**////Title: Growing Stacks of 2D Materials for Electronic Applications**

**////Standfirst:**

By stacking layers of atom-thick materials on top of each other, researchers are opening up a whole host of exciting new possibilities for technology and scientific research. Particularly interesting properties in these 2D materials could be achieved by stacking three or more of these layers – but so far, the large-scale production of these structures has proven difficult. Using carefully applied techniques, Dr Jakub Sitek and his team at Warsaw University of Technology have made important steps towards overcoming this challenge.

**////Main text:**

2D materials are among the most dynamic and rapidly-growing branches of modern physics. Perhaps the most famous of these materials is graphene – an atom-thick sheet of carbon atoms, arranged in a honeycomb lattice, which is renowned for its unique electrical, mechanical, and heat-conducting properties.

As our ability to synthesise new molecular structures improves, the existing family of 2D materials is expanding, with materials including hexagonal boron nitride and semiconducting transition metal dichalcogenides, which exhibit their own sets of fascinating characteristics. Recently, researchers have developed even more remarkable arrays of unique properties by stacking different 2D materials on top of each other.

In these structures, atom-thick layers stick together through weak interactions between the atoms and molecules they contain, named van der Waals forces. Van der Waals forces are responsible for allowing geckos to climb smooth, vertical walls without their feet slipping off. Through these interactions, new properties can emerge that could never be found in individual 2D materials.

With virtually endless possibilities for combinations and arrangements of 2D materials, these stacks, named ‘van der Waals heterostructures’, could one day provide a unique playground for studying fundamental physics. For example, some of these heterostructures are already known to conduct heat in just one single direction. Elsewhere, they could see uses across a wide array of applications in electronics, including nano-scale transistors, light detectors, and LEDs. Despite these immense benefits, there is still some way to go before van der Waals heterostructures can reach their full potential.

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Before these heterostructures can become ubiquitous in our everyday lives, it is crucial for 2D materials to be fabricated on large scales, using repeatable methods that maintain the structures of their orderly molecular lattices. Currently, the individual layers are typically grown on top of flat, solid substrates in separate synthesis processes, which are then mechanically transferred and stacked in the desired order.

In the process, the layers being transferred are prone to mechanical damage, such as stretching and tearing – inevitably damaging the device’s final performance. This ultimately means that although high-quality 2D materials can already be produced on large scales, the need for a transfer process is preventing the more widespread rollout of van der Waals heterostructure stacks.

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In a recent study, Dr Jakub Sitek and his colleagues in Poland, the UK, and Switzerland explored how this challenge could be addressed through a technique named chemical vapour deposition. In this method, a flat substrate is first exposed to a hot vapour of the material to be deposited. As this vapour deposits on the substrate under carefully controlled conditions, a thin solid layer forms on its surface.

So far, this technique has been used to fabricate high-quality 2D materials with uniform molecular structures, including conducting graphene, insulating hexagonal boron nitride, and semiconducting molybdenum disulphide. Even further, it has allowed researchers to fabricate two-layer van der Waals heterostructures in which one 2D material is deposited on top of another, without damaging the bottom layer. So far, however, adding three or more layers to these stacks has proven to be far more difficult.

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Dr Sitek’s team has now become one of the first to overcome this challenge. By carefully controlling their growth conditions, the researchers first grew crystals of another semiconductor, named tungsten disulphide, onto a layer of graphene – itself deposited onto a sapphire substrate. During tungsten disulphide deposition, the interaction between this substrate and the graphene layer held its carbon atoms in place, preventing any unwanted degradation. Finally, they grew a third layer of molybdenum disulphide onto the tungsten disulphide layer.

The team used a variety of techniques to verify that each layer had maintained its atom-thick structure during chemical vapour deposition, without any of the three layers diffusing into each other. Among these was Raman spectroscopy – which provides detailed information about the chemical structures of materials, based on their interaction with light passing through them.

In addition, they used atomic force microscopy – which involves ‘feeling’ the atomic-scale bumps, dips, and ridges in a material using a tiny mechanical probe. Furthermore, through secondary ion mass spectrometry, they used a powerful ion beam to eject ionised atoms from the structure’s surface, whose mass-to-charge ratios could then be analysed.

Having confirmed that each 2D material in their stack had maintained its structure during chemical vapour deposition, Dr Sitek and his colleagues also used these techniques to investigate the mechanisms involved in the material’s growth. Altogether, their analysis revealed that just two factors were necessary for describing the formation of the 2D materials.

The first of these was the chemical potential of the 2D material formation – a value encompassing the temperature, pressure, and the chemical compositions of the vapour used in the synthesis process. The only other value required to characterise the deposition process was the adhesion energy between the top-most layer and the newly synthesised 2D materials. The researchers concluded that growing 2D materials on other 2D materials is easier than on commonly used substrates, such as sapphire.

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The team’s results are already immensely promising for the future development of van der Waals heterostructures in both everyday technology and cutting-edge research. For example, the two semiconducting materials used in their experiment were chosen for their promising potential applications in light-detecting devices, while the graphene underlying them could act as a highly effective channel for conducting electrical current through the device.

These unique characteristics allowed Dr Sitek’s team to demonstrate a device that could store and read out memory, simply by proving it with light. The researchers now hope that the success of their approach will inspire a new wave of research into the exciting behaviours of stacked 2D materials, and the rich array of applications they may hold.

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This SciPod is a summary of the paper ‘Three-step, transfer-free growth of MoS2/WS2/graphene vertical van der Waals heterostructure’, from 2D Materials. [doi.org/10.1088/2053-1583/ac5f6d](https://doi.org/10.1088/2053-1583/ac5f6d)

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