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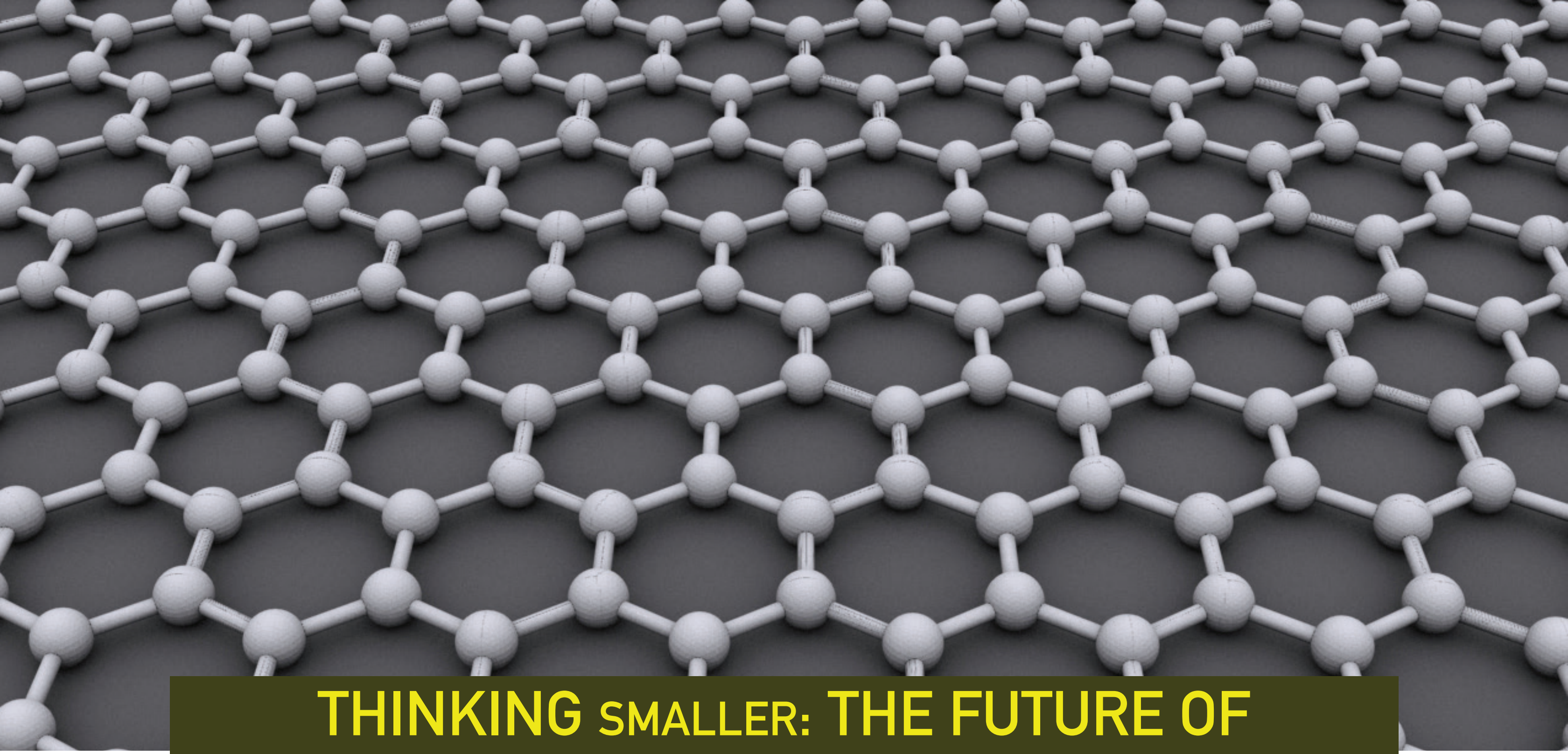

THINKING SMALLER: THE FUTURE OF TWO-DIMENSIONAL MATERIALS

BY MINA NAKATANI

Los Angeles, Chicago, New York. Huge metropolitan cities with skylines defined by towering skyscrapers and blinking lights that stretch high above the heads of those walking the streets. People crane their necks to see the literal heights of human accomplishment, because building higher in three-dimensional space—overcoming the limits of gravity—has long been an incredible feat of engineering and technology. But what if the path to advancement exists in two dimensions rather than three?

The field of two-dimensional materials is a fairly new one, focusing on materials that are only a single molecular layer thick. These materials are not like the physical matter that people come into contact with in daily life, which typically consist of many layers of atoms stacked on top of each other, forming a three-dimensional object. Instead, the structure of two-dimensional materials is a bit like that of sticky notes: if a three-dimensional material like graphite is like the block of notes purchased at a store, graphene is like a single note pulled off the block. Like the flexible single sheet compared to the rigid block of sticky notes, two-dimensional materials have different properties—electrical, chemical, and physical—from their three-dimensional counterparts, giving them enormous potential, despite the challenges they still need to overcome.

One such challenge for two-dimensional materials arises largely from the recency of their development. In the field of electronics, their structure is often incompatible with the shapes and structures used for three-dimensional materials. The process of conforming them to a certain geometry would most likely damage such thin sheets, ruining their electronic functions in the process.[1] Beyond that, recent studies show that, in terms of performance, two-dimensional materials such as molybdenum disulfide (MoS_2) can compete with silicon in electronic devices, but only by utilizing a delicate fabrication process involving the use of nanometer-wide wires in order to achieve particular geometries.[2] This need for structural changes also complicates the issue of synthesizing two-dimensional materials. Though it is true that merely peeling single-layers off of graphite using tape—a process first used in the early 2000s and later involved in Nobel Prize-winning research in 2010—does yield graphene, the shape and presence of defects cannot be reliably controlled.[3] For this reason, working

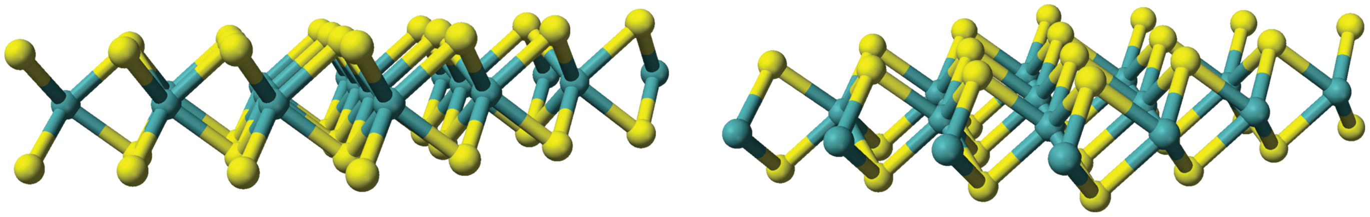

Figure 1: Structure of Molybdenum Disulfide (MoS_2). *Molybdenum disulfide is one type of two-dimensional material which exhibits unique electrical properties, allowing it to possibly be utilized in a number of different applications, from electronics to gas sensors.*

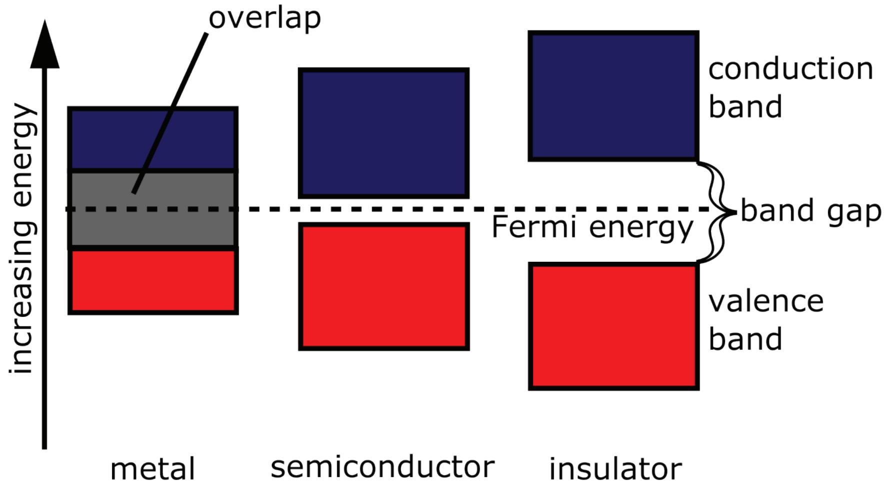

Figure 2: Band Gaps.[12] *Electricity flows through a material via movement of electrons from the valence band (red) to the conduction band (blue). Insulators have a big gap which electrons cannot cross—no electricity can flow. Metals have no gap, making them conductors. Semiconductors have a small gap that electrons can cross, but not as easily as in metals.*

with two-dimensional materials is more complicated and time-consuming. Creating a two-inch sheet of graphene, a relatively simple structure consisting only of carbon atoms arranged in hexagons, under controlled conditions can take upwards of seven hours. Creating more complex two-dimensional materials takes greater time and control over environmental conditions, no match for the relatively easy industrial production of silicon-based devices.[4]

Nonetheless, two-dimensional materials offer unique benefits that three-dimensional materials cannot. Materials such as MoS_2 exhibit properties of semiconductors; thus, they are similar to silicon in that their band gaps are fairly small (Fig. 2).[5] These properties imply that materials such as MoS_2 are theoretically capable of replacing silicon (Fig. 3) while offering even greater utility. As a two-dimensional structure, MoS_2 is able to withstand deformation, capable of bending and stretching without breaking. MoS_2 is flexible in ways that three-dimensional silicon is not.[5] This phenomenon is much like the way in which paper can be folded without tearing. As such, two-dimensional materials are attractive not only for the creation of stretchable and wearable electronics,[6] but also for their tunability, or the ability of a given material to have slightly different properties depending upon the intended use. MoS_2 in particular does have a bandgap indicative of a semiconductor, but the actual size of that gap is dependent on the strain experienced by the material. Therefore, physically stretching the material changes how well it is able to conduct electricity, and thus allows the material to be adapted to a variety of different needs. In fact, sufficiently stretching a layer of MoS_2 forces it to conduct electricity as if it were a metal, a versatility that silicon cannot match.[5]

"By running energy through the material and monitoring conductivity of only two to four layers of MoS_2, NO gas can be detected even at low concentrations of 0.8 ppm, less than one ten-thousandth of a percent."

Adjusting the chemical structure of these materials—by adding in other molecules or combining multiple kinds of two-dimensional layers—also allows for further control of their properties. Again, MoS_2 exhibits this ability well. By binding different functional groups to the surface—sticking new molecules onto the sheets—or changing the actual geometry of the bonds in MoS_2 itself, the size of the bandgap is theorized to change by 25%.[7] Though that may seem small, given the size of the electron itself, a change of 25% is significant. This change allows MoS_2 to fulfill a wide range of needs in electronics.

The tunability that comes from the sensitivity of MoS_2 to the presence of other molecules also allows it to function as a low-energy, highly effective gas sensor.[8] Considering that the conduction of MoS_2 should change with the introduction of other molecules, researchers found this principle to remain true with nitric oxide (NO) gas, a chemical linked to acid rain and the depletion of the ozone layer. By running energy through a MoS_2-based gas sensor and monitoring its conductivity, NO gas could be detected even at low concentrations of 0.8 ppm, or less than one ten-thousandth of a percent.[8] Furthermore, the unique tunability of two-dimensional materials also plays a part in their performance as gas sensors. By merely changing the thickness of the MoS_2 within the sensor from 18 nanometers to 2 nanometers—about the width of a strand of DNA—the sensor's sensitivity to nitrogen dioxide (NO_2) gas increased from 0.8% to 7%.[9] Beyond that, by binding platinum ions to the surface of the sensor, its sensitivity sensor is tripled, allowing it to detect NO_2 down to a concentration of 2 ppb, or 0.0000002 of a percent.[9]

"In fact, sufficiently stretching a layer of MoS_2 forces it to conduct electricity as if it were a metal, a versatility that silicon cannot match."

The flexibility of two-dimensional materials and their ability to respond to a number of different chemical environments also allows these gas sensors to detect both air pollutants and organic molecules. Namely, certain molecules such as toluene, ethanol, and acetone, are known markers of lung cancer, existing in the

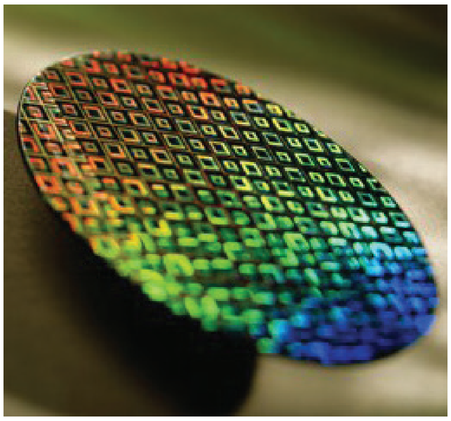

Figure 3: Silicon Computer Chip. *Silicon is the most widely used semiconductor, used to produce silicon chips for computers. As a semiconductor, it exhibits a small band gap, allowing it to be turned "on and off," acting as either a pure conductor or insulator—or something in between—depending on its environment. This variability in conductivity is the reason semiconductors are so useful to electronic devices.*

breath of diseased patients.[10] MoS$_2$-based sensors can detect these molecules much like they can detect NO or NO$_2$ gas; by binding a molecule called mercaptoundecanoic acid to the surface of MoS$_2$, the sensor can give unique responses to each different molecule, doing so to a limit of 1 ppm.[10] As such, this two-dimensional gas sensor can be used for more than pollution detection, also functioning as a simple breath analyzer for medical diagnosis.[10]

Much of modern technological advancement is exemplified by the huge structures of metropolitan cities. But some of the most remarkable feats of technology have come from making things smaller. Computers that fit in backpacks and phones that slide into back pockets are the most well-known examples, and two-dimensional materials are merely an extension of that same concept. They present the idea of thinking in new dimensions, looking for answers in places previously unexplored. The way to advancement—in all fields, not only technology—comes from new perspectives and courage to change the way things have always been done.

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Figure 4: Nitrogen dioxide (NO$_2$) gas.[13] *MoS$_2$-based gas sensors are capable of detecting gases such as NO$_2$ and toluene, even at low concentrations.*

IMAGE REFERENCES

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