

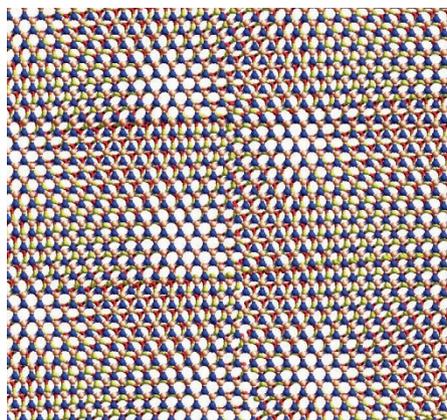
As thin as it gets

As the family of 2D materials expands to include transition metal dichalcogenides and Xenes, novel fundamental properties and applications come to light.

Graphene¹ is arguably the most famous material of the last decade; the fascination with its properties has spread beyond the scientific community, especially since the Nobel Prize was awarded in 2010 for its isolation. While research on graphene itself is still extremely active, one cannot overlook the trigger it constituted for the pursuit of atomically thin forms of other materials, such as semiconductors, boron nitride and, more recently, Xenes. All these 2D materials offer endless possibilities for fundamental research, as well as the demonstration of improved or even entirely novel technologies.

Transition metal dichalcogenides (TMDs) are atomically thin semiconductors of the type MX_2 , where a transition metal atom ($M = \text{Mo}, \text{W}, \text{Se}$ and so on) is sandwiched between two chalcogen atoms ($X = \text{S}, \text{Se}, \text{Te}$ and so on)^{2,3}. TMDs offer something that graphene doesn't have: a bandgap, which makes them immediately suitable candidates for semiconductor-based electronics and optoelectronics applications — even at room temperature. Additionally, the excitonic transitions in the $\pm K$ valleys (the local minimum and maximum in the conduction and valence band, respectively) can be selectively addressed with circularly polarized light, which has subsequently opened the door to the pursuit of valleytronic devices⁴, where the valley degree of freedom is used to carry information.

2D materials have a lot to offer in terms of optoelectronics applications, and in a wide range of wavelengths — from the microwave to the visible. Tony Low, Frank Koppens and colleagues review the field of polaritonics in layered 2D materials on page 182 of this issue. Graphene provides a solid alternative to metal plasmonics, due to the combination of high intrinsic mobilities (manifested when encapsulated in hexagonal boron nitride) with tunable carrier density (and therefore wavelength range). However, TMDs (in particular MoS_2) can exhibit much larger light confinement — about an order of magnitude higher than graphene. Hexagonal boron nitride (h-BN) is also a lot more than an ideal dielectric; its in-plane anisotropy renders it naturally hyperbolic (the principal components of the dielectric tensor have opposite signs). Hyperbolic phonon-polaritons do not suffer from losses and, although their lifetimes in multi-layered h-BN



A van der Waals heterostructure comprising two different 2D materials that are rotationally offset to generate a moiré pattern.

are comparable to those of optical phonons, the slow group velocity limits the overall propagation length. Theoretical investigations indicate that other 2D materials should also exhibit similar hyperbolic properties.

Excitonic effects are also well pronounced in layered materials. Exciton binding energies are about an order of magnitude higher than those of bulk semiconductors, such as Si, Ge and III–V or II–VI alloys, which allows for the direct observation of trions and biexcitons that are hard to see in bulk semiconductors. Exciton-polaritons have been recently observed in 2D materials inserted in microcavities^{5,6}, although polariton condensation is still elusive.

The latest group of 2D materials to be taking the stage are the so-called Xenes, where atoms from the group IVA elements are organized into a single layered, honeycomb-like lattice. Contrary to flat graphene, they suffer from inherent buckling, which has a profound effect on their properties. Silicene and germanene were the first ones to be epitaxially and chemically synthesized, given their extremely relevant technological potential. Stanene, and, very recently, borophene and phosphorene followed. The realization of transistors with remarkable properties based on phosphorene⁷ and silicene⁸ was big news recently. On page 163 of this issue, Alessandro Molle, Deji Akinwande and collaborators offer a critical overview of the issues that remain open (such as their

stability) and the theoretical studies predicting topological properties. Xenes, sharing the same Dirac physics with graphene, could exhibit topological insulator states, which should in principle enable the observation of the quantum spin Hall effect at room temperature and allow the development of topological field-effect transistors.

A unique characteristic of 2D materials, however, is the possibility to easily form horizontal or vertical van der Waals heterostructures (pictured), following the stacking of layers of different materials and thicknesses. Functionalities like diodes⁹ and field-effect transistors¹⁰ have triggered a lot of enthusiasm. However, the production of high-quality heterostructures over a large scale, which will be necessary for real-world applications, remains a serious technological issue.

Van der Waals heterostructures are not only limited to combinations of 2D materials. Deep Jariwala, Tobin Marks and Mark Hersam explain in their Review on page 170 that 2D materials can be combined with non-2D materials that adhere primarily through non-covalent interactions. Interfacing 2D materials with organic molecules and quantum dots (0D), carbon nanotubes (1D) and bulk Si, Ge, III–V and II–VI semiconductors (3D) can find applications in logic devices, photodetectors, photovoltaics and light-emitters. Clearly, while such an approach is free from the restriction of lattice match between the layers, the different combinations face distinct problems in fabrication and assembly.

Despite its young age, the field of 2D materials has advanced significantly in the last few years. And we are certainly far from the end of the road. As all the knowledge and experience gained from decades of studying bulk materials is poured into understanding and manipulating the monolayers, there is little reason to believe this storm will calm down any time soon. The game is most certainly on. □

References

1. *Nat. Nanotech.* **5**, 755 (2010).
2. *Nat. Mater.* **13**, 1073 (2014).
3. *Nat. Nanotech.* **7**, 683 (2012).
4. Schäibley, J. R. *et al. Nat. Rev. Mater.* **1**, 16055 (2016).
5. Liu, X. *et al. Nat. Photon.* **9**, 30–34 (2015).
6. Dufferwiel, S. *et al. Nat. Commun.* **6**, 8579 (2015).
7. Li, L. *et al. Nat. Nanotech.* **9**, 372–377 (2014).
8. Tao, L. *et al. Nat. Nanotech.* **10**, 227–231 (2015).
9. Withers, F. *et al. Nat. Mater.* **14**, 301–306 (2015).
10. Georgiou, T. *et al. Nat. Nanotech.* **8**, 100–103 (2013).