News & views

Materials science

Heat management with a twist

Mariusz Zdrojek

The misalignment of crystal lattices in stacked monolayers of materials has been shown to prevent heat flow between the layers, while retaining flow within them. This finding opens up an inventive way to control heat at the nanoscale. **See p.660**

Any electrical device will eventually break if it overheats. Heat management is therefore a constant challenge in the design of electrical systems – especially if the miniaturization of electronic devices is to continue, because the downsizing of electronic components results in greater amounts of heat being generated per unit volume of a device. On page 660, Kim *et al.*[1] report findings that might enable heat management to be achieved in dense electronic circuitry by means of highly directional heat dissipation. The trick is to use materials that consist of stacked, atomically thin layers.

The layers in question are 2D crystalline materials, such as graphene or molybdenum disulfide (MoS_2), that interact with each other through weak van der Waals forces when stacked. The resulting stacks have exceptional electronic properties (they can be semiconductors, metals or even superconductors) and optical features (they can be transparent or reflective to electromagnetic radiation). They also have excellent thermal conductivity[2], which is a measure of how fast a material can dissipate heat. Notably, these layered materials transfer heat slightly more efficiently along the plane of the 2D layers than in the third dimension[3,4] – a phenomenon called anisotropic thermal conductivity.

Kim *et al.* demonstrate a remarkable way to amplify this effect in MoS_2 films, simply by ensuring that the lattices of adjacent 2D layers are rotated with respect to each other (Fig. 1). Previously, the highest-recorded thermal anisotropy factor (the ratio of thermal conductivities measured in different directions) through artificially structured materials, including those consisting of stacked 2D sheets, barely exceeded 20. Kim *et al.* observe a ratio of up to about 880 in twisted MoS_2. This is one of the highest ratios ever reported and is much higher than that of graphite[3] (about 340), one of the best-known anisotropic thermal conductors. Moreover, the anisotropic thermal conductivity of twisted MoS_2 occurs at room temperature.

Large differences in heat-transfer capacity in different directions through layered materials are to be expected, mainly because the strength and character of atomic interactions in the planes of each layer are different from those along the out-of-plane axis. However, the extent to which the directionality of thermal conductivity can be controlled in a solid-state system was unknown. Remarkably, Kim and colleagues have introduced and experimentally validated a simple strategy for promoting directional heat transport in layered materials, providing unprecedented spatial control of the heat that can be routed along a desired direction in the material.

The sizeable anisotropy of thermal conductivity in MoS_2 films can be explained by considering the behaviour of phonons – the quanta of crystal-lattice vibrations, and the main heat carriers in crystals. When adjacent monolayers of MoS_2 are stacked so that their lattices are aligned, the overall arrangement is similar to that of the ordered lattice of a bulk crystal. Phonons therefore flow easily in all directions, but most efficiently within layers.

However, when the lattices are rotated with respect to each other, structural disorder is introduced, breaking the symmetry of the system in the out-of-plane direction. Phonon propagation and associated heat transfer in that direction are strongly suppressed, similar to the case for non-crystalline amorphous solids. Because the rotation does not affect long-range in-plane crystallinity in each layer, phonon-assisted thermal conductivity is maintained at a high level in that direction. Having the ability to maintain thermal conductivity in one direction, while lowering it in another, is key to obtaining the large thermal anisotropy in this system.

The sheets of material used in Kim and colleagues' experiments were polycrystalline – they contained relatively small, randomly oriented crystal grains. These helped to ensure that there were random lattice rotations between sheets across every interface

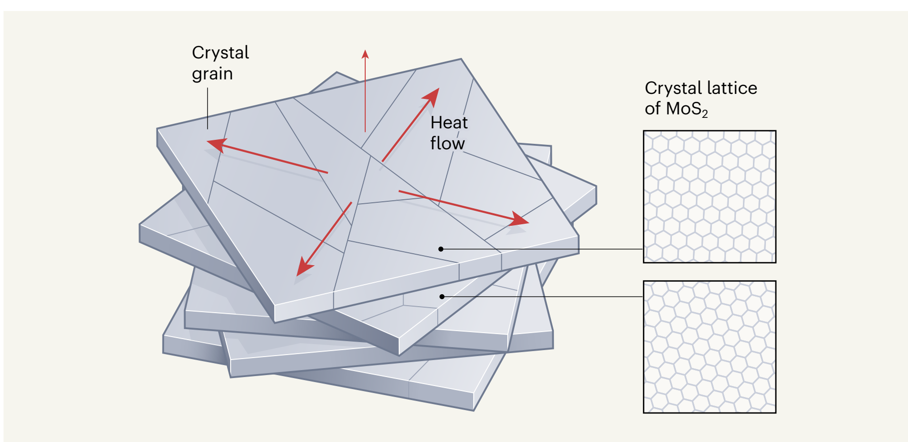

Figure 1 | Directional heat flow in layered materials. Kim *et al.*[1] assembled atomically thin layers of molybdenum disulfide (MoS_2) into stacks. Each layer was rotated with respect to the others, and contained micrometre- and sub-micrometre-scale crystal grains in which the crystal lattice of MoS_2 was randomly oriented. The lattices in equivalent sections of adjacent layers were therefore misaligned. The authors observed that heat flow (red arrows) through the layers in the stacks was about 880 times greater than that through the axis of the stacks. This finding opens up opportunities to use stacked materials such as these for heat management in electronic devices.

between the layers (Fig. 1). Future studies should investigate stacked monocrystalline layers, in which each sheet consists of a single 2D lattice. This would enable a better understanding of the relationship between thermal anisotropy and the angle of rotation.

Twisted bilayer graphene, which consists of two stacked sheets of graphene twisted out of lattice alignment, becomes a superconductor[5] at the 'magic' twist angle of 1.1°. Perhaps, in future, an analogous magic angle could be discovered for heat conduction, producing twisted layered systems that behave as superb thermal insulators or periodic heat-flux modulators (systems in which the anisotropic thermal conductivity alters in a regular spatial pattern across the layers). If so, Kim and colleagues' findings could signify the start of a new area of study, analogous to twistronics (the study of how the angle of rotation between layers of vertically stacked 2D structures triggers various electronic phenomena[6]).

Another follow-up to Kim and colleagues' work could be to engineer twisted heterostructures – stacks composed of combinations of 2D materials. These could be used to investigate the limits of the heat-transport directionality that can be achieved by rotating 2D layers. Because there are many combinations of 2D materials that could be tested, it would be helpful to establish a general approach for predicting which twisted heterostructures are most likely to have the best thermal properties, rather than relying on a trial-and-error approach. Nevertheless, on the basis of the current findings, it seems possible that systems containing large crystalline monolayers of 2D materials, such as graphene and hexagonal boron nitride, could reach a thermal anisotropy factor of much greater than 1,000.

Finally, Kim *et al.* demonstrated a potential application of their anisotropic thermal conductors by coating nanoscale gold electrodes with a film of the layered MoS_2 material. The authors observed that the coated electrodes can carry a greater current without breaking than can bare electrodes. They attribute this effect to the remarkable ability of the MoS_2 film to dissipate heat – channelling it in only one desired direction (that is, through the layers of MoS_2), and not to the surface of the coated electrodes. If this idea can be implemented in microchips, it could make a big difference to the number of electronic components that can be incorporated into future devices, such as laptops.

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1. Kim, S. E. *et al. Nature* **597**, 660–665 (2021).
2. Ghosh, S. *et al. Nature Mater.* **9**, 555–558 (2010).
3. Minnich, A. J. *Nanoscale Microscale Thermophys. Eng.* **20**, 1–21 (2016).
4. Jiang, P., Qian, X., Yang, R. & Lindsay, L. *Phys. Rev. Mater.* **2**, 064005 (2018).
5. Cao, Y. *et al. Nature* **556**, 43–50 (2018).
6. Hennighausen, Z. & Kar, S. *Electron. Struct.* **3**, 014004 (2021).

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Ecology

Pollination advantage of rare plants unveiled

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An analysis of plant–pollinator interactions reveals that the presence of abundant plant species favours the pollination of rare species. Such asymmetric facilitation might promote the coexistence of species in diverse plant communities. **See p.688**

Species diversification results from the balance between the formation of new species (speciation) and the loss of existing ones (extinction). The tremendous proliferation of different life forms on Earth can be attributed to both high rates of speciation and low rates of extinction. Flowering plants – a group called angiosperms – are one of the most diverse groups of non-mobile organism. There are approximately 352,000 plant species nearly 90% of which depend, to various extents, on insects and other animals for pollination and seed production[1]. These animal pollinators have been key to the unstoppable diversification of the angiosperms, starting at least 120 million years ago, with pollinators promoting speciation by acting as potent selection agents for a plethora of flower traits[2,3]. Pollinators also aid species persistence by enabling pollen transfer between relatively distant individuals in sparse plant populations[4]. Wei *et al.*[5] report on page 688 that, for plant species that flower at the same time, pollinators mediate interactions that might facilitate species coexistence in diverse plant communities.

Plant species that flower at the same time can compete for flower visits by shared pollinators, resulting in reduced pollination. For example, flowers of one species might be visited less frequently when more-attractive or more-rewarding flowers are produced nearby by other species. Alternatively, limited pollinator availability can result in an overall reduction in flower visitation if flowers of different species open simultaneously and are similarly attractive or rewarding. By contrast, there are situations in which one or more species might benefit by overlapping their flowering time with that of other species. This could be the case when species producing flowers with plentiful nectar attract pollinators that then 'spill over' their visits to neighbouring species that offer comparatively less pollen or nectar, or when multiple species of flowering plant clustered in the same patch attract more pollinators just by flowering together, thereby increasing flower visitation[6,7]. The phenomenon of certain plant species positively affecting the pollination of other plant species, termed pollinator-mediated facilitation, seems to be more common than was previously thought[6,8,9].

Pollinator-mediated facilitation can promote species coexistence in diverse communities, particularly if rare plant species benefit from pollinators being attracted by common 'co-flowering' plants[6,10] that act as pollinator 'magnets'. However, although rare species might profit from such an effect, there are still lingering costs associated with pollinator sharing that might outweigh the benefits. First, the transfer of pollen between plants of a given species might be reduced through pollen losses during intervening visits to flowers of other species, which would result in reduced pollination success. Second, pollen-receiving flower structures called stigmas might become clogged with pollen from other species, hampering the performance of a species' own pollen[11]. Such costs are projected to be high for rare species because shared pollinators are expected to visit more flowers of abundant species than of rare ones during single foraging bouts. However, these costs are reduced if rare plant species specialize in a particular pollinator or pollinator group, by increasing the shape match (morphological fit) between flowers and pollinators, which can improve the effectiveness of pollen transfer[7].

Wei and colleagues explored the benefits and costs of pollinator-mediated interactions in relation to plant abundance through plant–pollinator interactions (which pollinator species visit the flowers of which plant species), flower shape and quantitative patterns of pollen transfer within and between plant species. The authors studied pollination during the