2D MATERIALS

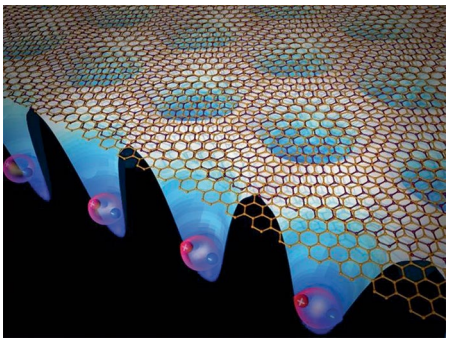
Making a case for moiré semiconductors

The recent advent of transition metal dichalcogenides moiré materials is a promising platform for studying correlated electron phenomena and moiré exciton physics.

A mix and match of monolayers of two-dimensional (2D) materials offers a fertile ground for the exploration of novel quantum phenomena in van der Waals material systems. When stacking individual 2D materials, a twist angle and/or a lattice mismatch between the layers may occur. Whether it happens naturally or by design, a moiré superlattice, that is, an interference pattern in the atomic lattice structures, emerges. Much to our scientific delight, the ability to create a variety of moiré patterns via twist angle engineering has provided the 2D materials community with the unique opportunity to prepare materials with highly tunable electronic, magnetic, optical, and phononic properties that strongly deviate from those of the aligned (that is, no twist angle) van der Waals systems.

A simple intuition suggests that the creation of a moiré superlattice would significantly increase the lattice constant of the original system, reducing the size of the Brillouin zone. Therefore, as far as the physics is concerned, the atomic lattice structure of the constituent materials can be practically neglected. In some cases, even a seemingly insignificant surface reconstruction caused by a less than a degree twist or a small lattice mismatch, can substantially modify the band structure of a resulting moiré material. For example, in twisted bilayer graphene (TBG) the formation of the flat bands occurs at the so-called magic angle, a twist of around 1.1° so small and precise that it took the 2D community many years to deliver the experimental proof after the initial theoretical prediction[1]. Following the discovery of superconducting domes between Mott insulating states in magic angle bilayer graphene[2,3], the field of moiré materials has expanded towards other, more complex systems, such as trilayer graphene, hexagonal-BN/graphene heterostructures, bilayer transition metal dichalcogenides (TMDs) and even two-dimensional magnets.

One particular class of moiré materials that has received tremendous research interest in recent years is moiré semiconductors that are typically prepared by stacking individual TMDs into different bilayers. Unlike twisted bilayer graphene



with its massless Dirac electrons and the magic angle condition, TMD semiconductors possess flat bands over a wide continuous range of twist angles, which largely simplifies the fabrication of these materials. In moiré materials, flat bands' electrons are strongly correlated and the correlation can be controlled via the moiré period as well as electron filling. Besides, due to the presence of a finite bandgap in TMD moiré systems, they support the formation of a type of bound electron-hole pairs trapped by moiré potentials known as moiré excitons. In 2019, drawing on the years of previous research on optoelectronic properties of TMDs and newly motivated by discoveries in TBGs, the part of the community specialized in the exciton phenomena in 2D materials set on the mission to unambiguously identify these elusive species. Eventually, the missing evidence of exciton resonances attributed to moiré mini-bands was reported by several groups in different high-quality TMD bilayers[4–6].

In their Review[7] in this issue, Huang et al. discuss the progress in the emergent field of moiré excitons focusing on the rapidly evolving albeit largely incomplete understanding of the influence of the moiré potential on the optical properties of some of the most common TMD heterostructures. The bulk of studies on photoluminescence emission from excitons in moiré potentials in near-commensurate and incommensurate TMD heterobilayers suggest that the exciton resonances in a given moiré superlattice are sensitive to a number of factors including stacking orders, twist angles and strain all of which can change the exciton dynamics of the system. Moreover, spatial inhomogeneity and defects are inevitable attributes of far-field measurements that hinder the possibility of probing an individual moiré supercell, making it challenging to assess the extent to which the moiré potential affects excitonic resonances in TMD bilayers. Despite these limitations, intralayer and interlayer moiré excitons, layer-hybridized moiré excitons, moiré exciton–polaritons, strongly coupled moiré excitons and photons as well as charged moiré excitons have already been experimentally observed.

In another recent review by Mak K. F. and Shan J.[8], in this issue, TMD moiré semiconductors are discussed from the perspective of Hubbard physics that is generally used to describe the transition between conducting and insulating systems and Kane–Mele–Hubbard physics that accounts for both electronic correlation and non-trivial band topology. In particular, the authors focus on twisted TMD herobilayers where isolated flat moiré bands can be described by generalized triangular lattice Hubbard models and describe the example of AA-stacked twisted TMD homo-bilayers and AB-stacked hetero-bilayers in which Kane–Mele–Hubbard physics can be realized. Similar to exciton studies, much of this exciting new physics remains experimentally unexplored even within the TMD moiré family. As these fundamental discoveries require the highest possible quality and homogeneity of semiconductor monolayers, all eyes are on the 2D materials growth community whose efforts could accelerate experimental realization of many theoretical predictions suggesting, among other possibilities, the realization of Kondo lattice physics or layer pseudospin liquid physics in Coulomb-coupled moiré double layers. ❐

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