

Preparation of atomically thin 2D metals

Jiaojiao Zhao(赵交交), Guangyu Zhang(张广宇), and Luojun Du(杜罗军)
Citation: Chin. Phys. B, 2025, 34 (**10**): 106104. DOI: 10.1088/1674-1056/ae04d7
http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Visualizing extended defects at the atomic level in a $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconducting wire

Kejun Hu(胡柯钧), Shuai Wang(王帅), Boyu Li(李泊玉), Ying Liu(刘影), Binghui Ge(葛炳辉), and Dongsheng Song(宋东升)
Chin. Phys. B, 2024, 33 (**9**): 096101. DOI: 10.1088/1674-1056/ad6ccd

FL-Online: An x-ray crystallographic web-server for atomic-scale structure analysis of biomolecule

Bintang Wang(王宾堂), Tongxin Niu(牛彤欣), Haifu Fan(范海福), and Wei Ding(丁玮)
Chin. Phys. B, 2024, 33 (**7**): 076104. DOI: 10.1088/1674-1056/ad47e5

DSAS: A new macromolecular substructure solution program based on the modified phase-retrieval algorithm

Xingke Fu(付兴科), Zhenxi Tan(谭振希), Zhi Geng(耿直), Qian Liu(刘茜), and Wei Ding(丁玮)
Chin. Phys. B, 2024, 33 (**5**): 056102. DOI: 10.1088/1674-1056/ad3c33

DSAS: A new macromolecular substructure solution program based on the modified phase-retrieval algorithm

Xingke Fu(付兴科), Zhenxi Tan(谭振希), Zhi Geng(耿直), Qian Liu(刘茜), and Wei Ding(丁玮)
Chin. Phys. B, 2024, 33 (**5**): 056102. DOI: 10.1088/1674-1056/ad3c33

Structure, phase evolution and properties of Ta films deposited using hybrid high-power pulsed and DC magnetron co-sputtering

Min Huang(黄敏), Yan-Song Liu(刘艳松), Zhi-Bing He(何智兵), and Yong Yi(易勇)
Chin. Phys. B, 2022, 31 (**6**): 066101. DOI: 10.1088/1674-1056/ac43a9

INVITED REVIEW

Preparation of atomically thin 2D metals

Jiaojiao Zhao(赵交交)[1,2,3], Guangyu Zhang(张广宇)[1,2,3,†], and Luojun Du(杜罗军)[1,2,‡]

[1] *Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing* 100190, *China*
[2] *School of Physical Sciences, University of Chinese Academy of Sciences, Beijing* 100049, *China*
[3] *Songshan Lake Materials Laboratory, Dongguan* 523808, *China*

(Received 30 June 2025; revised manuscript received 27 August 2025; accepted manuscript online 9 September 2025)

Two-dimensional (2D) metals, which are appealing for a plethora of emergent phenomena and technological applications, stand as one of the highly sought-after goals in condensed-matter physics and materials science. In stark contrast to the widely-studied 2D van der Waals (vdW) layered materials in which their weak interlayer interactions facilitate the isolation from their bulk, 2D metals are extremely challenging to achieve because of their thermodynamic instability and non-layered nature. In this review, we highlight the recent advances in the reliable production of atomically thin 2D metals, including but not limited to vdW squeezing technique, top-down exfoliation, mechanical pressing, chemical etching, epitaxial growth, and confinement growth. We also present our perspectives and discuss the future opportunities and research directions in this new field.

Keywords: two-dimensional (2D) metals, vdW squeezing, top-down strategy, bottom-up synthesis

PACS: 61.05.–a, 61.46.–w

DOI: 10.1088/1674-1056/ae04d7 **CSTR:** 32038.14.CPB.ae04d7

1. Introduction

Two-dimensional (2D) materials, starting with the ground-breaking exfoliation of graphene in 2004, have changed the way we think about materials and ushered in a new era of fundamental research and technological innovation, owing to the unique electronic, photonic, magnetic, and topological properties unattainable in their bulk counterparts.[1–6] Over the past two decades, the 2D family has markedly expanded and now includes hundreds of laboratory-accessible species with diverse properties, for example wide-bandgap insulators (e.g., h-BN), semiconductors (e.g., MoS_2 and black phosphorus), quantum spin liquids (e.g., $RuCl_3$), ferromagnets (e.g., CrI_3), and high-temperature superconductors (e.g., $Bi_2Sr_2CaCu_2O_{8+\delta}$).[3,7–13] However, these 2D materials are largely limited to van der Waals (vdW) layered crystals in which their weak interlayer interactions facilitate the isolation from their bulk, for example, by mechanical exfoliation. Exploring new atomically thin materials beyond 2D vdW crystals could not only significantly broaden the 2D family, but also bring more surprises and exotic insight into exciting phenomena and potential technological innovations.[14–19]

Atomically thin 2D metals composed of metallic elements from the periodic table stand as one of the highly sought-after goals in condensed-matter physics and materials science, which can not only broaden the 2D family beyond 2D vdW layered materials but also possess promising prospects for the exploration of completely new physics and device architectures, such as new quantum optical effects, topological edge states, superconductivity, metallic ferroelectricity, quantum Griffiths singularity, superior nonlinearity, catalysis, and all-metallic transistors.[20–33] However, unlike the widely-studied 2D vdW layered crystals, 2D non-vdW metals with highly symmetric crystal lattices tend to be thermodynamically unfavorable and typically become discontinuous when scaling the thickness down to several nanometers. Consequently, it is a great challenge to achieve intrinsic, large area (especially larger than 1 μm), uniform thickness, and ambient-stable 2D metals down to one-unit-cell thick. We note that when referring to 2D metals, we mean crystalline systems in which their thickness is of atomic scale (<10 nm), while their lateral dimensions are at least close to the μm-scale.

Over the past few years, substantial developments and progresses on producing atomically thin 2D metals have been witnessed. Especially, a universal vdW squeezing method has been developed recently,[19,34] producing, for the first time, large-scale (> 100 μm), truly 2D metals down to the ångström thickness limit.[19,35] This represents a major advance in the important research field of 2D metals (Fig. 1).[36] Here, we review the recent advances in the available methods for top-down exfoliation from bulk materials and for bottom-up synthesis of atomically thin 2D metals, and evaluate their relative merits (Table 1), including but not limited to the vdW squeezing technique, mechanical exfoliation, mechanical pressing,

†Corresponding author. E-mail: gyzhang@iphy.ac.cn
‡Corresponding author. E-mail: luojun.du@iphy.ac.cn

© 2025 Chinese Physical Society and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

chemical etching, epitaxial growth, confinement growth, and surface-nanoconfined growth. Finally, we conclude with perspectives on future research directions, opportunities and challenges in this new field.

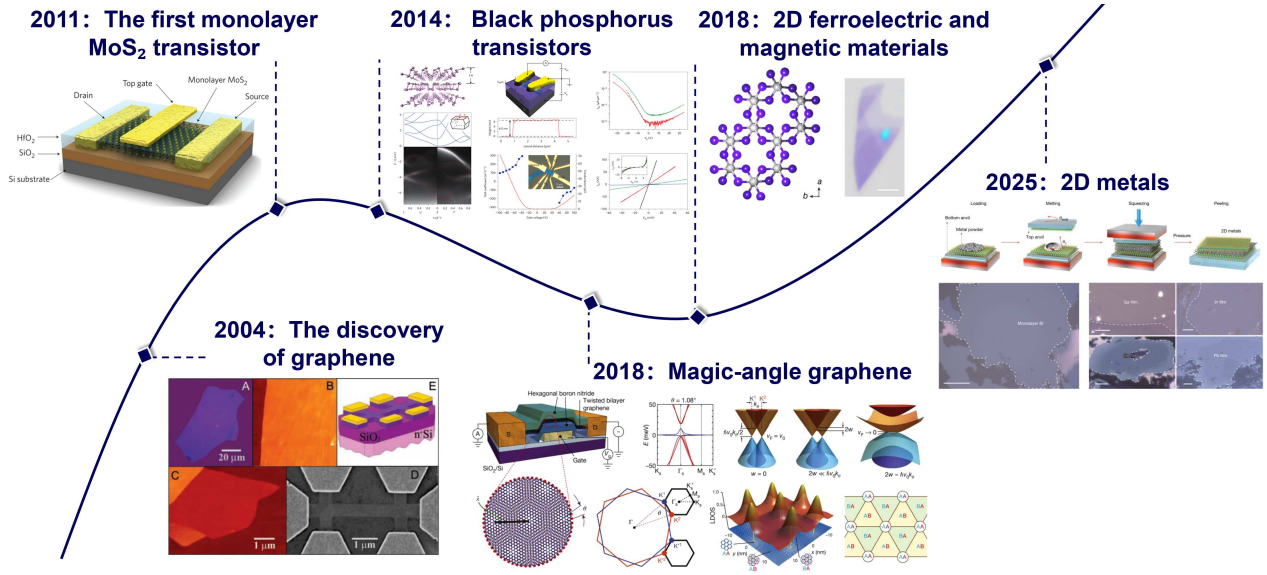


Fig. 1. Timeline of selected major advances in the 2D field with an emphasis on material systems. Adapted with permission from Refs. [1,10–13,19].

Table 1. Comparison between the available methods for the production of 2D metals.

Methods	Prepared 2D metal	Thinnest thickness	Lateral dimensions	Environmental stability	Single crystal	Intrinsic properties
vdW squeezing	Bi, Sn, Pb, In, and Ga	~ 5.8 Å	~ 100 μm	Stable	Yes	Non-bonded interfaces; intrinsic
Mechanical exfoliation	Bi and Sb	~ 12 Å	~ 3 μm	Unstable	Yes	Non-bonded interfaces; intrinsic
Mechanical pressing	Ag, Au, Ni, Cu and Fe	~ 29 Å	~ 1 μm	Unstable	No	Etchant residues; non-intrinsic
Chemical etching	Au	~ 19 Å	~ 40 μm	Unstable	Yes	Etchant residues; non-intrinsic
Solid-melt exfoliation	Ga	> 30 Å	~ 100 μm	Unstable	No	Chemical interaction with substrates
VPD	Sb	~ 40 Å	~ 10 μm	Unstable	Yes	Non-bonded interfaces; intrinsic
Confinement growth	Ga, Sn and In	~ 5 Å		Stable	Yes	Covalently bonded to substrates
Surface-nanoconfined growth	Pd	~ 8 Å	~ 10 μm	Stable	Yes	Forming compounds; non-intrinsic

2. The vdW squeezing

Recently, a convenient, universal method dubbed vdW squeezing has been developed for preparing 2D metals.[19] Figure 2(a) illustrates the vdW squeezing process. First, a certain amount of metal powder is placed on the bottom monolayer MoS_2/sapphire anvil and then heated until it melts to form a droplet (panel I in Fig. 2(a)). Then, another monolayer MoS_2/sapphire, serving as the top anvil, is placed face to face on the bottom anvil. The two anvils move towards each other until contact is made, with liquid metals sandwiched in between (panel II in Fig. 2(a)). Subsequently, external pressure is applied to both the top and bottom MoS_2/sapphire anvils and the metal droplet is gradually squeezed flat at a high pressure of ~ 200 MPa (panel III in Fig. 2(a)), roughly double the pressure at the bottom of the Mariana Trench. With squeezing, the droplet metal spreads rapidly between the MoS_2 monolayers and decreases its thickness. The squeezing process is maintained until the two opposite anvils are cooled down to room temperature naturally and 2D metals are formed eventually. Finally, the as-achieved sapphire/MoS_2/2D-metal/MoS_2/sapphire assembly is unloaded and mechanically cleaved. Since the vdW interaction of metal–MoS_2 is larger than that of MoS_2–sapphire, the cleaved interface occurs at the MoS_2/sapphire interfaces, resulting in MoS_2-encapsulated 2D metals on sapphire (Fig. 2(a), panel IV).

We highlight that a key trick to realizing 2D metals is the use of single crystalline monolayer MoS_2 epitaxially grown on sapphire as bottom and top anvils:[37] (1) the atomically flat and dangling-bond-free surface of MoS_2/sapphire anvil is critical to thickness uniformity of 2D metals over a large scale; (2) the high Young's modulus of both sapphire (about 430 GPa) and monolayer MoS_2 (around 300 GPa) is important to withstand the exerted high pressures, enabling 2D metals formed inside the two anvils to approach their ångström thickness limit. We envision that graphene, h-BN and other 2D layered materials can also be used as vdW anvils for preparing atomically thin 2D metals.[34]

With the vdW squeezing methodology, diverse 2D metals (including Bi, Ga, In, Sn and Pb) are realized (Fig. 2(b)).

Remarkably, the thicknesses of these as-produced 2D metals can all reach to the ångström limit, e.g., ∼ 6.3 Å for Bi, ∼ 5.8 Å for Sn, ∼ 7.5 Å for Pb, ∼ 8.4 Å for In, and ∼ 9.2 Å for Ga, as revealed in the atomic force microscope (AFM) images (Fig. 2(c)). The vdW squeezing represents a ground-breaking approach for producing 2D metals, featuring parameter metrics unattainable by previous methods. First, 2D metals by vdW squeezing technique can be reachable in large sizes, e.g., ∼ 100 μm for single crystalline Bi monolayer (Fig. 2(b)), two orders of magnitude larger than those reported previously.[18,28,32,33] Second, the full-vdW encapsulated characteristics also ensure that the as-produced 2D metals present non-bonded interfaces (i.e., 'all-vdW' nature), facilitating the access of intrinsic physical properties. By contrast, most 2D metals previously prepared are covalently bonded to substrates,[26] and thus the measured properties are usually non-intrinsic. Third, the as-produced 2D metal films are full-vdW encapsulated by atomically-smooth MoS_2 monolayers, and therefore are extremely environmentally stable. Notably, the encapsulated monolayer Bi can last at least one year in an atmospheric environment without degradation or oxidation. Fourth, the vdW squeezing methodology facilitates the realization of 2D metals with various thicknesses (such as one-, two- and three-unit-cell thick) by controlling the squeezing pressure, providing a firm basis for the exploration of fascinating layer-dependent physical properties. Last but not least, the vdW squeezing strategy can engineer the crystal orientation of 2D metals by controlling the twist angle between the top and bottom vdW monolayers. This promises the prospect of designing new moiré superlattice systems composed of 2D metals and 2D vdW layer materials, highlighting the great potential for new physics and technological advances in electronics, optoelectronics, and twistronics.[4]

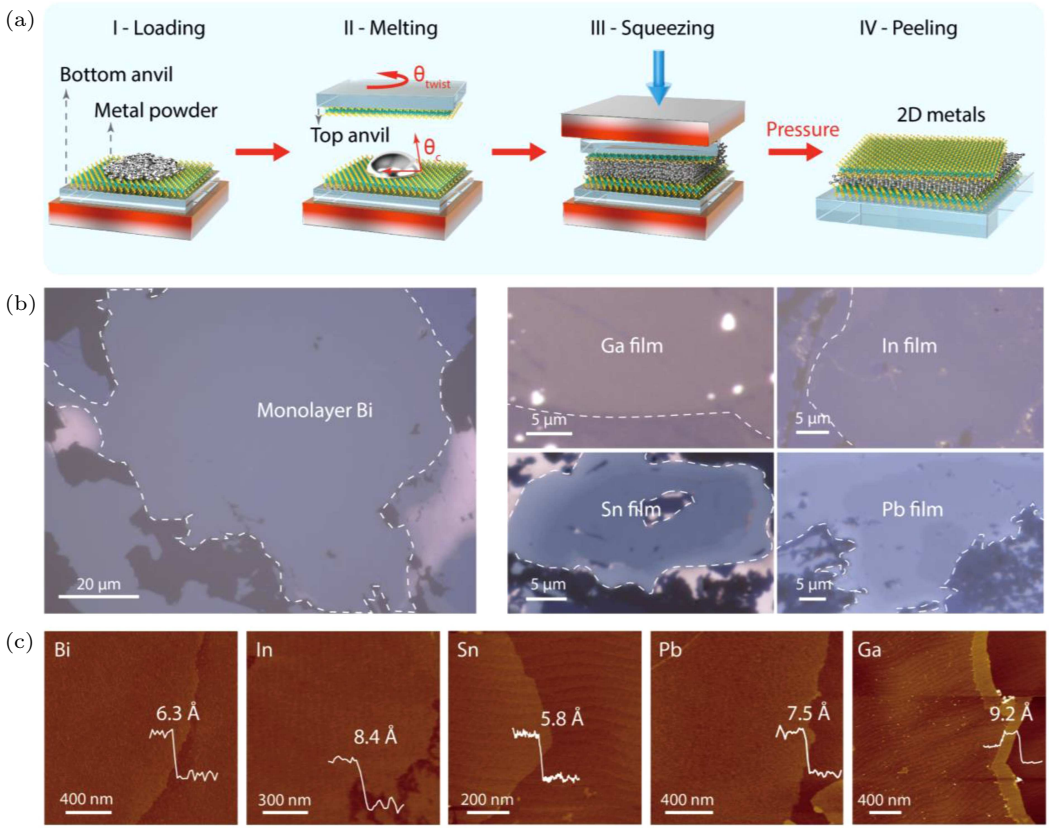


Fig. 2. The vdW squeezing for 2D metals. (a) Schematic of vdW squeezing process. (b) Optical microscope images of as-produced 2D metals by vdW squeezing, including Bi, Ga, In, Sn and Pb. (c) Atomic force microscope images of as-produced 2D metals in (b). The height profiles are superimposed on each individual image. Adapted with permission from Ref. [19].

3. Top-down strategy

Mechanical exfoliation Mechanical exfoliation from bulk crystals has proven to be an extremely effective method and plays a pioneering role in the production of high-quality 2D materials at the atomically thin limit. With the advancement of research, the top-down exfoliation approach has been improved accordingly to isolate a greater variety of 2D materials with larger lateral dimensions. For example, introducing a mediation layer (e.g., Al_2O_3 and Au) to enhance adhesion of the substrate with the target crystal can facilitate more efficient exfoliation.[38–40] Notably, Jiang *et al*. have recently refined the mechanical exfoliation by involving a calendaring pretreatment to drive lateral sliding between close-packed planes (Fig. 3(a)). The lateral sliding shifts the positions of atoms from the most stabilized 'groove' site and transforms the structure from a stable to a metastable phase. This largely

weakens the interlayer binding and reduces the exfoliation energy, making the mechanical exfoliation of non-layered 2D metals feasible. Indeed, the scotch tape mechanical exfoliation of the bulk counterpart after lateral sliding successfully produces two 2D metals, i.e., Bi of ∼ 1.3 nm and Sb of ∼ 1.2 nm (Fig. 3(b)).[18] In addition, we would like to point out that further work is needed to improve mechanical exfoliation of 2D metals as the currently obtained 2D metals have not yet reached the monolayer limit and lateral size is relatively small (in the order of a few microns).

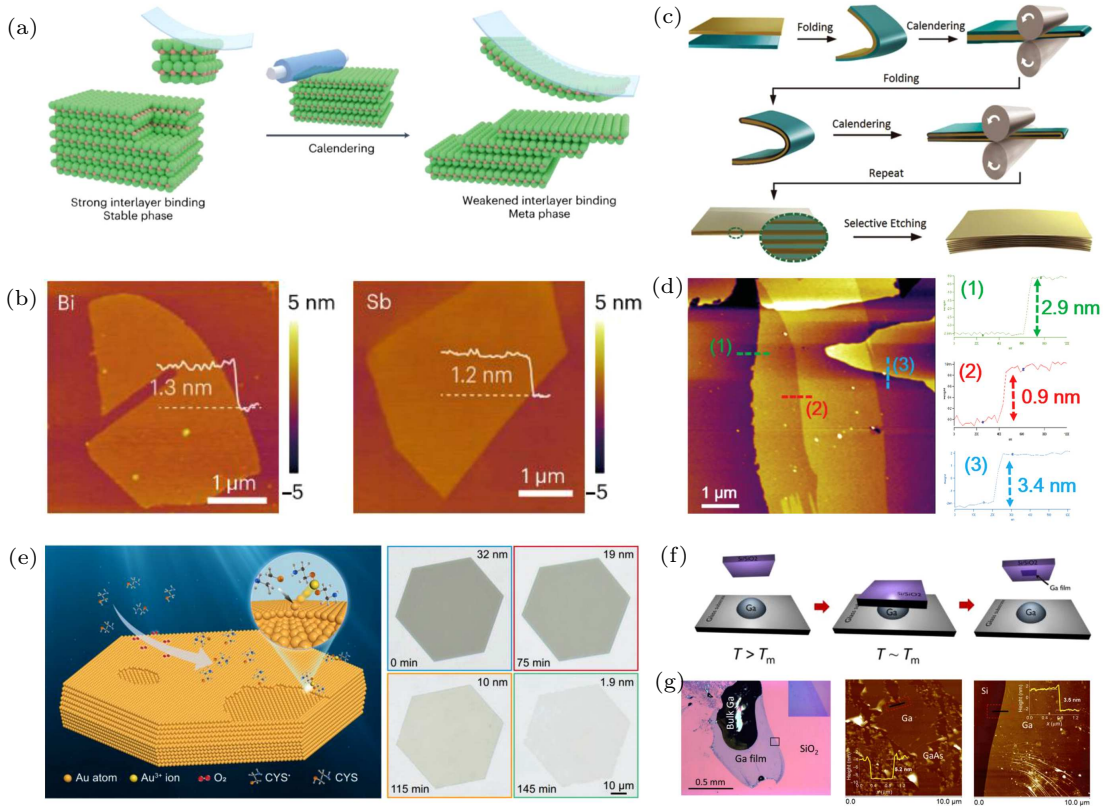


Fig. 3. Some 2D metals prepared by top-down methods. (a) Schematic of mechanical exfoliation by involving a calendaring pretreatment to drive lateral sliding. (b) AFM images of Sb and Bi films by mechanical exfoliation. (c) Schematic of the fabrication of 2D metals by repeated mechanical rolling. (d) AFM image of 2D Ag prepared by mechanical pressing with thicknesses of 2.9 nm, 0.9 nm, and 3.4 nm. (e) Left: schematic illustration of the atomic-level precision etching approach. Right: Optical transmission micrographs of a gold film thinned down by chemical etching. (f) Illustration of the solid-melt exfoliation process. (g) Left: optical image of exfoliated Ga films on SiO_2 substrate. Right: AFM images of Ga film exfoliated on GaAs and Si substrates. Adapted with permission from: (a), (b) Ref. [18]; (c), (d) Ref. [41]; (e) Ref. [44]; (f), (g) Ref. [45].

Mechanical pressing Given metals generally exhibit superb ductility and malleability, mechanical pressing is expected to offer a possible route to thin down bulk metals and achieve 2D metal films. Indeed, repeated mechanical rolling and hot-pressing methods have been developed to produce 2D metals with thickness thinned down to a few nanometers (although not yet reaching the monolayer limit), and sizes of the order of micrometers.[41–43] Figure 3(c) illustrates the fabrication of 2D metals by repeated mechanical rolling.[41] The fabrication begins from stacked heterogeneous metal sheets (e.g., Al/Ag binary metal plates). By repeated folding and calendering (RFC) process with a rolling machine (e.g., 20 times), multilayered metallic plates with heterogeneous metals stacked alternately are obtained. Concurrently, the thickness of each heterogeneous metal layer is significantly reduced to a few nanometers. Finally, 2D metals can be prepared by selective chemical etching of the sacrificial metals. For example, 2D Ag can be prepared by dissolving the Al from Al/Ag multilayered structure in alkaline solutions (Fig. 3(d)). The repeated RFC can also offer a general strategy to fabricate other 2D metals, such as Au, Cu, Ni, and Fe. However, it is noteworthy that the 2D metals by repeated RFC are not single crystalline but polycrystalline.[41]

Chemical etching An atomic-level precision chemical etching approach has been developed for fabricating single crystal 2D Au flakes (Fig. 3(e)).[44] Large-area single crystal Au flakes synthesized on a substrate with an atomically smooth surface (e.g., mica) are used as the starting materials. Then, the Au single crystals are immersed into a cysteamine solution to initiate chemical etching. By controlling the etching parameters, the surface Au atoms can be gradually etched in layer-by-layer manner via an oxidation-reduction process, ultimately resulting in the production of 2D Au flakes. The right panel of Fig. 3(e) presents the optical transmission micrographs of the as-produced 2D Au flakes taken at various etching times. The minimum thickness can be as thin as ∼ 1.9 nm and the lateral size can reach dozens of micrometers. It is worth noting that because of the thickness fluctuations of the

initial materials, it is essentially impossible to obtain large-area, sub-nanometer 2D metals with this chemical etching approach. In addition, the chemical etching often leaves etchant residues on the surface of as-synthesized 2D metals, which can compromise the intrinsic physical properties of the 2D metals, especially when the thickness is only one or a few atomic layers.

Solid-melt exfoliation A solid-melt exfoliation approach has been developed for fabricating 2D Ga layers (Fig. 3(f)).[45] The low-melting Ga metal is first heated at a high temperature to achieve uniform melting, and then the temperature is reduced to 30 °C, slightly above the melting point (i.e., ∼ 29.7 °C). At this point, a clean substrate (e.g., Si/SiO_2) is brought into contact with the surface of the Ga droplet. The lower temperature of the substrate will result in the solidification of the surface Ga and thus the formation of a 2D Ga layer, which can be exfoliated onto the substrate. Although the size of the as-produced 2D Ga can be hundreds of micrometers, the thickness is far from the atomically thin limit and thicker than 3 nm (Fig. 3(f)).[45] In addition, the solid-melt exfoliation method typically requires the strong chemical interaction of metal with the substrate, preventing the access to the intrinsic physical properties of 2D metals.

4. Bottom-up synthesis

Epitaxial growth Molecular beam epitaxy (MBE) has been employed for growing atomically thin metals for a long time, even before the discovery of monolayer graphene.[46–49] Although these early studies have certainly advanced our understanding of the exotic quantum phenomena of metals with atomically thin thickness, the achieved metals typically feature nanometer-size segmented islands (that is, are not truly 2D metals, Fig. 4(a)) or are strongly bonded to substrates thus preventing the investigation of their intrinsic properties (Fig. 4(b)).[21,25,28,31–33,50–53] Consequently, the short review here does not focus on the MBE growth.

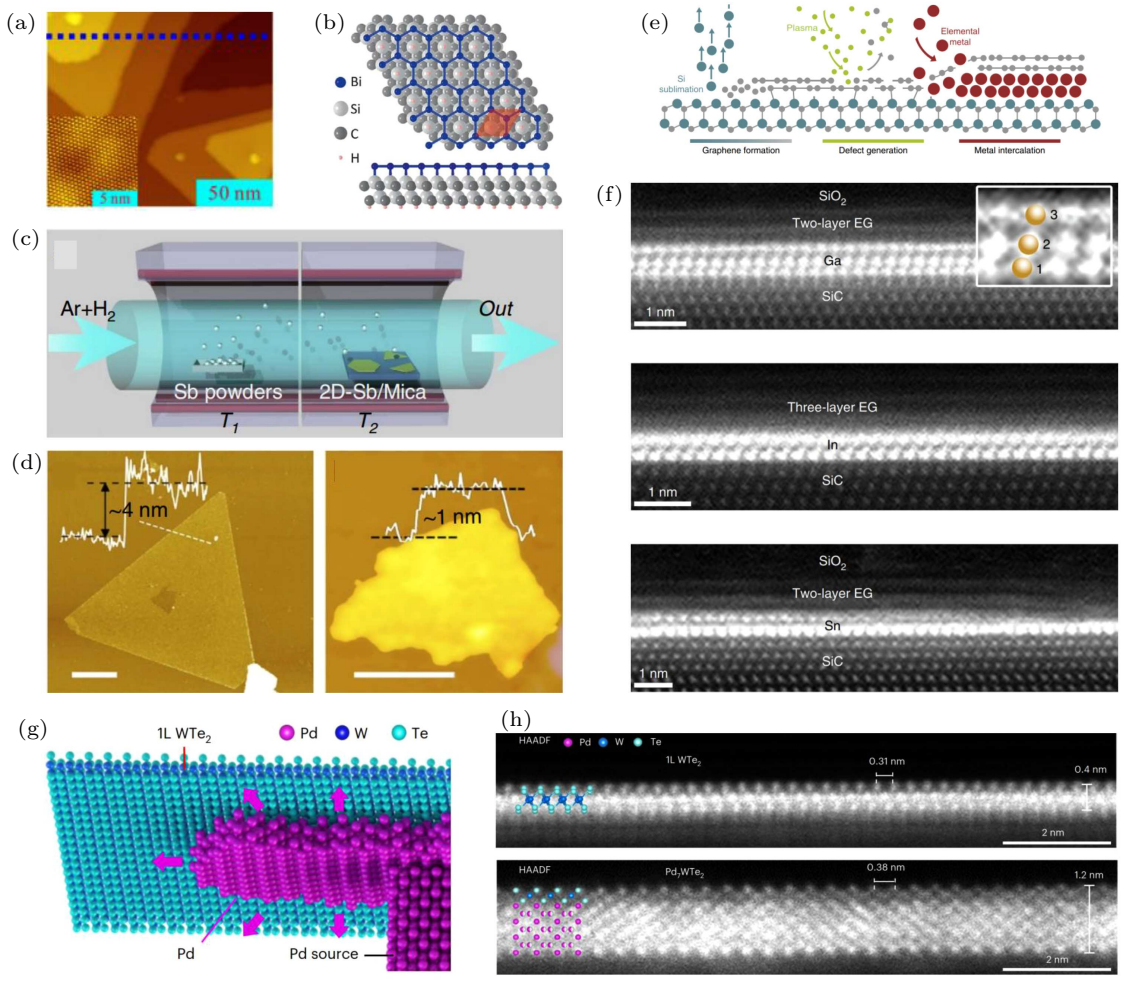


Fig. 4. Some 2D metals grown by bottom-up methods. (a) STM image of β-phase Bi films on $NbSe_2$. (b) In-plane (upper) and cross-sectional views (lower) of monolayer Bi on SiC substrate. Monolayer Bi is strongly bonded to substrates. (c) Schematic illustration of the VPD synthesis configurations. (d) AFM images of 2D Sb films on mica substrate. The scale bars in left and right panels are 1 μm and 50 nm, respectively. (e) Schematic illustration of confinement growth showing graphene growth, plasma treatment and intercalation steps. (f) Cross-sectional view TEM images of Ga, In and Sn films confined between graphene and SiC substrate. (g) Cartoon illustration of the surface-nanoconfined growth of 2D metals. (h) Cross-sectional view TEM images of monolayer WTe_2 (upper) and crystalline 2D Pd synthesized. Adapted with permission from: (a) Ref. [52]; (b) Ref. [32]; (c), (d) Ref. [59]; (e), (f) Ref. [26]; (g), (h) Ref. [62].

Vapor-phase deposition (VPD) has been proven as a facile technique in synthesizing 2D materials and their heterostructures.[9,54–58] Ji *et al*. have demonstrated the vdW epitaxy growth of few-layer Sb crystals on fluorophlogopite mica substrates by VPD method.[59] Figure 4(c) schematically illustrates the VPD process. Commercial Sb powder placed in the source zone is vaporized via heating. The evaporated Sb is transported downstream through the carrier gas, deposited onto the mica substrate and finally grows into 2D Sb. The typical 2D Sb features a thickness down to $\sim$ 4 nm, and a lateral size around 5–10 μm (left panel, Fig. 4(d)). Very tiny samples can be as thin as $\sim$ 1 nm, but only $\sim$ 100 nm in size (right panel, Fig. 4(d)).[59] In the future, further investigations are required to elucidate whether the VPD method can facilitate the synthesis of other 2D metals and whether thicknesses can be pushed to the monolayer limit.

Confinement growth A free-standing metal monolayer, in principle, is thermodynamically unstable, and environmental confinements are typically required to stabilize a 2D metal structure. Consequently, confinement growth offers a possible route for 2D metal preparation. Previous studies have widely demonstrated that metal atoms can intercalate into the interfaces between a 2D vdW layered material and its growth substrate through defects.[60,61] By defect engineering of the epitaxially grown graphene on silicon carbide (SiC) substrate, the increased intercalation sites facilitate the vaporized metal precursors' adhesion and transport to the graphene/SiC interface (Fig. 4(e)).[26] Notably, large-area, environmentally stable, single-crystal 2D metals such as Ga, Sn and In that are one to three atomic layers thick are realized (Fig. 4(f)). We highlight that the encapsulating layer graphene protects the as-produced 2D metals from environmental degradation, which greatly facilitates ex-situ characterization and enables facile processing and device fabrication. In addition, it is noteworthy that the 2D metals present a non-bonded vdW interface to the graphene overlayer, but are covalently bonded to the SiC substrate below. In other words, as-produced 2D metals are only 'half-vdW' metals, rather than highly sought-after 'all-vdW' metals, hindering the access to truly intrinsic properties.[26]

Surface-nanoconfined growth Recently, Jia *et al*. uncover a surface-nanoconfined growth method for preparing 2D metals, as illustrated in Fig. 4(g).[62] Predeposited Pd source above/underneath crystalline monolayer WTe_2 undergoes a rapid, long-distance, non-Fickian transport when the temperature exceeds a certain value ($\sim$ 190 °C), resulting in the formation of a uniform atomically thin 2D Pd layer on monolayer WTe_2. Surprisingly, the critical temperature is far below the melting point of Pd ($\sim$ 1550 °C). The as-produced 2D Pd has seven atomic layers and is $\sim$ 0.8 nm in thickness (Fig. 4(h)).[62] The surface-nanoconfined growth method is very surprising, as the metal source can achieve fast, non-Fickian mass transport at a temperature much lower than the melting point. In addition, highly uniform thickness is also astonishing. Although the authors have tried to provide some possible explanations (for example, the authors suspect that the surface layer of Pd that directly contacts with WTe_2 might melt and form an atomically thin 2D liquid metal), further experiments and theories are needed to elucidate the underlying physical mechanisms of this novel growth method. Meanwhile, we are also curious about whether this surface-nanoconfined method can achieve 2D metals of only one atomic-layer thick.

5. Conclusions and perspectives

Because 2D materials are one of the highly sought-after goals in condensed-matter physics and provide a wide range of possibilities for the exploration of completely new physics and device architectures, researchers have been dedicated to their scalable synthesis, despite significant challenges. Substantial developments and progresses on producing atomically thin 2D metals have been witnessed over the past few years. In this review, we highlight the recent advances in the reliable production of atomically thin 2D metals, including but not limited to vdW squeezing technique, top-down exfoliation, mechanical pressing, chemical etching, epitaxial growth, and confinement growth. Among these, we believe that vdW squeezing stands out and represents a breakthrough in the field of 2D metals, because it produces, for the first time, large-scale, truly 'all-vdW' 2D metals.

Undoubtedly, this is just the beginning of 2D metal field, and there are plenty of new opportunities and emerging technological applications to be eagerly awaited. First, the currently as-produced 2D metals are very limited. For example, only five 2D metals with low melting points have been prepared by the vdW squeezing method. Consequently, one intriguing research direction is to develop new design paradigms and manufacturing technologies under extreme conditions such as high temperature and pressure and to break through the current bottleneck, achieving a greater variety, larger size, and controllable phase structure of 2D metals, and expanding the research boundaries of 2D metals. Second, the physical properties of 2D metals are a 'new frontier' but have not yet been explored. Consequently, another future research frontier is to develop advanced transport and spectroscopy methods, and combine with external degrees of freedom engineering to explore the unique properties of 2D metals, underpinning emerging quantum states of matter, addressing important fundamental problems in condensed-matter physics and materials science, and initiating original breakthroughs 'from 0 to 1'. Last but not least, 2D metals, by integrating with other systems

(e.g., optical cavities, resonances, silicon-based waveguides, and fibers), will undoubtedly outline a bright vision for numerous emerging electronic, photonic and optoelectronic applications.

Acknowledgements

This work is supported by the Strategic Priority Research Program of Chinese Academy of Sciences (CAS) (Grant No. XDB0470101), the National Natural Science Foundation of China (Grant Nos. 12422402, 62488201, 12274447, 62204166, and 52325201), and the National Key Research and Development Program of China (Grant Nos. 2021YFA1202900 and 2023YFA1407000).

References

[1] Novoselov K S, Geim A K, Morozov S V, Jiang D, Zhang Y, Dubonos S V, Grigorieva I V and Firsov A A 2004 *Science* **306** 666
[2] Geim A K and Grigorieva I V 2013 *Nature* **499** 419
[3] Novoselov K S, Mishchenko A, Carvalho A and Castro Neto A H 2016 *Science* **353** aac9439
[4] Du L, Molas M R, Huang Z, Zhang G, Wang F and Sun Z 2023 *Science* **379** eadg0014
[5] Du L, Hasan T, Castellanos-Gomez A, Liu G B, Yao Y, Lau C N and Sun Z 2021 *Nat. Rev. Phys.* **3** 193
[6] Du L, Huang Z, Zhang J, Ye F, Dai Q, Deng H, Zhang G and Sun Z 2024 *Nat. Mater.* **23** 1179
[7] Du L, Huang Y, Wang Y, Wang Q, Yang R, Tang J, Liao M, Shi D, Shi Y, Zhou X, Zhang Q and Zhang G 2019 *2D Mater.* **6** 015014
[8] Yu Y, Ma L, Cai P, Zhong R, Ye C, Shen J, Gu G D, Chen X H and Zhang Y 2019 *Nature* **575** 156
[9] Liu C, Liu T, Zhang Z, Sun Z, Zhang G, Wang E and Liu K 2024 *Nat. Nanotechnol.* **19** 907
[10] Huang B, Clark G, Navarro-Moratalla E, Klein D R, Cheng R, Seyler K L, Zhong D, Schmidgall E, McGuire M A, Cobden D H, Yao W, Xiao D, Jarillo-Herrero P and Xu X 2017 *Nature* **546** 270
[11] Radisavljevic B, Radenovic A, Brivio J, Giacometti V and Kis A 2011 *Nat. Nanotechnol.* **6** 147
[12] Li L, Yu Y, Ye G J, Ge Q, Ou X, Wu H, Feng D, Chen X H and Zhang Y 2014 *Nat. Nanotechnol.* **9** 372
[13] Cao Y, Fatemi V, Demir A, Fang S, Tomarken S L, Luo J Y, Sanchez-Yamagishi J D, Watanabe K, Taniguchi T, Kaxiras E, Ashoori R C and Jarillo-Herrero P 2018 *Nature* **556** 80
[14] Puthirath Balan A, Radhakrishnan S, Woellner C F, Sinha S K, Deng L, Reyes C d l, Rao B M, Paulose M, Neupane R, Apte A, Kochat V, Vajtai R, Harutyunyan A R, Chu C W, Costin G, Galvao D S, Martí A A, van Aken P A, Varghese O K, Tiwary C S, Malie Madom Ramaswamy Iyer A and Ajayan P M 2018 *Nat. Nanotechnol.* **13** 602
[15] Zhao X, Song P, Wang C, Riis-Jensen A C, Fu W, Deng Y, Wan D, Kang L, Ning S, Dan J, Venkatesan T, Liu Z, Zhou W, Thygesen K S, Luo X, Pennycook S J and Loh K P 2020 *Nature* **581** 171
[16] Zhang P, Wang X, Jiang H, Zhang Y, He Q, Si K, Li B, Zhao F, Cui A, Wei Y, Liu L, Que H, Tang P, Hu Z, Zhou W, Wu K and Gong Y 2022 *Nat. Synth.* **1** 864
[17] Wu H, Zhang W, Yang L, Wang J, Li J, Li L, Gao Y, Zhang L, Du J, Shu H and Chang H 2021 *Nat. Commun.* **12** 5688
[18] Jiang K, Ji J, Gong W, Ding L, Li J, Li P, Li B and Geng F 2023 *Nat. Synth.* **2** 58
[19] Zhao J, Li L, Li P, Dai L, Dong J, Zhou L, Wang Y, Zhang P, Ji K, Zhang Y, Yu H, Wei Z, Li J, Li X, Huang Z, Wang B, Liu J, Chen Y, Zhang X, Wang S, Li N, Yang W, Shi D, Pan J, Du S, Du L and Zhang G 2025 *Nature* **639** 354
[20] Chen Y, Fan Z, Zhang Z, Niu W, Li C, Yang N, Chen B and Zhang H 2018 *Chem. Rev.* **118** 6409
[21] Xing Y, Zhang H M, Fu H L, Liu H, Sun Y, Peng J P, Wang F, Lin X, Ma X C, Xue Q K, Wang J and Xie X C 2015 *Science* **350** 542
[22] Huang X, Tang S, Mu X, Dai Y, Chen G, Zhou Z, Ruan F, Yang Z and Zheng N 2011 *Nat. Nanotechnol.* **6** 28
[23] Maniyara R A, Rodrigo D, Yu R, Canet-Ferrer J, Ghosh D S, Yongsunthon R, Baker D E, Rezikyan A, García de Abajo F J and Pruneri V 2019 *Nat. Photon.* **13** 328
[24] Zhang T, Cheng P, Li W J, Sun Y J, Wang G, Zhu X G, He K, Wang L, Ma X, Chen X, Wang Y, Liu Y, Lin H Q, Jia J F and Xue Q K 2010 *Nat. Phys.* **6** 104
[25] Jäck B, Xie Y, Li J, Jeon S, Bernevig B A and Yazdani A 2019 *Science* **364** 1255
[26] Briggs N, Bersch B, Wang Y, Jiang J, Koch R J, Nayir N, Wang K, Kolmer M, Ko W, De La Fuente Duran A, Subramanian S, Dong C, Shallenberger J, Fu M, Zou Q, Chuang Y W, Gai Z, Li A P, Bostwick A, Jozwiak C, Chang C Z, Rotenberg E, Zhu J, van Duin A C T, Crespi V and Robinson J A 2020 *Nat. Mater.* **19** 637
[27] Sahu T K, Kumar N, Chahal S, Jana R, Paul S, Mukherjee M, Tavabi A H, Datta A, Dunin-Borkowski R E, Valov I, Nayak A and Kumar P 2023 *Nat. Nanotechnol.* **18** 1430
[28] Gou J, Bai H, Zhang X, Huang Y L, Duan S, Ariando A, Yang S A, Chen L, Lu Y and Wee A T S 2023 *Nature* **617** 67
[29] Steves M A, Wang Y, Briggs N, Zhao T, El-Sherif H, Bersch B M, Subramanian S, Dong C, Bowen T, Fuente Duran A D L, Nisi K, Lassaunière M, Wurstbauer U, Bassim N D, Fonseca J, Robinson J T, Crespi V H, Robinson J and Knappenberger Jr K L 2020 *Nano Lett.* **20** 8312
[30] Xiong Y, McLellan J M, Chen J, Yin Y, Li Z Y and Xia Y 2005 *J. Am. Chem. Soc.* **127** 17118
[31] Zhu F F, Chen W J, Xu Y, Gao C L, Guan D D, Liu C H, Qian D, Zhang S C and Jia J F 2015 *Nat. Mater.* **14** 1020
[32] Reis F, Li G, Dudy L, Bauernfeind M, Glass S, Hanke W, Thomale R, Schäfer J and Claessen R 2017 *Science* **357** 287
[33] Jin K H, Oh E, Stania R, Liu F and Yeom H W 2021 *Nano Lett.* **21** 9468
[34] Chen L, Wu A X, Tulu N, Wang J, Juanson A, Watanabe K, Taniguchi T, Pettes M T, Campbell M A, Xu M, Gadre C A, Zhou Y, Chen H, Cao P, Jauregui L A, Wu R, Pan X and Sanchez-Yamagishi J D 2024 *Nat. Mater.* **23** 741
[35] Sanchez-Yamagishi J 2025 *Nature* **639** 309
[36] Peer review report of "*Realization of 2D metals at the ångström thickness limit*"
[37] Li L, Wang Q, Wu F, Xu Q, Tian J, Huang Z, Wang Q, Zhao X, Zhang Q, Fan Q, Li X, Peng Y, Zhang Y, Ji K, Zhi A, Sun H, Zhu M, Zhu J, Lu N, Lu Y, Wang S, Bai X, Xu Y, Yang W, Li N, Shi D, Xian L, Liu K, Du L and Zhang G 2024 *Nat. Commun.* **15** 1825
[38] Deng Y, Yu Y, Song Y, Zhang J, Wang N Z, Sun Z, Yi Y, Wu Y Z, Wu S, Zhu J, Wang J, Chen X H and Zhang Y 2018 *Nature* **563** 94
[39] Liu F, Wu W, Bai Y, Chae S H, Li Q, Wang J, Hone J and Zhu X Y 2020 *Science* **367** 903
[40] Huang Y, Pan Y H, Yang R, Bao L H, Meng L, Luo H L, Cai Y Q, Liu G D, Zhao W J, Zhou Z, Wu L M, Zhu Z L, Huang M, Liu L W, Liu L, Cheng P, Wu K H, Tian S B, Gu C Z, Shi Y G, Guo Y F, Cheng Z G, Hu J P, Zhao L, Yang G H, Sutter E, Sutter P, Wang Y L, Ji W, Zhou X J and Gao H J 2020 *Nat. Commun.* **11** 2453
[41] Liu H, Tang H, Fang M, Si W, Zhang Q, Huang Z, Gu L, Pan W, Yao J, Nan C and Wu H 2016 *Adv. Mater.* **28** 8170
[42] Huang K, Hou J, Zhang Q, Ou G, Ning D, Hussain N, Xu Y, Ge B, Liu K and Wu H 2017 *Chem. Commun.* **54** 160
[43] Hussain N, Liang T, Zhang Q, Anwar T, Huang Y, Lang J, Huang K and Wu H 2017 *Small* **13** 1701349
[44] Pan C, Tong Y, Qian H, Krasavin A V, Li J, Zhu J, Zhang Y, Cui B, Li Z, Wu C, Liu L, Li L, Guo X, Zayats A V, Tong L and Wang P 2024 *Nat. Commun.* **15** 2840
[45] Kochat V, Samanta A, Zhang Y, Bhowmick S, Manimunda P, Asif S A S, Stender A S, Vajtai R, Singh A K, Tiwary C S and Ajayan P M 2018 *Sci. Adv.* **4** e1701373
[46] Ford W K, Guo T, Lessor D L and Duke C B 1990 *Phys. Rev. B* **42** 8952
[47] Nagao T, Doi T, Sekiguchi T and Hasegawa S 2000 *Jpn. J. Appl. Phys.* **39** 4567

[48] Ernst K H, Ludviksson A, Zhang R, Yoshihara J and Campbell C T 1993 *Phys. Rev. B* **47** 13782
[49] Qian D, Jin X F, Barthel J, Klaua M and Kirschner J 2001 *Phys. Rev. Lett.* **87** 227204
[50] Shao Y, Liu Z L, Cheng C, Wu X, Liu H, Liu C, Wang J O, Zhu S Y, Wang Y Q, Shi D X, Ibrahim K, Sun J T, Wang Y L and Gao H J 2018 *Nano Lett.* **18** 2133
[51] Fang A, Adamo C, Jia S, Cava R J, Wu S C, Felser C and Kapitulnik A 2018 *Sci. Adv.* **4** eaaq0330
[52] Sun H H, Wang M X, Zhu F, Wang G Y, Ma H Y, Xu Z A, Liao Q, Lu Y, Gao C L, Li Y Y, Liu C, Qian D, Guan D and Jia J F 2017 *Nano Lett.* **17** 3035
[53] Li L, Wang Y, Xie S, Li X B, Wang Y Q, Wu R, Sun H, Zhang S and Gao H J 2013 *Nano Lett.* **13** 4671
[54] Zhang T, Wang J, Wu P, Lu A Y and Kong J 2023 *Nat. Rev. Mater.* **8** 799
[55] Wang Q, Tang J, Li X, Tian J, Liang J, Li N, Ji D, Xian L, Guo Y, Li L, Zhang Q, Chu Y, Wei Z, Zhao Y, Du L, Yu H, Bai X, Gu L, Liu K, Yang W, Yang R, Shi D and Zhang G 2022 *Natl Sci. Rev.* **9** nwac077
[56] Qin B, Ma C, Guo Q, Li X, Wei W, Ma C, Wang Q, Liu F, Zhao M, Xue G, Qi J, Wu M, Hong H, Du L, Zhao Q, Gao P, Wang X, Wang E, Zhang G, Liu C and Liu K 2024 *Science* **385** 99
[57] Yang P, Wang D, Zhao X, Quan W, Jiang Q, Li X, Tang B, Hu J, Zhu L, Pan S, Shi Y, Huan Y, Cui F, Qiao S, Chen Q, Liu Z, Zou X and Zhang Y 2022 *Nat. Commun.* **13** 3238
[58] Li J, Yang X, Zhang Z, Yang W, Duan X and Duan X 2024 *Nat. Mater.* **23** 1326
[59] Ji J, Song X, Liu J, Yan Z, Huo C, Zhang S, Su M, Liao L, Wang W, Ni Z, Hao Y and Zeng H 2016 *Nat. Commun.* **7** 13352
[60] Huang L, Pan Y, Pan L, Gao M, Xu W, Que Y, Zhou H, Wang Y, Du S and Gao H J 2011 *Appl. Phys. Lett.* **99** 163107
[61] Calleja F, Ochoa H, Garnica M, Barja S, Navarro J J, Black A, Otrokov M M, Chulkov E V, Arnau A, Vázquez de Parga A L, Guinea F and Miranda R 2015 *Nat. Phys.* **11** 43
[62] Jia Y, Yuan F, Cheng G, Tang Y, Yu G, Song T, Wang P, Singha R, Uzan-Narovlansky A J, Onyszczak M, Watanabe K, Taniguchi T, Yao N, Schoop L M and Wu S 2024 *Nat. Synth.* **3** 386