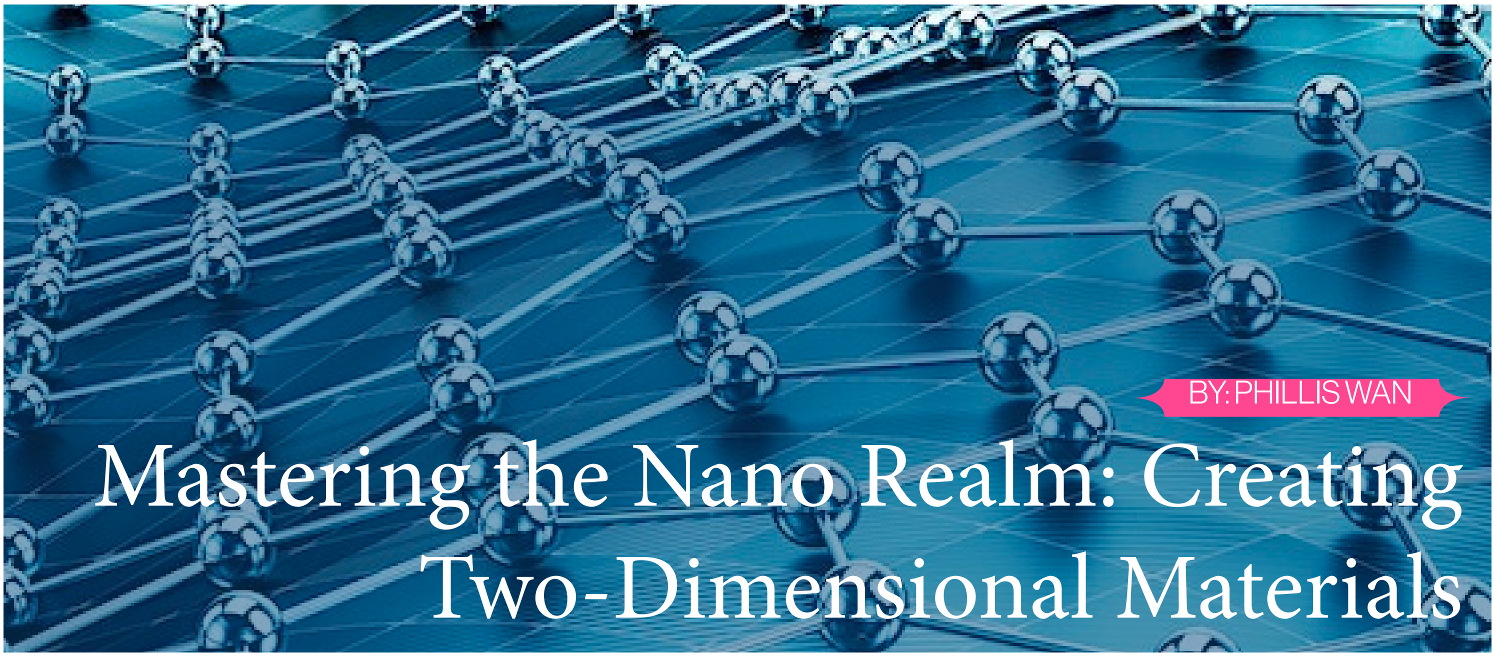

BY: PHILLIS WAN

# Mastering the Nano Realm: Creating Two-Dimensional Materials

What would you do if you had scotch tape and pencil lead? For physicists Andre Geim and Konstantin Novoselov, the answer was simple: use scotch tape to peel off each layer of graphite one by one until one single layer of carbon sheet is obtained.

This was made possible because of the unique structure of pencil lead, also known as graphite. Graphite is composed of stacks of neatly arranged carbon sheets which are held together by intermolecular forces (IMFs); IMFs are relatively weak compared to the covalent bonds that fix the carbon atoms in a honeycomb pattern within each layer. On a macroscopic level, the dark pencil markings we leave on the paper are the shedding layers of graphite.

After the tedious work of isolating and characterizing a thin two-dimensional layer of carbon atoms—scientifically known as graphene—Geim and Novoselov discovered that this material exhibits exceptional capability to conduct electricity, transfer heat, and resist tensile forces. Their discovery sparked a wildfire of interest in the field of two-dimensional materials science, and they were awarded with the Nobel Prize in 2010 for being the first to isolate and characterize graphene.

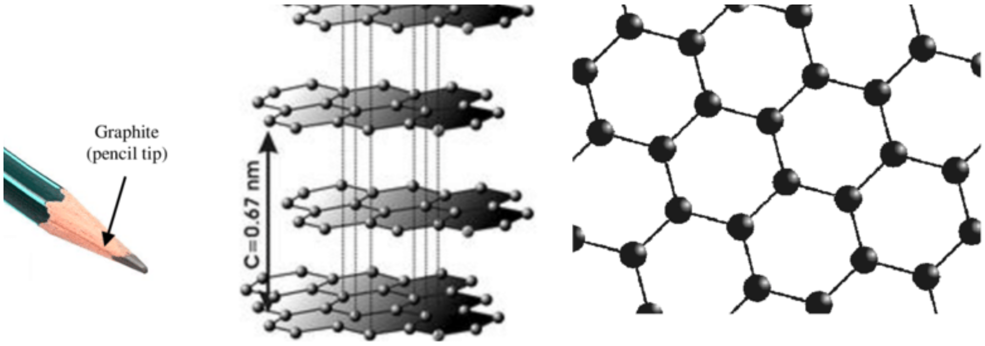

**Figure 1: This image shows the structure of graphite, commonly known as pencil lead.** The structure in the middle is graphite, made up of stacks of carbon sheets and held together by weak London Dispersion forces. The rightmost structure is graphene, which is a single layer of carbon atoms held together by strong covalent bonds.

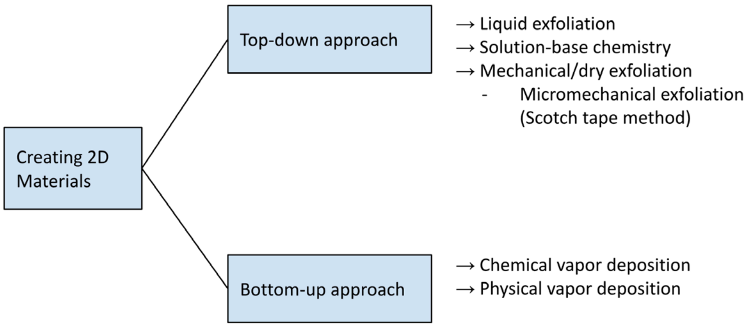

**Figure 2: The two main approaches to isolating or creating two-dimensional materials.**

As the name suggests, 2D materials are atomically thin and form two-dimensional structures. Conductive 2D materials, such as graphene, can help create nanoscale electronics with increased efficiency and processing power.[1] Additionally, the ability to control the growth and synthesis of an atomically-thin film empowers scientists to facilitate innovation in diverse fields: developing hydrophobic (water-repelling) coating that creates a barrier that protects metals from rusting, improving the strength and resilience of durable concrete structures, and creating large surface area for drug delivery within the human body.

However, the challenge lies in the ability to manufacture these atomically thin materials. Currently, the two main methods for doing so are the "Bottom-up" approach and "Top-down" approach.[2]

## TOP-DOWN APPROACH: EXFOLIATION TECHNIQUES

The "top-down" approach seeks to create 2D nanosheets by separating bulk materials into nanosheets, often using either liquid exfoliation and mechanical exfoliation. As their names suggest, both exfoliation methods

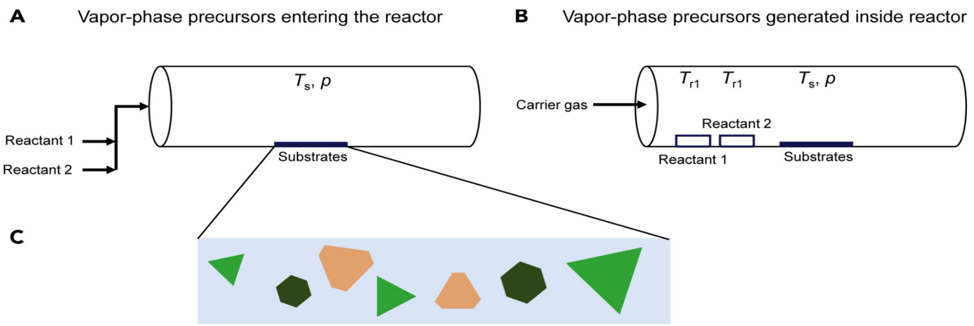

**Figure 3: CVD mechanism.** In figure A, gas-phase precursors are introduced into the reactor via mass flow controllers. Figure B depicts another variation of CVD mechanism not discussed in this article. Figure C shows that a variety of shapes that are typically formed on the substrate from graphene and materials of similar crystalline structures.

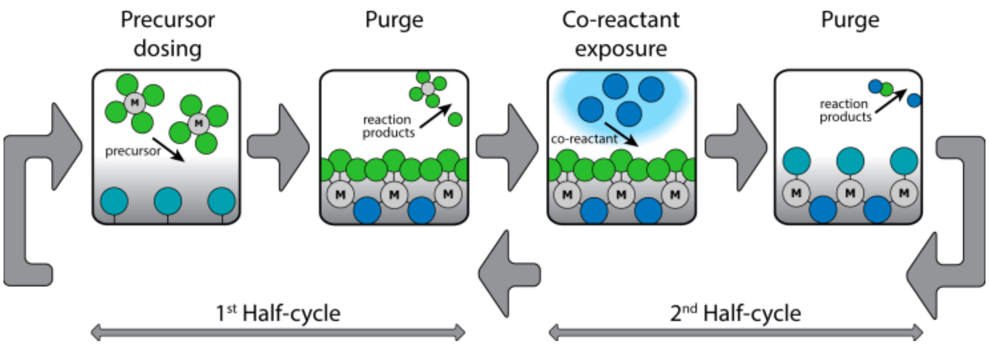

**Figure 4: Schematic illustration of a typical ALD cycle consisting of two half-cycles.** Sequential precursor (reactants) and co-reactant doses are separated by purge or pump steps, leading to self-limiting film growth. 'M' indicates the metal atom, which can for instance be bound to oxygen or nitrogen atoms (in blue), to form a metal oxide or metal nitride, respectively. Precursor ligands are colored green and are eliminated by reaction with the co-reactant before being purged away.

are focused on peeling away thin layers or flakes of a material from a larger surface. For liquid exfoliation, "peeling" takes place in a solvent that weakens the intermolecular forces between each layer of the bulk materials and allows for the extraction of each nanosheet. Dry exfoliation splits bulk materials through mechanical forces, where specially-designed adhesive tape are used to extract uniform sheets from the starting material, which includes the scotch tape technique that Geim and Novoselev used to isolate graphene.[3]

However, since not all materials can be broken down into singular sheets, top-down approaches are not able to arrange and engineer thin films for specific properties and applications. In contrast, the bottom-up approach is not only more scalable in production, it also provides more control over the size, shape, and purity of the desired 2D material.

## BOTTOM-UP APPROACH: CHEMICAL VAPOR DEPOSITION AND ATOMIC LAYER DEPOSITION

The "bottom-up" approach constructs 2D materials from molecular precursors (reactants) that react and grow or self-assemble into a more complex structure.[4] The two most common techniques under this approach are chemical vapor deposition and atomic layer deposition.

In chemical vapor deposition (CVD), a thin film is grown on top of a surface (called the substrate) by vaporizing the desired compounds and introducing them to the substrate surface to form a layer of atoms. This layer acts as the starting point for the growth of the surface, where the absorption of additional precursor gases allows the film to grow and expand.

As shown in Figure 3, the process begins with compounds that contain the desired elements for the formation of the 2D materials. As the compounds are vaporized (via heating or reducing air pressure), they enter the reactor containing the substrate that is to be coated.[5] The initial layer of molecules formed on the substrate surface serves as the starting point for the growth of the 2D materials. With the flow of additional precursor gases into the reactor, the thin film undergoes chemical reactions that lead to the growth of the coated surface.

CVD allows scientists to work with hydrophobic (insoluble in water) materials, which would not have been possible to accomplish using the conventional solution-based methods of creating 2D materials. Atomic layer deposition (ALD) is very similar to the chemical vapor deposition. Both involve the vaporization of desired compounds and the deposition of the thin film upon a substrate. However, the vaporized monomers in ALD are introduced sequentially into the chamber with purging steps in between.[6]

In each cycle, a single atomic layer is deposited on the substrate in a self-regulating manner, where excess gas will be purged in the next step once all the available space is filled up. This is distinct from CVD, which is characterized by a continuous flow of precursor gases, and allows ALD to have higher precision control over film thickness and the ability to create extremely thin and uniform films.

## POTENTIAL APPLICATIONS

High precision, uniformity and crystallinity, and control of film thickness are essential properties required in the semiconductor industries. ALD and two-dimensional materials have much to contribute to future development of nanoscale transistors; their capabilities to precisely adjust thickness and change the physical properties of surfaces by adding specific chemical components allows them to protect and enhance semiconductor performance on a nanoscale level.[7]

The clean energy sector may also benefit from the ability to create and modify thin films for enhancing the efficiency and durability of materials for solar panels. Additionally, 2D materials might be the answer to producing clean energy via hydrogen fuel cells, which garners the energy released by the synthesis of water from hydrogen gas and oxygen gas.[8] The only limit to its feasibility is an efficient way to generate hydrogen gas, and a 2D material coating, which increases the efficiency of the electrodes in artificial photosynthesis to split water, might be one step closer to the clean energy source we desire.

As a relatively new field, 2D materials hold great potential in technological innovations with applications spanning from electronics to healthcare to energy and beyond. Learning to leverage and fine tune specific properties within these materials allows researchers to reshape the future and expand the existing possibilities of science.

## ACKNOWLEDGEMENTS

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