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Growing moiré with DNA

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Twisting two-dimensional materials gives them novel properties, but it is challenging to program them. Now DNA origami has been shown to seed the growth of twisted superlattices at new scales and with better programmability.

Moiré patterns emerge when two periodic structures are stacked with a slight offset, rotation or difference in period, resulting in a larger periodicity that can dramatically alter material properties. This phenomenon is directly observed in everyday life, such as when looking through overlapping window mesh screens or photographing a digital display. Now, writing in *Nature Nanotechnology*, Jing and colleagues describe an elegant and generalizable method for creating DNA-based moiré superlattices, filling the size gap between angstrom- and micrometre-scale lattices¹. This approach leverages programming principles from DNA nanotechnology to control the size of the sublattice, the twist angle and the interlayer spacing between overlaid lattices with flexibility and ease – all currently challenging to achieve in the moiré field.

Twisted bilayer graphene helped to launch the field of twistronics by demonstrating that small twist angles can give rise to exotic quantum phenomena such as superconductivity². Soon after, moiré lattices were demonstrated at much larger scales in photonics, providing new ways to control light³. Two-dimensional materials, such as graphene, which have atomic-scale lattices, are readily available. Larger photonic architectures can also be fabricated using well-established top-down lithographic methods. However, it has remained extremely difficult to produce similarly twisted bilayer architectures at intermediate length scales, with sublattice sizes of a few nanometres, owing to a lack of suitable materials, fabrication methods and the problems of achieving precise placement and rotational alignment between the lattice layers.

Jing and colleagues address this challenge by developing a seeded growth method that combines DNA origami with single-stranded DNA tiles (SSTs). In this approach, DNA strands are folded into a defined three-dimensional shape to create a DNA origami structure that serves as a template for seeding the growth of two-dimensional lattices made of SSTs (Fig. 1). This origami seed nucleates lattice growth from SSTs using capture DNA strands strategically placed on the surface of the seed⁴. These strands guide the self-assembly of SST-based lattice sheets at specific heights, resulting in stacked lattices. The origami seed also introduces a small, programmable twist between the lattices, causing them to rotate relative to one another. This twist results in moiré patterns with periodicities of tens of nanometres.

The key innovations of Jing and colleagues lie in the use of DNA origami to precisely control the twist angle, the lattice topology and the vertical distance between stacked lattices. Unlike traditional epitaxial growth of two-dimensional materials, which is confined to crystal lattice matching⁵, the DNA origami moiré system uses highly

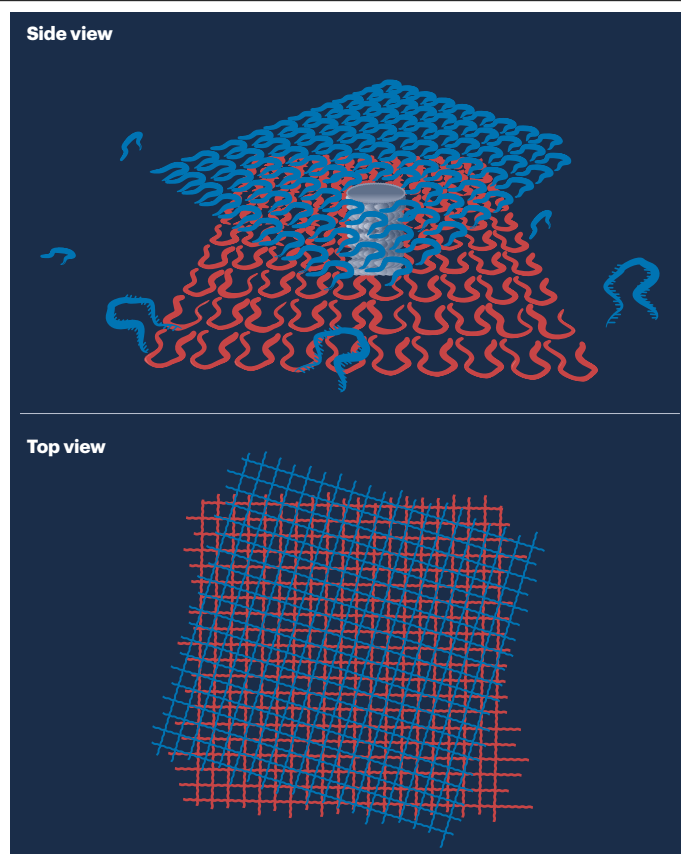


Fig. 1 | Seeding the growth of two-dimensional lattices made of SSTs. Schematics illustrating two DNA lattices (blue and red), each assembled from oligonucleotide strands and oriented at distinct angles as programmed by a central DNA origami seed (white). The resulting angular offset is programmed by the seed and gives rise to a moiré interference pattern.

programmable principles of DNA nanotechnology, thus enabling more programmable moiré engineering. For example, a designed twist between two lattice nucleation sites acts like a built-in rotator, determining the interlayer rotation with a precision of better than two degrees. Moreover, the topology of each layer can be independently programmed to include square, kagome and honeycomb lattices by using well established design principles that are simple to implement experimentally. Additionally, the growth characteristics of the seeded SST lattice can be tuned by modifying the interactions between the capture strands on the origami seed and the SSTs.

To better understand and optimize growth, the authors drew inspiration from wetting phenomena. By adjusting the arrangement of capture strands on the seed surface, they explore cooperative, partially cooperative and non-cooperative nucleation modes. This strategy not only guides the layer-by-layer assembly but also suppresses unwanted

nucleation, resulting in bilayers with a yield of over 90% and no mixing of topologies within a single layer. These seeded bilayers exhibit uniform twist and spacing across micrometre-sized domains, as verified through transmission and scanning electron microscopy analyses.

Jing and colleagues extend their approach by creating a gradient moiré superlattice, in which the twist angle changes gradually along one spatial dimension of the superlattice. This produces a continuously varying moiré periodicity within a single superlattice, an ability previously limited to lithographic or scanning probe fabrication techniques. Gradient lattices could support spatially varying phononic or photonic responses, opening the door to devices with position-dependent bandgaps⁶.

The implications of this work are broad. In the future, DNA moiré superlattices could be transformed into high-performance materials by templating metals, dielectrics or semiconductors onto the DNA superlattice. Such transformations could be realized through methods such as electroless plating, atomic layer deposition cladding or silification⁷. The DNA superlattices could also serve as masks for nanometre-scale lithography, transferring moiré patterns onto functional materials⁸.

Beyond using DNA moiré lattices as templates or masks, programmable DNA assemblies could be used to interface with existing electronic or optical materials. For example, DNA origami tiles can be used to precisely position and rotate two-dimensional materials such as MoS₂ by attaching them via thiolated DNA strands, enabling controlled twist-angle engineering⁹. At larger, photon-relevant scales, DNA origami tiles larger than SSTs could be used to build complex and reconfigurable photonic moiré structures. Furthermore, the reconfigurable nature of DNA nanostructures¹⁰ suggests that dynamically tuneable moiré lattices could be made using DNA origami. These reconfigurable moiré structures could be used to geometrically amplify nanometre-scale movements for various sensing modalities. For example, small mechanical deformations or conformational changes in the DNA origami seed could produce measurable shifts in moiré

periodicity or optical interference patterns, thus enabling optical sensing of molecular binding events or force-induced distortions.

Despite these promising future directions, challenges remain. DNA structures are relatively fragile on their own. Scaling to larger areas while maintaining defect-free ordering will also require further development. Nonetheless, the modularity and programmability demonstrated by Jing and colleagues represent an important advance. Moiré patterns are rapidly gaining traction as a method of creating next-generation functional materials. With this work, the intermediate nanometre-scale regime no longer remains an uncharted space between atomic- and micrometre-scale moiré lattice structures. This work enables more programmable nanometre-scale moiré engineering, bridging a longstanding gap between the angstrom and submicrometre scales and leveraging the capabilities of DNA-based programming.

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Competing interests

The authors declare no competing interests.