam, and A. Luican-Mayer, "Moiré patterns in graphene–rhenium disulfide vertical heterostructures," J. Appl. Phys. **128**, 044303 (2020).
[38]Ł. Kipczak, M. Grzeszczyk, K. Olkowska-Pucko, A. Babiński, and M. R. Molas, "The optical signature of few-layer $ReSe_2$," J. Appl. Phys. **128**, 044302 (2020).
[39]H. Liu, A. T. Neal, Z. Zhu, Z. Luo, X. Xu, D. Tománek, and P. D. Ye, "Phosphorene: An unexplored 2D semiconductor with a high hole mobility," ACS Nano **8**, 4033–4041 (2014).
[40]L. Li, Y. Yu, G. J. Ye, Q. Ge, X. Ou, H. Wu, D. Feng, X. H. Chen, and Y. Zhang, "Black phosphorus field-effect transistors," Nat. Nanotechnol. **9**, 372–377 (2014).
[41]A. Castellanos-Gomez, L. Vicarelli, E. Prada, J. O. Island, K. L. Narasimha-Acharya, S. I. Blanter, D. J. Groenendijk, M. Buscema, G. A. Steele, J. V. Alvarez, H. W. Zandbergen, J. J. Palacios, and H. S. J. van der Zant, "Isolation and characterization of few-layer black phosphorus," 2D Mater. **1**, 025001 (2014).
[42]X. Ling, H. Wang, S. Huang, F. Xia, and M. S. Dresselhaus, "The renaissance of black phosphorus," Proc. Natl. Acad. Sci. U.S.A. **112**, 4523–4530 (2015).
[43]F. Xia, H. Wang, J. C. M. Hwang, A. H. C. Neto, and L. Yang, "Black phosphorus and its isoelectronic materials," Nat. Rev. Phys. **1**, 306–317 (2019).
[44]X. Wang, A. M. Jones, K. L. Seyler, V. Tran, Y. Jia, H. Zhao, H. Wang, L. Yang, X. Xu, and F. Xia, "Highly anisotropic and robust excitons in monolayer black phosphorus," Nat. Nanotechnol. **10**, 517–521 (2015).
[45]M. H. Doha, J. I. Santos Batista, A. F. Rawwagah, J. P. Thompson, A. Fereidouni, K. Watanabe, T. Taniguchi, M. El-Shenawee, and H. O. H. Churchill, "Integration of multi-layer black phosphorus into photoconductive antennas for THz emission," J. Appl. Phys. **128**, 063104 (2020).
[46]A. Sibari, Z. Kerrami, A. Kara, and M. Benaissa, "Strain-engineered p-type to n-type transition in mono-, bi-, and tri-layer black phosphorene," J. Appl. Phys. **127**, 225703 (2020).
[47]Y. Betancur-Ocampo, E. Paredes-Rocha, and T. Stegmann, "Phosphorene pnp junctions as perfect electron waveguides," J. Appl. Phys. **128**, 114303 (2020).

[48]S. M. Poh, S. J. R. Tan, H. Wang, P. Song, I. H. Abidi, X. Zhao, J. Dan, J. Chen, Z. Luo, S. J. Pennycook, A. H. Castro-Neto, and K. P. Loh, "Molecular-beam epitaxy of two-dimensional In_2Se_3 and its giant electroresistance switching in ferroresistive memory junction," Nano Lett. **10**, 6340–6346 (2018).
[49]F. Liu, L. You, K. L. Seyler, X. Li, P. Yu, J. Lin, X. Wang, J. Zhou, H. Wang, H. He, S. T. Pantelides, W. Zhou, P. Sharma, X. Xu, P. M. Ajayan, J. Wang, and Z. Liu, "Room-temperature ferroelectricity in $CuInP_2S_6$ ultrathin flakes," Nat. Commun. **7**, 12357 (2016).
[50]L. You, F. Liu, H. Li, Y. Hu, S. Zhou, L. Chang, Y. Zhou, Q. Fu, G. Yuan, S. Dong, H. J. Fan, A. Gruverman, Z. Liu, and J. Wang, "In-plane ferroelectricity in thin flakes of van der Waals hybrid perovskite," Adv. Mater. **30**, 1803249 (2018).
[51]S. Barraza-Lopez, B. M. Fregoso, W. J. Villanova, S. S. P. Parkin, and K. Chang, "Colloquium: Physical behavior of group-IV monochalcogenide monolayers," Rev. Mod. Phys. (to be published) (2020), arXiv:2009.04341.
[52]K. Chang and S. S. P. Parkin, "Experimental formation of monolayer group-IV monochalcogenides," J. Appl. Phys. **127**, 220902 (2020).
[53]L. C. Gomes and A. Carvalho, "Electronic and optical properties of low-dimensional group-IV monochalcogenides," J. Appl. Phys. **128**, 121101 (2020).
[54]A. Du, Z. Pendergrast, and S. Barraza-Lopez, "Tuning energy barriers by doping 2D group-IV monochalcogenides," J. Appl. Phys. **127**, 234103 (2020).
[55]L. Seixas, "Janus two-dimensional materials based on group IV monochalcogenides," J. Appl. Phys. **128**, 045115 (2020).
[56]J. C. Sandoval-Santana, V. G. Ibarra-Sierra, A. Kunold, and G. G. Naumis, "Floquet spectrum for anisotropic and tilted Dirac materials under linearly polarized light at all field intensities," J. Appl. Phys. **127**, 234301 (2020).
[57]M. Araidai, M. Itoh, M. Kurosawa, A. Ohta, and K. Shiraishi, "Hydrogen desorption from silicane and germanane crystals: Toward creation of free-standing monolayer silicene and germanene," J. Appl. Phys. **128**, 125301 (2020).
[58]L. Vannucci, U. Petralanda, A. Rasmussen, T. Olsen, and K. S. Thygesen, "Anisotropic properties of monolayer 2D materials: An overview from the C2DB database," J. Appl. Phys. **128**, 105101 (2020).
[59]K. Lee, A. H. Dismukes, E. J. Telford, R. A. Wiscons, X. Xu, C. Nuckolls, C. R. Dean, X. Roy, and X. Zhu, "Magnetic order and symmetry in the 2D semiconductor CrSBr," arXiv:2007.10715 (2020).
[60]L.-Z. Liu, K.-H. Jin, and F. Liu, "Prediction of room-temperature multiferroicity in strained $MoCr_2S_6$ monolayer," J. Appl. Phys. **127**, 155302 (2020).
[61]A. F. May, J. Yan, and M. A. McGuire, "A practical guide for crystal growth of van der Waals layered materials," J. Appl. Phys. **128**, 051101 (2020).