Two-dimensional materials

https://doi.org/10.1038/s41565-026-02293-z

Sliding ferroelectricity scales up

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Wafer-scale growth of a metastable rhombohedral boron nitride polytype takes sliding ferroelectricity from handcrafted structures in the laboratory towards integrated devices.

The properties of layered crystals depend not only on their chemical composition but also on how their atomically thin layers are arranged. Researchers have exploited this freedom by combining different two-dimensional materials into van der Waals heterostructures and, more recently, by rotating neighbouring layers to create the electronic landscapes of twistronics[1]. Now, writing in *Nature Nanotechnology*, Qi et al. report the reproducible growth of four-inch single-crystal rhombohedral boron nitride (rBN) wafers and their integration into sliding-ferroelectric memory arrays and transistors with channel lengths down to 30 nm (ref. 2). The work locks a metastable stacking sequence into a wafer-scale functional material.

Stacking order, also known as polytype, is a powerful but comparatively underused design variable in van der Waals materials. Different polytypes preserve the same composition and individual layers but differ in their stacking sequence, producing markedly different electronic, optical, magnetic and superconducting properties[3].

In 2021, two independent studies showed that artificially stacked exfoliated BN can adopt stable AB and BA stackings with opposite out-of-plane polarizations[4,5], which are switched by an out-of-plane electric field through lateral layer sliding. Unlike conventional ferroelectrics, which switch through ionic displacements within a bonded crystal lattice, this mechanism can operate at the atomic thickness limit and may offer improved fatigue resistance.

Sliding ferroelectricity has since been observed in rhombohedrally (manually) stacked bilayers of several semiconducting transition-metal dichalcogenides[6,7]. Rhombohedral BN is distinctive because, unlike most sliding ferroelectrics explored so far, it is a wide-bandgap insulator. Its non-centrosymmetric ABC stacking produces a net out-of-plane polarization while retaining the dielectric strength and thermal robustness of boron nitride, making it well suited for gates and tunnel barriers.

The challenge is to manufacture this metastable sequence reproducibly at the wafer scale. The formation energy of rBN is just ~2 meV per atom larger than that of the stable hexagonal phase[2]. Previous bevel-edge epitaxy on specially prepared single-crystal nickel produced centimetre-scale rBN with controlled ABC stacking and switchable ferroelectricity[8]. However, such precisely treated single-crystal metal substrates are difficult to reproduce at wafer scale, batch after batch. Qi and colleagues develop a reusable step-templated growth strategy that enables the reproducible production of 4-inch rBN wafers with uniform stacking order and thicknesses of up to 45 nm (Fig. 1a,b).

The critical part is the growth template. Annealed *m*-plane sapphire develops parallel surface steps (Fig. 1a, step 1), which are replicated by the nickel–boron (Ni–B) film sputtered on top (Fig. 1a, step 2). The N-terminated zigzag edges of the boron nitride layers preferentially attach to these solid-state step edges, promoting the unidirectional growth of each layer. Boron is supplied by the Ni–B film, whereas nitrogen diffuses from the gas phase to the buried growth interface. Each new layer therefore forms underneath the previous ones, where the same stepped template continues to guide its orientation and favours the parallel, rhombohedral stacking sequence (Fig. 1a, step 3).

Control experiments support this mechanism: removing or disrupting the solid surface steps, either by changing the sapphire orientation or approaching the Ni–B melting temperature, favours hexagonal rather than rhombohedral BN. Importantly, the authors demonstrated how the stepped template can be reused for repeated wafer growth while maintaining consistent crystal quality across batches (Fig. 1a, step 4).

Crucially, the wafer-grown material preserves the defining characteristics of sliding ferroelectricity. Electron microscopy of oppositely poled regions shows that polarization reversal proceeds through the ABC-to-CBA stacking transformation (Fig. 1c, inset), directly connecting the switchable polarization to the stacking order. Qi and colleagues then integrate this wafer-grown rBN into ferroelectric field-effect transistors (FeFETs), where it serves as the gate dielectric and a graphene channel provides electrical readout of the polarization state. In these devices, switching reaches the nanosecond timescale, endurance exceeds 2×10^9 cycles and projected retention exceeds ten years, placing the wafer-grown material alongside the best artificially stacked sliding ferroelectrics[9,10].

For wafer-scale integration, the authors adopt a metal–ferroelectric–metal–insulator–semiconductor architecture, in which rBN provides the switchable polarization and monolayer MoS_2 serves as the channel (Fig. 1c), to reduce the depolarization field and to help maintain a uniform electrostatic potential, promoting more complete switching of the rBN layer.

Device arrays fabricated from the wafer-grown rBN show reproducible non-volatile switching, with ON/OFF ratios reaching 10^6. Transistors scaled to channel lengths as short as 30 nm — only a few times larger than the calculated domain-wall width — retain sizeable memory windows and remain ferroelectrically active up to 473 K. Together, these results show that wafer-grown sliding ferroelectricity remains robust under large-area integration and aggressive device scaling.

Important challenges nonetheless remain. The rhombohedral boron nitride films must still be transferred from their growth substrate, a step that can introduce contamination, wrinkles and alignment errors at device interfaces. Technologically relevant operation will also require lower programming voltages, most likely through thinner ferroelectric layers and improved interface electrostatics. From a more fundamental perspective, real-time operando microscopy of domain-wall nucleation and propagation would help clarify how polarization reversal proceeds through multilayer crystals and could ultimately guide the design of faster, more reliable sliding-ferroelectric devices.

The longer-term opportunity extends beyond boron nitride. If growth surfaces can be designed to select not only composition and orientation but also the translation of each successive layer, polytype could become a programmable materials parameter.

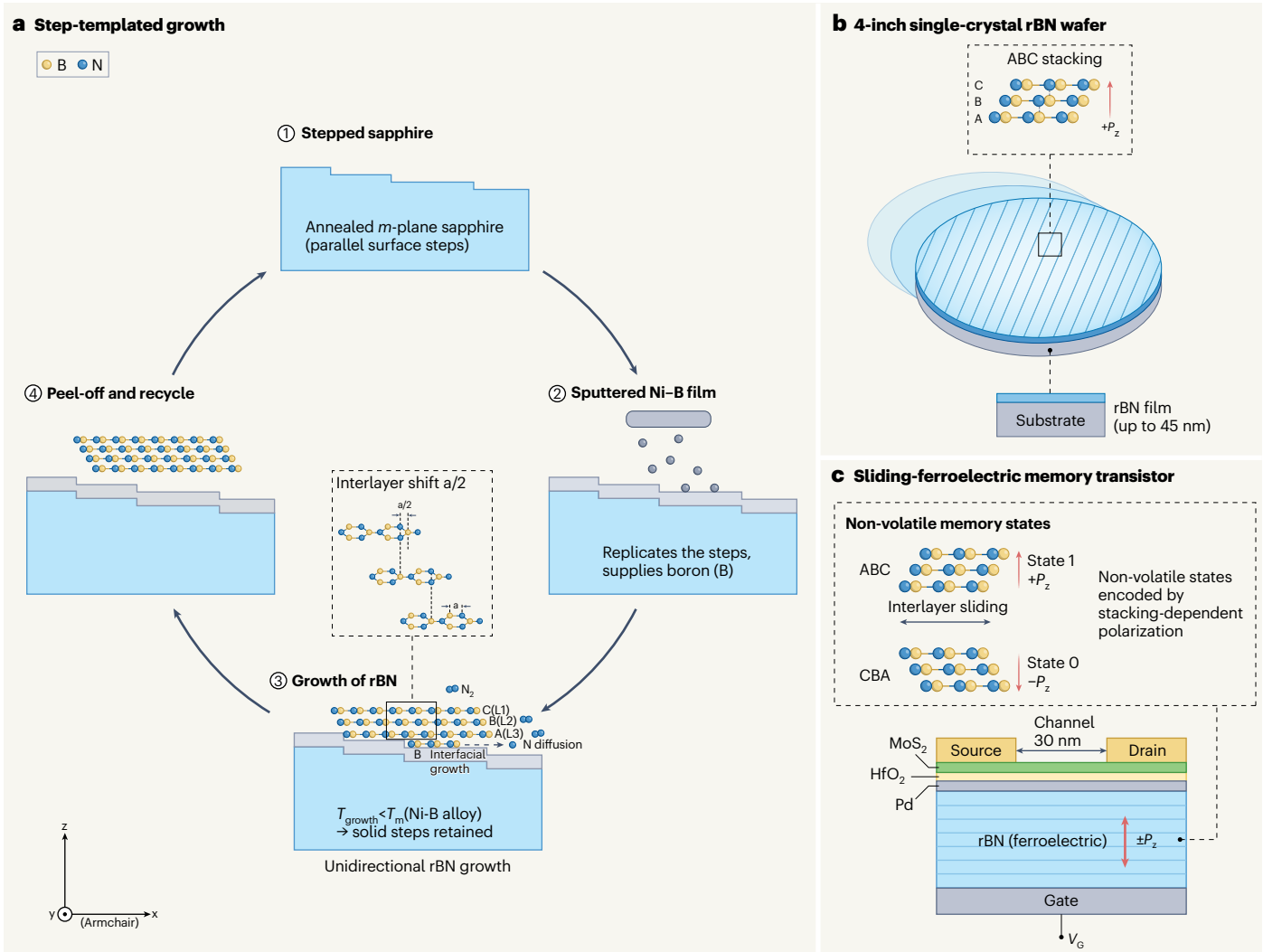


Fig. 1 | From stepped sapphire to wafer-scale sliding-ferroelectric memory transistor. a, Reusable step-templated growth of rhombohedral boron nitride (rBN). Annealed *m*-plane sapphire develops parallel surface steps (1), and a sputtered Ni–B film replicates the steps and supplies boron (2). During growth (3), boron nitride attaches at the step edges and new layers form at the buried interface via nitrogen diffusion. Each successive layer (L1, L2, L3) is laterally shifted by half of the in-plane lattice constant *a* (magnified view), which enforces the rhombohedral stacking. The finished film is then peeled off and the stepped template is reused (4). **b**, The approach yields 4-inch single-crystal rBN wafers with uniform ABC stacking and film thicknesses of up to 45 nm. The ABC sequence produces an out-of-plane polarization P_z (inset). **c**, In a ferroelectric field-effect transistor, the rBN film acts as a switchable gate dielectric beneath a thin Pd screening electrode, a HfO_2 barrier and a MoS_2 channel. Devices operate at channel lengths down to 30 nm, retaining a 4-V memory window up to 473 K. A gate field reverses P_z through interlayer sliding between the ABC and CBA stacking orders, which encode the nonvolatile memory states 1 and 0 (inset). Panel **a** (central schematic) adapted from ref. 8, Springer Nature Ltd.

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Published online: 14 October 2026

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Competing interests

The authors declare no competing interests.