Interlayer excitons and how to trap them

Interlayer excitons trapped within van der Waals heterostructures hold great promise for the design of quantum materials, but investigations into their fundamental properties are crucial for future developments in the field.

Two-dimensional (2D) materials, such as graphene or transition metal dichalcogenides (TMDs), can form heterostructures held together by weak van der Waals (vdW) forces (pictured), endowing scientists with a rich toolbox for engineering their optoelectronic properties. Recently, TMD heterostructures have been used to study interlayer excitons (IXs), pairs of bound electrons and holes each residing in distinct 2D sheets¹. This spatial separation between charges increases exciton lifetimes and creates an electric dipole moment, allowing electrical control of their properties. Moreover, peculiar features are derived from the 2D nature of the TMD layers hosting the IXs, such as enhanced exciton binding energies, enabling the observation of high-temperature Bose–Einstein exciton condensation². Charge carriers in TMDs are characterized by additional degrees of freedom — the valley index and the layer index — that are coupled to their spin and can be controlled by optical excitations^{1,3}. This phenomenon, named spin–valley–layer locking, has previously been shown for intralayer excitons³ and opens potential connections to the larger fields of spintronics and valleytronics.

VdW multilayers may also form moiré patterns — a periodic variation of the alignment between corresponding atoms in adjacent layers — by twisting the sheets by a relative angle and/or combining materials with different lattice constants. Such patterns are expected to modulate the electronic bandgap of TMD heterostructures at the nanoscale, forming an ordered arrangement of energy traps that may affect the propagation of excitons or spatially confine them. IXs localized in these traps (referred to as moiré IXs) are predicted to behave as a superlattice of (possibly interacting) quantum emitters that can be tuned electrically or via local strain to study exotic phases of matter and to design programmable quantum optics components^{1,4}. Evidence for the effect of moiré superlattices on the IX states in TMD heterobilayers has been reported by various groups^{5–8}, but questions remain about their properties, particularly on the role of the trapping potentials arising from moiré patterns or lattice imperfections⁹.

Illustration of atomic moiré patterns in a van der Waals heterostructure. Credit: Science Photo Library/Alamy Stock Photo

This issue of *Nature Materials* presents three studies on the behaviour of trapped interlayer excitons (IXs) and the effect of moiré patterns on the optical properties of TMD heterostructures.

An [Article](#) by Long Yuan and colleagues reports time- and spatially resolved ultrafast measurements of IX population in WS₂/WSe₂ heterobilayers, showing that the distance over which IXs can propagate after excitation depends on the exciton density and the twist angle between the 2D sheets. These results allowed the researchers to extract the depth of the potential wells created by the periodic moiré patterns for different twist angles and investigate how the screening effect generated by repulsive interactions between excitons in the high-density regime can mitigate the influence of the trapping potentials.

The repulsive dipolar interactions between localized IXs are also studied in another [Article](#) by Weijie Li and collaborators, who investigated the optical response of MoSe₂/WSe₂ heterobilayers in the few-exciton regime. They report synchronized spectral jittering of electric-field-tunable sharp photoluminescence peaks, indicating interacting IXs confined within the same potential trap. Moreover, as they increased the excitation power, they observed emission features compatible with the formation of an interlayer biexciton, a quasiparticle formed of two IXs. Although it does not provide a definitive conclusion on the nature of the trapping sites, this study shows the potential of interacting IXs as a possible platform to

obtain quantum optical nonlinearity and for the study of many-body exciton physics.

Further insights into the role of moiré potentials for IX localization are instead offered by another [Article](#), where Mauro Brotons-Gisbert and collaborators report helicity-resolved photoluminescence and magneto-optical measurements of vdW trilayers, composed of a WSe₂ monolayer below a MoSe₂ bilayer. They identify two IX species corresponding to distinct spin–valley–layer configurations, composed of holes confined within the WSe₂ monolayer and electrons localized either in the top or bottom MoSe₂ layer. This approach allows them to investigate different atomic registries of the moiré potentials and demonstrate spin–layer locking for IXs, which represents an extra degree of freedom for the design of quantum states in vdW heterostructures.

While these works reveal intriguing features of IXs trapped within vdW heterostructures, the scientific community still seeks strategies to verify the nature of the trapping sites and understand the role of sample imperfections, as noted by Alexander Tartakovskii in a related [News & Views](#) commenting on the latter two Articles. A combination of experimental methods could be employed to clarify the role of atomic reconstruction, strain and other defects, correlating optical measurements and non-invasive microscopy techniques⁹. Furthermore, researchers might design hybrid nanostructures to amplify the IX emission rate and so be able to exploit moiré IXs for quantum optics applications. Within a field particularly rich in opportunities, science moves at an impressive pace and it seems that many of these obstacles may be overcome soon. The future of vdW heterostructures certainly looks bright. □

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