of elevated topography in the overriding plate increases the frictional resistance of the plate interface, and therefore reduces plate velocities[11,12]. Yet simultaneously, the growth of mountain ranges induces surface erosion and increases sediment supply. Moreover, volcanic activity and the burial of carbon at subduction zones affect the global climate, and therefore erosion. Which of these processes dominates over specific timescales and how the processes are coupled are poorly understood.

It would also be valuable to assess sediment fluxes and budgets (the differences between inputs and outputs), and the geochemical tracers of these sediments from continental mountain belts to subduction trenches. Such an assessment would need to take into account how Earth's lithosphere and climate at these early times differed from those of today. From the viewpoint of geology, better constraints from natural rocks and experiments on material strength for both the shallow (frictional) and deep (viscous) plate interface are needed to quantify the importance of changes in the physical characteristics of subducted rocks on interface properties. ■

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MATERIALS SCIENCE

The thinnest sheets of metal oxides

2D crystalline membranes are easily made from some materials, but not from those with strong 3D lattices, such as technologically useful perovskite oxides. Free-standing perovskite monolayers have finally been made. **SEE LETTER P.87**

YORICK A. BIRKHÖLZER & GERTJAN KOSTER

Science often benefits from the discovery of extremes. Once we have proved the existence of an extreme, it can help us to build models that explain scientific phenomena. In the field of materials science, an outstanding experimental goal has been to prepare sheets of technologically useful transition-metal oxides, such as perovskites, at their fundamental minimum thickness. On page 87, Ji *et al.*[1] report the preparation of the first such sheets for the perovskite oxides strontium titanate ($SrTiO_3$) and bismuth ferrite ($BiFeO_3$), and provide a glimpse of their properties.

Many technologically beneficial materials are crystalline, including transition-metal oxides. The atomic or molecular order in a crystal is defined by the unit cell, which is the smallest repeating unit of the crystal structure. In the case of strontium titanate, for example, the unit cell is a cube that has edges about 0.4 nanometres long[2]. This represents the smallest possible length or thickness of the objects (2D sheets, 1D rods or 0D 'dots') that can be made from this material — and is therefore of interest to nanotechnologists, who try to reduce the size of materials in search of previously unseen properties and functions.

Sometimes, nature offers a helping hand to nanotechnologists by producing crystalline materials that are intrinsically layered and which have weak bonding between the layers. 2D sheets can be isolated (exfoliated) more-or-less spontaneously from such materials — as is the case for the most famous 2D material, graphene, which is exfoliated from graphite. Since the Nobel-prizewinning isolation and characterization of graphene in 2004 (ref. 3), hundreds of other 2D materials have been discovered that fascinate scientists and engineers alike. The list encompasses single-element materials as well as compounds, and spans the full range of electrical properties, from metallic conductors to semiconductors and insulators. The vast majority of these 2D materials are derived from parent materials that have weakly bonded layers, including the transition-metal dichalcogenides[4] (a well-characterized class of semiconductor) and certain oxides[5].

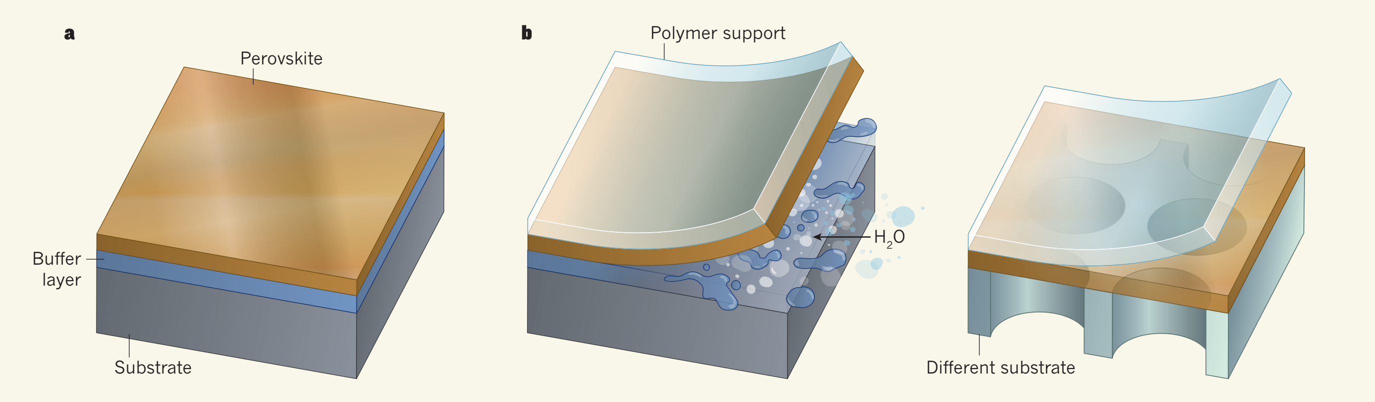

Figure 1 | The synthesis of monolayer perovskite films. **a**, Ji *et al.*[1] have prepared the thinnest possible free-standing sheets of two perovskite oxide semiconductors, using an established technique called molecular beam epitaxy (MBE) in combination with a previously reported method[9] for separating thin films of materials from substrates. The authors used MBE to 'spray paint' an ultrathin layer of a perovskite oxide semiconductor onto a buffer layer of a water-soluble material on the surface of a crystalline substrate. **b**, Ji and colleagues could release the ultrathin perovskite film by dissolving the buffer layer in water, and, equally remarkably, could use a polymer support to transfer it to other substrates (including some that contain holes, shown). They also imaged its cross-section at atomic resolution (not shown). The findings demonstrate that free-standing monolayers of perovskites can be made, contrary to what had been thought.

But in most crystalline materials, the bonding between atoms or molecules is isotropic (has the same strength in all dimensions). These materials therefore spontaneously form as 3D objects, which makes it considerably more difficult to produce quasi-2D sheets. The only feasible way to make ultrathin sheets of these materials is to deposit a thin film on the flat surface of another crystalline starting material, and to monitor the process in real time at the atomic level. The grown film is said to be epitaxial if its unit cells align with the unit cells of the substrate.

For oxides, such techniques came to fruition in the late 1980s and early 1990s as a result of intensive research on copper oxides (cuprates) that exhibit high-temperature superconductivity. These cuprates have a layered structure, but are strongly bonded together, and so scientists explored their superconductivity by engineering layers in epitaxial thin films[6]. Perovskite oxides display a rich variety of potentially useful physical effects, including multiferroic behaviour and colossal magnetoresistance[7], due to electron–electron correlations (interactions) in the constituent transition-metal ions[8]. Up to now, these properties have generally been studied in thin films grown on top of a substrate.

Ji *et al.* now report that free-standing films of perovskite oxides can be made using a careful combination of a state-of-the-art technique for fabricating thin films, called molecular beam epitaxy (MBE), and a previously developed method[9] for exfoliating thin films from substrates (Fig. 1). The authors used MBE to 'spray paint' ultrathin epitaxial layers of a perovskite and a water-soluble buffer layer onto a substrate, so that the buffer layer is sandwiched between the perovskite oxide and the substrate. The thickness of the resulting perovskite oxide films could be controlled at the atomic level.

The authors freed square-millimetre-sized, single-crystal perovskite oxide films from the substrate by dissolving the buffer layer in water, and then transferred them onto a variety of other substrates, such as carbon substrates that contained micrometre-scale holes. Remarkably, the overall process could produce films near the extreme limit of thickness — a single unit cell. The researchers studied the membranes using scanning transmission electron microscopy, an imaging technique that can resolve single atoms and quantitatively determine their positions. Intriguingly, they observed that the thin film of bismuth ferrite undergoes an unexpected phase transition to form a different crystal lattice.

Ji and colleagues' findings demonstrate that free-standing films of perovskite oxides can be made at thicknesses that are less than a previously proposed critical limit[10] below which it was thought that the lattice of the film would collapse. A long-standing question for those working with 2D materials has been whether a minimum thickness is required to stabilize crystalline order. The new findings suggest that no such minimum thickness is needed for free-standing thin films of perovskite oxides.

Many questions are raised by this work. Ji and co-workers demonstrate the method for only two archetypical examples out of many possible perovskite oxides, which raises the questions of how broadly applicable it is to other oxides and what new phenomena might emerge in those systems. Moreover, now that it has been shown that perovskite oxides do not apparently need to have a fundamental minimum thickness, other fabrication methods for making thin films of these materials should also be explored.

Free-standing thin films are an ideal platform for studying certain materials' properties, such as phase transitions that occur only when materials are confined within a certain number of dimensions, or nanoscale elasticity in the absence of substrates. Free-standing specimens are especially useful for analytical studies that work in transmission mode (in which, for instance, light, X-rays or electrons are passed through a sample to analyse it), because the absence of a substrate prevents unwanted background signals from being produced that could interfere with the signal from the specimen. Ji and colleagues' work also opens up the technological potential of 2D perovskite oxides, because they can now be extensively studied in the way that intrinsically layered materials such as graphene have been. ■

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NEUROSCIENCE

Closing in on what motivates motivation

The neurotransmitter dopamine facilitates learning, motivation and movement. Evidence of its release independently of the activity of dopamine-producing neurons in rat brains forces a rethink of dopamine regulation. SEE ARTICLE P.65

MARGARET E. RICE

Dopamine is a neurotransmitter molecule that influences brain pathways that are involved in motivation, movement, cognition and reward-driven learning. How it contributes to such varied behaviours is the subject of ongoing investigation. On page 65, Mohebi *et al.*[1] shed light on how dopamine release is regulated in the rat brain to accomplish different functions.

Dopamine is produced by neurons located in the midbrain, in regions known as the ventral tegmental area (VTA) and the substantia nigra pars compacta. The long axons of these neurons extend to other parts of the brain, including the nucleus accumbens, the dorsal striatum and the prefrontal cortex. Within these target sites, the axons branch extensively[2] to form a structure known as an arbor. The textbook description of dopamine signalling suggests that the activation of dopamine-producing neurons in the midbrain generates electrical signals that travel along their axons to their target regions, where they cause a dopamine release that is 'broadcast' throughout the territories covered by the axonal arbors. This concept is fundamental to current ideas about how reward-based learning occurs: an unexpected reward leads to an increase in the activity of dopamine neurons that is assumed to transmit a dopamine signal throughout the target regions to facilitate learning[3,4].

Yet dopamine release in the target regions is more complicated than its textbook description. For example, it can be regulated locally by neurotransmitters and other molecules[5]. Moreover, studies in animals of the activity of dopamine neurons using an imaging approach to monitor the activity of dopamine neurons or a microelectrode method to assess dopamine release indicate that an unexpected reward can cause the predicted increase in the activity of the axonal arbor, and dopamine release in the nucleus accumbens[6,7]. However, these features are absent in the neighbouring dorsal striatum[6,7], providing an argument against a role for dopamine as a universal broadcast signal.