

Chalcogenides fill the gap

Two-dimensional semiconductors such as transition metal dichalcogenides can complement graphene in applications where a sizeable natural energy bandgap is required. Recent studies aim at bringing these materials to a higher level of maturity.

Graphene, a “rising star on the horizon of materials science” in the words of Andre Geim and Kostya Novoselov¹, is moving closer to deliver on some of its envisioned applications on an industrial scale². However, its applicability for high-performing electronic switches and other optoelectronic devices is challenged by the absence of a natural energy bandgap. This is where alternative 2D materials such as transition metal dichalcogenides (TMDs), which have a sizeable bandgap³, can help. Four research articles in this issue exemplify recent progress in controlling the synthesis of TMDs and in understanding their fundamental properties, and suggest that these 2D semiconductors could be used to fill the gap in applications left by graphene.

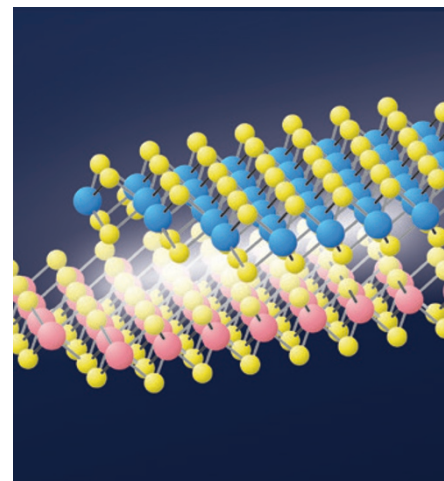
For example, single TMD layers achieve bright emission^{4,5} and good switching behaviour⁶, and are now being extensively studied for optoelectronic applications. However, detailed understanding of their optical and electronic behaviour lags behind their use in devices, and only now the effects of charge-carrier confinement in these 2D structures are being quantified. As now shown by a team led by Michael Crommie on page 1091, strong Coulomb interactions between the charges confined in a single layer of MoSe₂ enable the creation of excitons — bound electron-hole pairs — with a binding energy that is orders of magnitude higher than that of the excitons in conventional bulk semiconductors. The researchers have also observed that such binding energy — relevant for the efficiency of photodetectors, solar cells and light-emitting devices — is affected by screening effects of the surrounding environment, and that its value significantly changes when the TMD is deposited on graphite or on a graphene bilayer.

In addition to understanding the behaviour of single layers, gaining insight into the interaction between vertically stacked layers of different 2D materials is key for the development of van der Waals heterostructures³ — the assembly of multilayers of TMDs, graphene, boron nitride and other 2D systems, bound together by weak van der Waals forces. In a News & Views article on page 1075, Georg Duesberg discusses the technological implications of atomically thin heterojunctions created by

putting into contact 2D semiconductors with different bandgap energies. Although similar architectures have already been realized by mechanically transferring one monolayer on top of another, this approach does not result in a perfect crystallographic alignment between the layers, a condition that was predicted to allow for light emission from the recombination of an electron and a hole localized on different layers⁷. Now, Pulickel Ajayan, Wu Zhou and collaborators report on page 1135 that chemical vapour deposition can be used to realize vertically stacked heterostructures with WS₂ and MoS₂ monolayers in a single growth step, ensuring the same orientation between the two TMDs. They observe luminescence from interlayer electron-hole recombination, which confirms the improved quality of the deposition process.

These researchers also show that this growth method allows the synthesis of in-plane heterostructures by varying the atomic composition of TMDs within the same monolayer. Similar results are reported by Sanfeng Wu, Ana Sanchez and co-workers on page 1096 and also by a collaboration led by Xiangfeng Duan in *Nature Nanotechnology*⁸; both teams demonstrated the formation of seamless lateral heterojunctions between different TMD materials. Initial electronic characterizations revealed preferential charge transport through the junctions in one direction, a rectifying behaviour that is typical of electronic diodes and that, as Duesberg notes, suggests the possibility to incorporate device functionalities in one-layer-thick systems at the growth stage.

Whereas improved synthesis is essential for boosting the intrinsic quality of 2D semiconductors, good interfacing with external metallic contacts is also necessary to achieve improved performance in devices. Debdeep Jena, Kaustav Banerjee and Grace Huili Xing argue in a News & Views article on page 1076 that carrying out heavy doping of the semiconducting material at the contact region — a strategy to lower contact resistance that is well established for 3D semiconductors — is just beginning to be harnessed effectively for TMD materials. An alternative approach that makes use of the intrinsic metallic behaviour of a



Controlled growth of a WS₂ monolayer on top of a MoS₂ monolayer leads to unusual optoelectronic properties.

metastable phase of MoS₂ is demonstrated by Aditya Mohite, Manish Chhowalla and co-workers on page 1128. They locally modified by chemical means the arrangement of S atoms in the crystalline structure of a few layers of semiconducting MoS₂, and then deposited metallic contacts on these converted regions. This decreased the energy barrier between the external circuit and the semiconducting MoS₂ flakes, a marked improvement towards the theoretical minimum contact resistance value of TMDs.

Research on 2D TMDs is still in its infancy, and a set of challenges related to their distinctive structural and optoelectronic properties would have to be addressed. As the research articles and News & Views pieces included in this issue indicate, progress in this field benefits from the knowhow acquired for graphene over the last ten years, and is likely to close the technological gap left by graphene soon. □

References

1. Geim, A. K. & Novoselov, K. S. *Nature Mater.* **6**, 183–191 (2007).
2. <http://www.nature.com/nnano/focus/graphene-applications/index.html>
3. Geim, A. K. & Grigorieva, I. V. *Nature* **499**, 419–425 (2013).
4. Mak, K. F. *et al. Phys. Rev. Lett.* **105**, 136805 (2010).
5. Splendiani, A. *et al. Nano Lett.* **10**, 1271–1275 (2010).
6. Fiori, G. *et al. Nature Nanotech.* **9**, 768–779 (2014).
7. Kosmider, K. & Fernandez-Rossier, J. *Phys. Rev. B* **87**, 075451 (2013).
8. Duan, X. *et al. Nature Nanotech.* <http://dx.doi.org/10.1038/nnano.2014.222> (2014).