Fig. 2 | Motor abundance varies inversely with size and increases as technology progresses. Since the first steam engine was invented, engines, motors and actuators have multiplied and evolved into serving an immense variety of functions. Today, the Earth is occupied by tens of billions of small electric motors spinning hard drives, several billion motors powering appliances, a billion car engines, a hundred million truck engines, and so on, all the way to a few giant turbines weighing hundreds of tonnes for pumped-storage hydroelectric power stations. While the biggest engines attract the attention, the growth is on the small side, where continuously shrinking motors aim to become as ubiquitous as mosquitoes.

From a higher vantage point, it is interesting to consider the need for contractile materials. While actuation in animals is typically achieved via the generation of tensile forces by contracting muscles, modern technology typically mimics plant biology[9] in relying on extensile forces generated by pneumatic and hydraulic systems. These systems in turn are powered by motors. Miniaturization presents a challenge to this dichotomous design, since frictional losses increase and motor efficiencies drop as the systems decrease in size. To continue on the technological path towards smaller and more numerous actuators[10] an integration of hydraulics and motors at the nanoscale is desirable (Fig. 2).

Nanoscale integration is achieved in the sarcomere, the basic functional unit of the muscle, where the force generation by myosin motor proteins leads to the interdigitation of thick and thin filaments without the generation of fluid flow. An almost crystalline stacking of sarcomeres into muscle tissue then scales force and velocity up, providing actuators suited for mosquitoes and whales. Actuators for future ubiquitous microdevices will similarly require molecular motors, or a mechanism used to generate mechanical work from some energy input. Similar to the first steam engines, the motor's energy conversion efficiency has to exceed 1%, otherwise the actuators relying on it would consume an unacceptably large portion of the energy budget[10]. This efficiency has to be maintained as the motors are integrated into a system that achieves force multiplication, and a method for controlled activation has to be implemented. The final challenge is to maintain the assembly in an operational state for an extended time. The work by Nitta and co-workers is the most fully developed effort to date to meet these challenges on the biotechnological route. As in the early days of climbing Mount Everest, the most feasible approach to the peak of potential performance is still under consideration. ☐

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METAL OXIDES

Adding oxides to the 2D toolkit

Two-dimensional (2D) metal oxides that can be exfoliated are produced via direct oxidation of their elemental metals, providing a simple and easy way to incorporate these materials in van der Waals heterostructures.

Gareth S. Parkinson

Building heterostructures from different combinations of 2D materials has become one of the most exciting playgrounds in modern physics. The selection of materials that can be easily produced and exfoliated into atomically thin monolayers has expanded dramatically in recent years, yet one class of technologically vital materials, metal oxides, have until now offered limited choices. This is because most of their conventional bulk counterparts do not have layered structures, and those that have ion-stabilized lamellar structures often require complex chemical procedures to obtain individual layers. Now, writing in *Nature Materials*, Bao Yue Zhang and colleagues[1] demonstrate a simple approach to create and mechanically exfoliate 2D layered metal oxides from their elemental metal surface, bringing metal oxides into the game at last.

Zhang and colleagues[1] oxidize metal samples such that a metastable, stoichiometric, graphitic layer forms at the surface rather than the thermodynamically stable bulk oxide. This layer, which is strongly bound within the plane but weakly bound to the metal surface, can be transferred to another substrate by simply pressing it against the target surface like a stamp (Fig. 1). Surface science studies on metal-oxide thin films with a similar graphitic structure can be dated back to 2007[2]. It is known that the metastable phases result from the 'polar instability' of certain surfaces in ionic crystals[3]. Viewed in certain
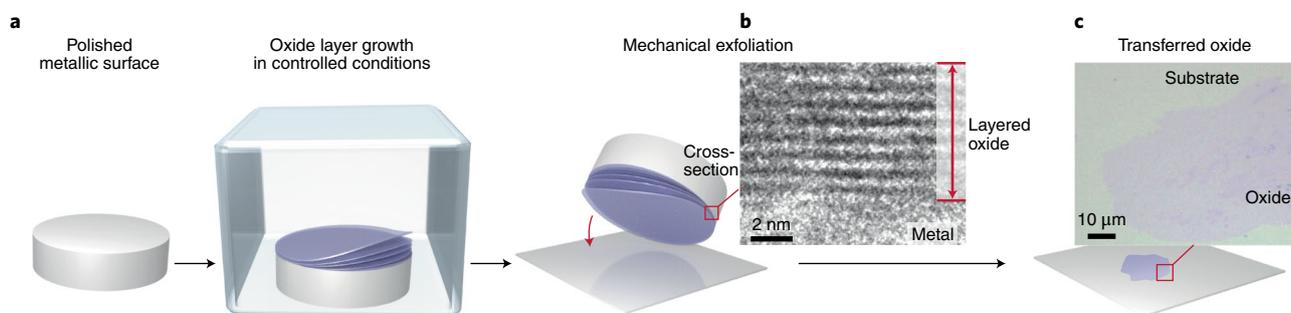
Fig. 1 | A schematic of the 2D layered metal oxide growth and mechanical transfer. a, The oxide layer is grown on the polished metallic surface under controlled conditions and transferred onto a substrate through 'stamping'. **b**, A cross-sectional high-resolution transmission electron microscopy image of the metal-layered oxide interface. **c**, An optical microscope image of the transferred oxide. Credit: adapted with permission from ref. [1], Springer Nature Ltd.

directions, such crystals consist of charged planes of cations and anions. Each pair of charged planes generates an electrostatic field like a capacitor, and the total field becomes huge in a macroscopic crystal. Many compensation mechanisms have been observed, including surface metallization, surface reconstruction, and surface stoichiometry change. In a two-layer system, the simplest solution is to relax the cations and anions into the same plane, expanding the lattice parameter. The resulting graphitic structure contains only in-plane bonding, like graphene, and is an ideal candidate for mechanical exfoliation[4]. Multiple layers can be stabilized in some cases, and the different layers interact primarily through van der Waals forces. The critical aspect is precisely determining the conditions at which the graphitic structures form on the metals to avoid irreversible transformation into the thermodynamically stable metal oxide phase. Zhang and colleagues achieved this by highly polishing the metal surfaces and oxidizing in an oxygen poor environment.

As we have seen from graphene, hexagonal boron nitride, and molybdenum disulfide, much interesting and exotic physics may be hiding in the transition from 3D to 2D symmetry. 2D metal oxides that have a different structure than the bulk possess very different properties. Zhang and colleagues show their titania thin film with a hexagonal phase to be a p-type semiconductor with high hole mobility, and highlight exciting potential for applications in electronics devices. It is also well

conceived that the chemical reactivity differs in this 2D from, as has been demonstrated for zinc oxide layers in contact with a copper surface[5], which promises a degree of tunability for applications in catalysis.

The simple oxidation approach to produce 2D layered metal oxides has been successfully demonstrated for very different elemental metals, from transition metals, post-transition metals, to lanthanides and metalloids. However, one potential limitation is that, while it seems ideal to produce binary oxides, many technologically important metal oxides are more complex. For example, the perovskite family of oxide materials has drawn substantial interest recently because they exhibit tremendous property tunability. There has been some early success mechanically prying apart layers of Ruddlesden–Popper perovskites[6,7], which have a suitably layered structure, and there are wet chemical approaches[8] in which intercalation from solution aids in separating the component layers. It seems difficult to imagine such materials arising from controlled oxidation of an alloy, and alternative methods might need to be explored.

In their heavily cited review[9], Geim and Grigorieva highlighted the potential of van der Waals heterostructures built using the 'atomic-scale Lego' approach. One example was the intriguing possibility of mimicking layered high-critical-temperature bismuth strontium calcium copper oxide superconductors, in which graphene

could play the part of conductive copper oxide planes, with a 2D high-κ dielectric such as mica providing the interplanar spacing. Until now, challenges to produce the requisite 2D oxide layers and a lack of knowledge over their properties blocked the road. The growth of the oxide dielectric directly on the graphene was promoted to combine such materials[10]. The approach proposed by Zhang and colleagues enables a much simpler way to integrate 2D metal oxides layer by layer into heterostructures and certainly expands the list of materials to choose from. ❐

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