2D MATERIALS

Monolayer mosaic heterostructures

A combination of periodic laser patterning, anisotropic thermal etching and endoepitaxial growth enables the realization of monolayer mosaic heterostructures with atomically sharp interfaces.

Can Liu and Kaihui Liu

After 50 years of development and device scaling, metal-oxide-semiconductor-field-effect transistors (MOSFETs) for integrated circuits (ICs) have reached the sub-10-nm node by gate length reduction and architecture optimization. Additionally, the channel thickness has to be reduced along with scaling of the gate length to improve the electrostatic control[1]. However, the carrier mobility for conventional semiconductors, such as silicon, degrades dramatically when the channel thickness is reduced to the nanometre scale due to the enhanced scattering at the interface between the semiconductor and the insulator[2]. Theoretically, two-dimensional (2D) materials are suitable candidates for device scaling because of their ultimately thin thickness and dangling bond-free surfaces. Therefore, 2D materials could potentially provide a viable solution for the 1.5-nm node, the idea that has been implied in the most recently projected 2020 International Roadmap for Devices and Systems (IRDS)[3].

To truly apply 2D materials to modern ICs, the batch production of high-quality single crystals and their precise manufacturing are two prerequisites for high-performance devices. During the past decade, the growth of metre-sized single-crystal graphene[4], decimetre-sized single-crystal hexagonal boron nitride[5,6], and wafer-scale single-crystal transition metal dichalcogenides[7,8] have been successfully demonstrated. In contrast, precise manufacturing of 2D materials at atomic scale remains in its early stage. The conventional lithography and etching process is too drastic for atomic-layered structures and easily causes undesired residues or damages on the 2D surfaces. For example, monolayer mosaic heterostructures, a representative that heavily relies on the precise manufacturing of atoms, are still challenging to fabricate.

The bottom-up '*Atom Manufacturing*' is an accessible route to achieve precise control of monolayer mosaic heterostructures in principle. Now, writing in *Nature Nanotechnology*, Z. Zhang and colleagues have reported an appealing method to fabricate 2D mosaic heterostructure arrays with atomic accuracy (Fig. 1)[9]. Unlike previous random nucleation after the lithographic or nanofabrication process, the developed anisotropic thermal etching process can provide triangular holes with atomically sharp and clean edges. Further endoepitaxial growth leads to lateral heterostructure arrays of monolayer mosaics, such as WSe_2-in-WS_2, MoS_2-in-WS_2 and MoS_2-in-WSe_2 patterns. Systematic microstructural and spectroscopic characterizations reveal highly elaborated periodic modulation of chemical compositions, lattice strains and electronic band gaps throughout all these 2D mosaic heterostructures. More intriguingly, the atomically sharp and straight interfaces in the mosaic heterostructures are unambiguously demonstrated by atomically resolved transmission electron microscopy.

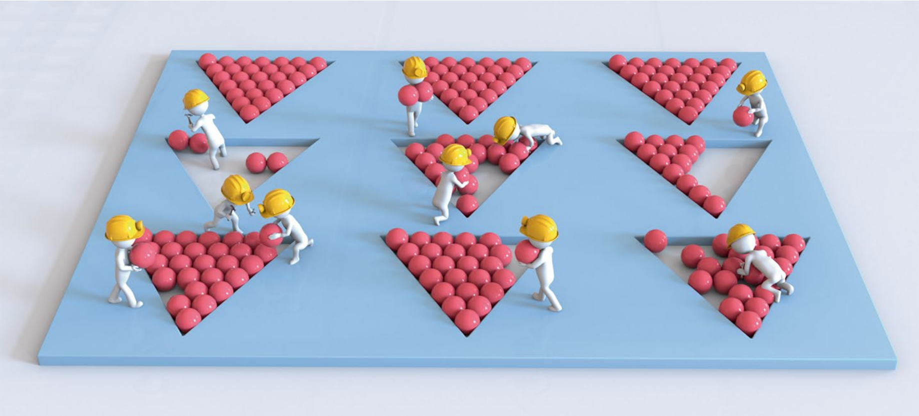

Fig. 1 | Lateral endoepitaxial growth of 2D mosaic heterostructures. Endoepitaxial growth of transition metal dichalcogenides occurs at the created periodic array of triangular holes, forming atomically sharp interfaces and periodic arrangements of 2D mosaic heterostructures.

The study by Zhang and colleagues provides an alternative route for the precise manufacturing of 2D materials and is likely to proceed with the applications of 2D materials in ICs. However, it should be noted that the high-temperature endoepitaxy up to 1000 °C in this work is incompatible with the state-of-the-art IC fabrication process. In addition, there are several targets to be fulfilled towards high-integration-density ICs using 2D materials, including material integration compatibility, high-throughput quality characterization, device-to-device uniformity control, and stability performance for heat/cold/wet resistance. This work indicates the possibility of the utilization of 2D materials with accurately controlled structures for ICs. ❐

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Competing interests

The authors declare no competing interests.