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Moiré materials keep on giving

Thanks to improved control of device fabrication and an expanding characterization toolbox, moiré materials stay in the spotlight as we discover more about the unique phenomena they realize.

In 2004, Andre Geim and Kostya Novoselov reported the isolation of the first flake of graphene. Twenty years on, two-dimensional materials still keep physicists and materials scientists busy. The discovery in 2018 that two layers of graphene superimposed at a slight twist angle host a superconducting state — tantalizingly reminiscent of those observed in high-temperature superconductors — sent the field spinning in a new direction, which we explored in a Viewpoint[1] 3 years ago and now revisit in this Focus issue.

Moiré materials, the material family of which twisted bilayer graphene is the poster child, are characterized by long-range interference patterns (the so-called moiré superlattice) arising from the interaction between the layers, which can either be rotationally misaligned or have different atomic constants. These moiré patterns induce unconventional and tunable electronic, magnetic and optoelectronic properties, such that moiré materials provide an exciting playground for materials design.

Properties can be tuned through several control knobs. Beyond the choice of constituent layers, which can be selected from an extensive materials library ranging from graphene and transition metal dichalcogenides to ferroelectric perovskites and topological insulators, parameters such as the twist angle, external electric field, pressure and strain all control the hybridization between the layers and hence the properties. The Perspective by Archana Raja and collaborators in this issue examines the different ways these externally tunable parameters can be combined to optimize material properties.

Intriguingly, moiré materials host almost every known electronic phase of matter and also several unexpected ones that have never been observed in other material classes. Understanding these exotic phases will not only advance our understanding of physical phenomena at a fundamental level, but also our ability to engineer material properties for future technologies, such as quantum electronic devices and quantum computers. Mandar Deshmukh and collaborators discuss in their Review how transport and optical studies are helping to elucidate the rich topological physics in moiré systems. Beyond globally averaged measurements, local probes enable the investigation of materials' behaviour at the microscopic level, shedding light on phenomena that include topology, magnetism and superconductivity (the nature of the superconducting states in magic-angle twisted bilayer graphene, which arose the initial excitement in the field, is yet to be elucidated). In their Review, Ali Yazdani and Kevin Nuckolls survey recent advances in local probe techniques and the new insights they are unlocking.

Cross-pollination between different communities could also help unveil the physics at play. Strongly correlated materials, which have been investigated for decades, display properties reminiscent of those of moiré materials, and Silke Paschen and colleagues argue in a Perspective article that the mechanisms underpinning the behaviours of these two classes of materials could share some underlying principles.

Finally, one particular phenomenon has been stealing the spotlight in the past few months: the fractional quantum anomalous Hall effect — a fractional Hall effect that is observed in the absence of a magnetic field — was discovered in two different moiré materials and is stimulating a lively discussion. The exotic electronic states that emerge in the fractional Chern insulator states hosting the new Hall effect hold promise for topological quantum computing, and the community is excited by the perspective of more fundamental physics discoveries. These new results are delineated in a Viewpoint by Long Ju, Allan MacDonald, Kin Fai Mak, Jie Shan and Xiaodong Xu.

Twenty years after the discovery of graphene, 2D materials are still very much an active focus of research, and moiré materials, in particular, are injecting new excitement in the community. We look forward to seeing what the next 20 years will bring.

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References

1. Andrei, E. Y. et al. The marvels of moiré materials. *Nat. Rev. Mater.* **6**, 201–206 (2021).