remain a mystery, hidden in the mists of the Scottish Highlands.

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The authors declare no competing interests.
This article was published online on 25 May 2022.

Electronics

A 2D insulator for the post-silicon generation

Soo Ho Choi & Soo Min Kim

A method has been developed for fabricating thin films of the 2D insulator hexagonal boron nitride with a uniform crystal orientation. The advance makes this material a key contender for replacing silica substrates in future electronics. **See p.88**

As the electronics industry looks beyond silicon as its material of choice, many 2D materials are being investigated as candidates for the next generation of transparent and stretchable devices[1,2]. The electrical insulator hexagonal boron nitride is a popular choice as a substrate for transistors in these devices, because thin films of the material are transparent and stable – both mechanically and chemically. But obtaining 2D hexagonal boron nitride samples that have a uniform crystal-lattice structure (in other words, a single crystal) is challenging. And building them into multilayered structures that are compatible with common industry practices is even more difficult. On page 88, Ma *et al.*[3] report the synthesis of five stacked layers of single-crystal hexagonal boron nitride using a technique called chemical-vapour deposition.

Thin films of hexagonal boron nitride have already been shown to be excellent substrates for field-effect transistors, the central component of a silicon microchip. For example, when a hexagonal boron nitride film is used as a substrate for a molybdenum disulfide field-effect transistor, the mobility of electric charge carriers is four times greater than that of the same device on a standard silica substrate[4,5]. But to become truly useful for electronics, these films need to be fabricated on a sufficiently large scale for use as a wafer – the substrate on which a chip sits.

Single-crystal hexagonal boron nitride monolayers (of single-atom thickness) have previously been synthesized on a wafer scale through a technique known as surface-mediated growth, using chemical-vapour deposition with liquid-gold and single-crystal copper substrates[6–8]. However, monolayer films have fewer applications than do multilayer ones. For example, when used as an insulator between two layers of the 2D material graphene, a monolayer might not be enough to fully suppress the transport of electrons between the two graphene layers – instead, stacks of layers are needed.

Multilayer hexagonal boron nitride films are typically grown by the precipitation of boron and nitrogen solutes from nickel and iron substrates. However, these substrates are polycrystalline, meaning that they have regions with locally perfect crystal structure, separated by boundaries at which the lattices do not always match up[9,10]. Precipitation occurs at different rates at these boundaries, causing the hexagonal boron nitride films to be polycrystalline, too, and to have varying thicknesses. Such polycrystalline structure degrades the mechanical and chemical stability of the film. And the varying

From the archive

A step forward for international efforts to curb pollution, and a warning about the perils of broadcasting.

50 years ago

The principle that the polluter must pay to clean up the environment has finally been accepted by the OECD ... The effect of companies having to pay to clean up their pollution will be to raise the price of goods whose production would otherwise greatly damage the environment. The ministers also resolved that subsidies should not be provided to offset this effect. The ministers also agreed that more stringent anti-pollution controls are needed, but that care must be taken not to create barriers to trade. Where such controls will affect products that are traded internationally, governments should seek common standards ... In the guiding principles that accompany the agreement, the ministers state that national pollution policies are bound to differ because of different social priorities and different levels of industrialization.

From *Nature* 2 June 1972

100 years ago

It is obvious that anything like secrecy in conversation over the radio-telephone, as it is now often called, is out of the question, as any one in possession of a half-guinea licence and a receiving set, which can be tuned to the wave-length employed, can "listen in" and pick up the message irrespective of the station for which it was primarily intended. On account of the publicity which thus attends the utterances of the wireless telephone, its field, except in such special cases as aeroplane work, is practically limited to the dissemination of public information, news, music, and other entertainment items, or as it is now commonly called, "broadcasting." Unless, however, these broadcasting stations are rigorously controlled, they will not only defeat their own ends by drowning each other's messages in a confused babel of sounds, but will interfere with other forms of radio-communication, as already happens to a considerable extent in America.

From *Nature* 3 June 1922

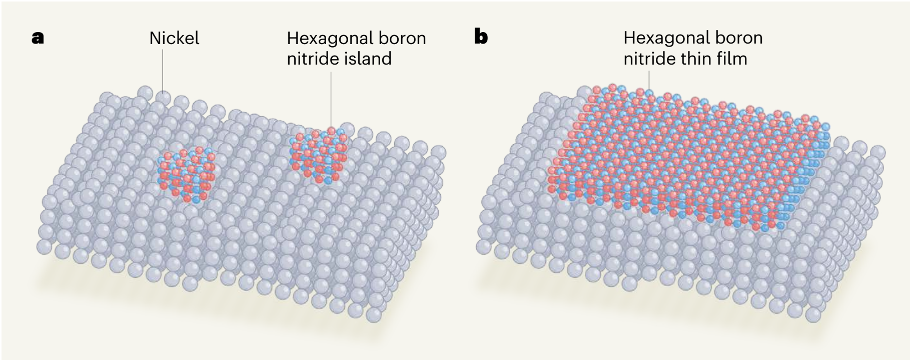

Figure 1 | Synthesis of a thin-film insulator with a uniform crystal structure. Ma *et al.*[3] devised a technique for growing thin films of the electrical insulator hexagonal boron nitride that had a uniform crystal orientation (a single crystal). The method enables growth of up to five single-atom-thick layers on a scale sufficiently large for use as a wafer — the substrate on which a microchip sits. **a**, In the authors' approach, islands of hexagonal boron nitride first nucleate at the stepped edges of a single-crystal substrate that exposes the (111) crystallographic plane of nickel. **b**, The nickel ensures that the islands have the same crystal orientation, and this leads to the growth of a single-crystal film when the separate islands coalesce.

thicknesses can lead to disparities in device performance, which ultimately limits the scale on which hexagonal boron nitride films can be used in electronics.

Clearly, a new technique for growing single-crystal multilayer hexagonal boron nitride films was required. Ma *et al.* have now delivered such an approach: a state-of-the-art growth technique for wafer-scale single-crystal hexagonal boron nitride films of up to five layers. The method uses a single-crystal sheet that exposes the (111) crystallographic plane of nickel — an atomic array with stepped edges.

Getting the temperature right is key to the success of the process. The team found that when the films are grown at 1,020 °C, a polycrystalline structure results. However, at higher temperatures of between 1,120 and 1,220 °C, the method gives rise to grains comprising three layers of hexagonal boron nitride with exactly the same crystal orientation (Fig. 1a). This, in turn, leads to the growth of a single-crystal film when the separate grains coalesce (Fig. 1b). During this initial growth stage, islands of trilayer hexagonal boron nitride nucleate at the stepped edges of the nickel surface, which ensures that the orientation of their crystal lattices are aligned. Over time, these islands grow larger and eventually merge without forming grain boundaries.

The authors showed that they could go beyond trilayer hexagonal boron nitride by varying the growth conditions, because the thickness is determined by surface-mediated growth, rather than by the precipitation mechanism. They succeeded in synthesizing samples containing five layers. However, controlling the thickness of multilayer samples was not straightforward. The binding energy of the sample to the nickel substrate decreases for one, two and three layers, but for samples comprising four or more layers, the binding energy does not change appreciably with each layer, making it difficult to control sample thickness above three layers.

Curiously, although the authors showed that it was possible to fabricate hexagonal boron nitride films comprising five layers, they could not synthesize samples containing four or six layers. The physics underlying this property remains unclear, as does the growth mechanism itself, and both will need to be elucidated before the technique can be used in soft electronics.

Finally, to be used as a substrate for transistors or as an insulating barrier between other 2D materials, hexagonal boron nitride films need to be around ten nanometres thick[11]. Whether or not Ma and colleagues' method can achieve such thicknesses is not known. However, a preliminary demonstration by the authors suggests that trilayer single-crystal films synthesized using this technique can increase the charge-carrier mobility in a molybdenum disulfide field-effect transistor.

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The authors declare no competing interests.

Neuroscience

Closing the window on memory linking

Andrea Terceros & Priya Rajasethupathy

An immune molecule has an unexpected role in memory formation — specifically, in limiting the window of time in which newly forming memories can be contextually linked. **See p.146**

Memories acquired close together in time often become linked, such that recalling one memory leads to recall of another. For instance, one of us (P.R.) recently visited the Metropolitan Museum of Art in New York City and remembered that the last time she'd been there, she had walked through Central Park just afterwards and spotted a rare and beautiful snowy owl. The museum and snowy owls had become forever linked in her memory. In 2009, two groups[1,2] observed that neurons in the brain can participate in multiple memory networks that are laid down closely in time, thus enabling memory linking. The activity of a transcription-factor protein called CREB promotes this neural co-allocation, but what limits it? On page 146, Shen *et al.*[3] make the unexpected discovery that the answer lies in an immune molecule that segregates memories by limiting the time available for linking to occur.

How does the brain know that two events are occurring closely in time? Addressing this question requires an understanding of how time is encoded in memory — a major unknown in memory research. Time can be encoded in an absolute or relative manner and encompasses varied scales. For example, some models suggest a moment-to-moment perception of time through a centralized internal clock[4]. Others suggest a more distributed representation, in which time is an emergent