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Matter of Opinion

2D layered materials and heterostructures: Past, present, and a bright future

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Two-dimensional (2D) materials are ultrathin layered materials that serve as building blocks for engineering properties at the atomic scale. By harnessing the design space of these versatile pieces of matter, advanced technologies integrated into everyday life will be possible in the not-so-distant future. Here, we introduce three perspective articles addressing the past, present, and future of 2D materials and heterostructures.

The nanomaterials revolution has spearheaded many groundbreaking discoveries in physics, biology, medicine, chemistry, and materials science. The past two decades in particular have seen the explosion of research investment in two-dimensional (2D) materials, which represent layered materials at the ultimate thickness scaling limit. While 2D materials have captured the imagination of the scientific community, significant efforts are still needed to propel these materials from the lab to everyday life in the form of devices, components, coatings, and other advanced technologies. There is no doubt, however, that 2D materials have a bright future.

The brief history of these 2D atomic building blocks is shown in Figure 1. The seminal work in this field is attributed to researchers at the University of Manchester, who in 2004 described remarkable stability and peculiar electronic properties in "monocrystalline graphitic films… a few atoms thick." This material was named "graphene," as the atomically thin layer of sp2 bonded carbon atoms, similar to graphite, contained numerous double bonds within the lattice structure. The proceeding decades of research into this vast material set have seen the community transition into different periods of development, starting from the Period of Discovery to the Period of Engineering and Building and finally to the Period of Design and Architecture. In the Period of Discovery (2004–2014), the library of 2D building blocks expanded beyond graphene to include hexagonal boron nitride (h-BN), transition metal dichalcogenides (TMDs), elemental 2D materials, MXenes, and more. Isolation of the 2D materials began with the mechanical exfoliation using scotch tape and progressed quickly into vapor phase synthesis of single crystal materials. The community raced to map the landscape of fundamental layer-dependent excitonic, electronic, optical, magnetic, and structural properties. Graphene was shown to be the strongest material ever developed with an ultimate tensile strength of 130 GPa, 1,000 times stronger than steel. Quantum confinement within MoS_2 was shown to transition the bandgap from a bulk indirect gap at ~1.3 eV to a direct gap at ~1.8 eV for monolayer films. Within this decade, the leveraging of existing mainstream nanomaterials characterization strategies (Raman spectroscopy, scanning probe microscopy, and transmission electron microscopy, to name a few) combined with new characterization strategies further elucidated more exciting physical phenomena at a rapid pace. The first lab-scale devices and components with 2D materials showed extraordinary promise in electronics, optics, optoelectronics, medicine, and structural applications, setting the foundation for future technologies.

The second phase of exploration and development is currently underway: the Period of Engineering and Building (2014–present). In this phase, the atomic building blocks are being pieced together. A transition from scotch-tape exfoliation to exquisite single-crystal, wafer-scale 2D materials is finally reaching maturity, providing access to these materials for researchers across the globe through academic, consortium, and industry partnerships. Various 2D materials are being stacked together to form lateral and vertical heterostructures with hybrid properties both in the bulk and at the interface. Layers are being stacked at controlled twist angles, many times at the "magic" angle, to reveal new physics and layer coupling in a new field known as twistronics. More complex interactions are beginning to be studied between 2D materials and 0D/1D/3D materials with an endless playground of possibilities. The design and understanding of 2D/3D heterojunctions are becoming increasingly necessary for electronic and optical devices, as 2D materials will have to interface with metallic contacts, dielectrics, substrates, and

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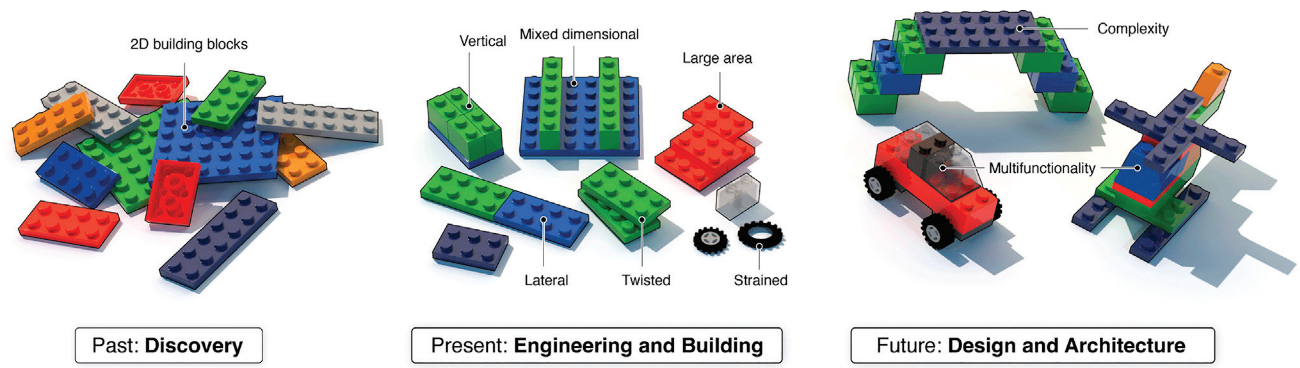

Figure 1. The brief history of 2D atomic building blocks and their heterostructures

more. Several methods have emerged to apply a controlled strain on the ultra-thin materials, showing that strain can manipulate electronic, optical, and magnetic properties at will and can even induce emission of single photons. The design space for 2D atomic building blocks only continues to grow, and the tools developed during this period will help shape the technological landscape in the next phase.

At a rapid pace, we are entering the next chapter of 2D materials: the Period of Design and Architecture. Researchers and scientists have successfully pieced together materials and subcomponents, a stepping stone to true multifunctional, complex systems. Manufacturing is beginning to emerge as both small and large businesses are interfacing 2D materials with silicon complementary metal-oxide-semiconductor (CMOS) electronics. 2D materials are being seamlessly integrated into advanced sensor constructs for wearable and internet-of-things applications where the sensor device is only a piece of a much larger puzzle. Developments are underway for twistronic circuitry, where devices using twisted systems can be harnessed at scale. True layer-by-layer engineering will result in customizable bulk optical materials, which will be further integrated with all kinds of 3D structures. With all of these developments combined with the worldwide enthusiasm, it is clear that 2D materials will change the world—it's not a question of "if," but of "when."

The December special issue of *Matter* features three perspective articles of "Pieces of Matter" focused on 2D layered materials and heterostructures. Three prominent research groups share their perspectives on 2D organic-inorganic hybrid perovskites and their heterostructures (Kai Leng/Kian Ping Loh, The Hong Kong Polytechnic University); 2D layered materials and heterostructures for flexible electronics (Jong-Hyun Ahn, Yonsei University); and bio-realistic neuronal computing networks based on 2D layered materials and heterostructures (Mark Hersam, Northwestern University).

- Leng, Loh and coauthors[1] discuss the peculiarities of 2D hybrid organic-inorganic perovskite and its heterostructure with 2D inorganic materials, as well as the various schemes used for hybridizing such heterostructures and the physics that can arise from the hetero-interfaces.
- Ahn and coauthors[2] present the recent development of 2D layered materials and heterostructures for flexible electronics. They share their perspectives on current challenges at both the materials and device levels, including impurity/doping, defects, interface properties, and compatibility with manufacturing, and further suggest development of advanced techniques for commercialization.
- Hersam and coworkers[3] show the promise of 2D layered materials and heterostructures for realizing bio-realistic synaptic and neuronal functionality. The fundamental versatility of 2D materials is introduced as a critical advantage to accelerating neuromorphic hardware development that has been challenging to emulate in 3D bulk material counterparts.

These topics showcase the emerging research trends in the field of 2D layered materials and heterostructures where innovations in materials processing, device integration, and manufacturing could lead to the realization of the exciting potential of 2D layered materials and heterostructures.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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