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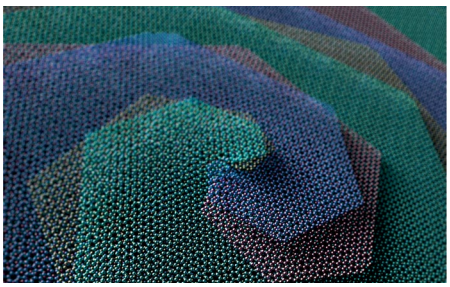
Crafting moiré and chirality in two dimensions

Misalignment-induced moiré patterns and chirality in two-dimensional materials offer vast opportunities for manipulating their properties, but they face challenges in synthesis and structural control.

Two-dimensional (2D) materials consist of a single or a few atomic layers. Misalignment between the adjacent layers can modify the interlayer and intralayer interactions, and hence allow the manipulation of the structure and functions of 2D materials. A typical misalignment arises from the mismatch of lattice constants between the two layers, exemplified by diverse 2D heterostructures investigated for electronics. More recently, the burgeoning field of 'twistronics' has grown rapidly, exploring the exotic electronic states and quantum transport phenomena in twisted 2D materials that form moiré patterns. Additionally, a structural chirality, marked by the absence of mirror symmetry in atomic lattices, can be realized in 2D materials, which enables asymmetric optical, electrical and magnetic properties. Although studies on the properties of moiré and chiral structures are expanding, synthetic methods for reliably obtaining these intricate structures with precise control present great difficulties, because many of these configurations are thermodynamically unfavourable. In this issue of *Nature Materials*, we present a Focus consisting of research articles, News & Views pieces and a Perspective that discusses the growth and characterization of twisted structures, moiré patterns and chirality in 2D layered materials.

In an Article, Zhu-Jun Wang and colleagues present a process for forming twisted graphene stacks through spiral growth. It involves the initiation of wrinkles in single-layer graphene, tearing wrinkles into segments that are folded towards opposite sides, and subsequent regrowth, resulting in twisted graphene spirals. The two neighbouring spirals with oppositely rotated growth fronts can coalesce seamlessly layer by layer. This process offers an approach for controlling twist angle by manipulating the orientation of the initial wrinkle. But further refinement in controlling wrinkles is still needed. Notably,



Graphene spirals.

the intertwined spiral structure can be a template for growing devices that might need a double-helix DNA-like structure, as commented by Pascal Pochet and Harley Johnson in a linked News & Views article.

The purpose of twisting 2D materials is to generate and tune moiré patterns, creating a long-periodicity potential and additional moiré electronic bands. However, the period of directly synthesized twisted moirés is typically restricted to discrete values determined by the lattice parameters and structures. In an Article, Matthieu Fortin-Deschênes and colleagues report the growth of aligned transition metal dichalcogenide heterostructures with a continuously tuned moiré period ranging from 10 nm to 45 nm, by adjusting chalcogen ratios in two constituent WSSe layers. David Geohegan and colleagues comment in a linked News & Views article that this alloying growth strategy, which forms orientation-aligned moirés with thermodynamic stability, offers distinct advantages for large-scale manufacturing and moiré design.

Moiré superlattices have become a rich platform for studying correlated and topological physics, where the identification of the local atomic stacking and symmetry is pivotal. In an Article, Isaac Craig and colleagues reveal the spontaneous structural reconstruction in twisted trilayer graphene and visualize the complex hierarchical moiré superstructure by interferometric 4D scanning transmission electron microscopy. This technique, combined with in situ transport measurements and local spectroscopy techniques, holds the potential to unravel the mystery of strongly correlated physics in twisted 2D systems, as underscored by Ruichun Luo and Wu Zhou in a linked News & Views article. In another Article, Naiyan James Zhang and colleagues, leveraging angle-resolved transport measurements, identify spontaneous broken symmetries in mirror-symmetric twisted trilayer graphene and a series of momentum-polarized states that might explain the zero-field superconducting diode effect in twisted trilayer graphene.

Beyond the moiré patterns that have attracted substantial interest in 2D materials research, structural chirality emerges as another feature that can be harnessed through different strategies, such as the adsorption of chiral molecules on 2D layers, the rolling-up of 2D sheets into quasi-1D tubes, and geometrical rotation or bending of 2D lattices. In a Perspective article, Hanyu Zhu and Boris Yakobson discuss the approaches for constructing nearly 2D chiral materials, the emergent properties arising from structural chirality and the opportunities for manipulating chiral functionalities in 2D layered materials, which would potentially lead to unconventional optoelectronic materials beyond the current landscape of 2D moiré structures.

As an example of chirality control, an Article by Qinwei An and colleagues reports the growth of transition metal dichalcogenide nanotubes with single chiral angles using gold nanoparticles as the catalyst, under carefully controlled growth temperature. This catalyst-assisted growth method could stimulate more research on functional nanotubes of layered materials, beyond the widely studied carbon nanotubes. Additionally, as M. Bar-Saden and R. Tenne point out in a linked News & Views article, these nanotubes can be grown at any pre-selected place where gold nanoparticles are pre-deposited, presenting opportunities for applications such as field-emission probes, electrical conduits or waveguiding polaritonic modes.

A fascination with 2D materials lies in the abundant parameter space of stacking and misalignment, granting tremendous freedom to play with atomic structures and electronic properties. But this potential must be underpinned by precise structural control and characterization of these atomic structures, laying the fundamental basis for exploring their physics and applications.

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