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Received: 26 March 2021 | Revised: 16 April 2021 | Accepted: 17 April 2021

DOI: 10.1002/est2.244

REVIEW

ENERGY STORAGE WILEY

Recent trends and emerging challenges in two-dimensional materials for energy harvesting and storage applications

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Abstract

By itself, the physics of two-dimensional (2D) materials are often fascinating. All the atoms of these elemental 2D materials are exposed to the surface, making it relatively easier to tune the structure and physical properties of the materials using surface treatments. The discovery of graphene has sparked a flurry of research into graphene-related 2D materials such as silicene, germanene (a hexagonal network of silicon and germanium), stanene, borophene, and a zoo of other 2D materials. In this article, the discussion is on the 2D materials, the synthesis methods of the 2D materials, and the energy applications of the 2D materials.

KEYWORDS

2D materials, graphene, energy applications

1 | INTRODUCTION

In the 21 century, the development in technology increases very speedily. For the development of technology, one factor that is very important to understand is a material system. Material system means the nature of the material, properties of the material, and so forth. Different materials have specific properties for different applications. Just take the example of different things, the copper wires are used to build electric circuits, rubber is important for tires and the elasticity and toughness of that rubber is very important. As we understand more the properties of the material, we further push the technology. To study the properties of any material, first study what the material made of, what is the size of the material, what is the shape of the material, and many more other things.[1]

The size of the material is very important it affects the properties of the material. The nature of the material changes with its size. The materials have different properties at the nanoscale. When the size of the material is at the nanoscale the electrical, chemical, mechanical properties are changed, even the behavior of material interacting which light is changed at the nanoscale.[2] There is a range of 1 to 100 nm for the size on this scale, which may apply to all three dimensions. For any object, either one dimension or all three dimensions may be nanoscale.[3] There are four groups for all these dimensioned nanomaterials, such as three-dimensional (3D), two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) materials. Based on their characteristics, such materials may be of varying size, structure, state, and shapes to be bulk, liquid, or solution form. There is also a layered structure of some of the materials. Their wide implementations will also rely on the form and dimension of materials in the electronic and technological industries.[4]

Such materials are divided into the following types also shown in Figure 1[5]:

1.1 | 3D materials

If all dimensions of a substance are greater than nanosize (ie, they are either micro or larger) such that it can be

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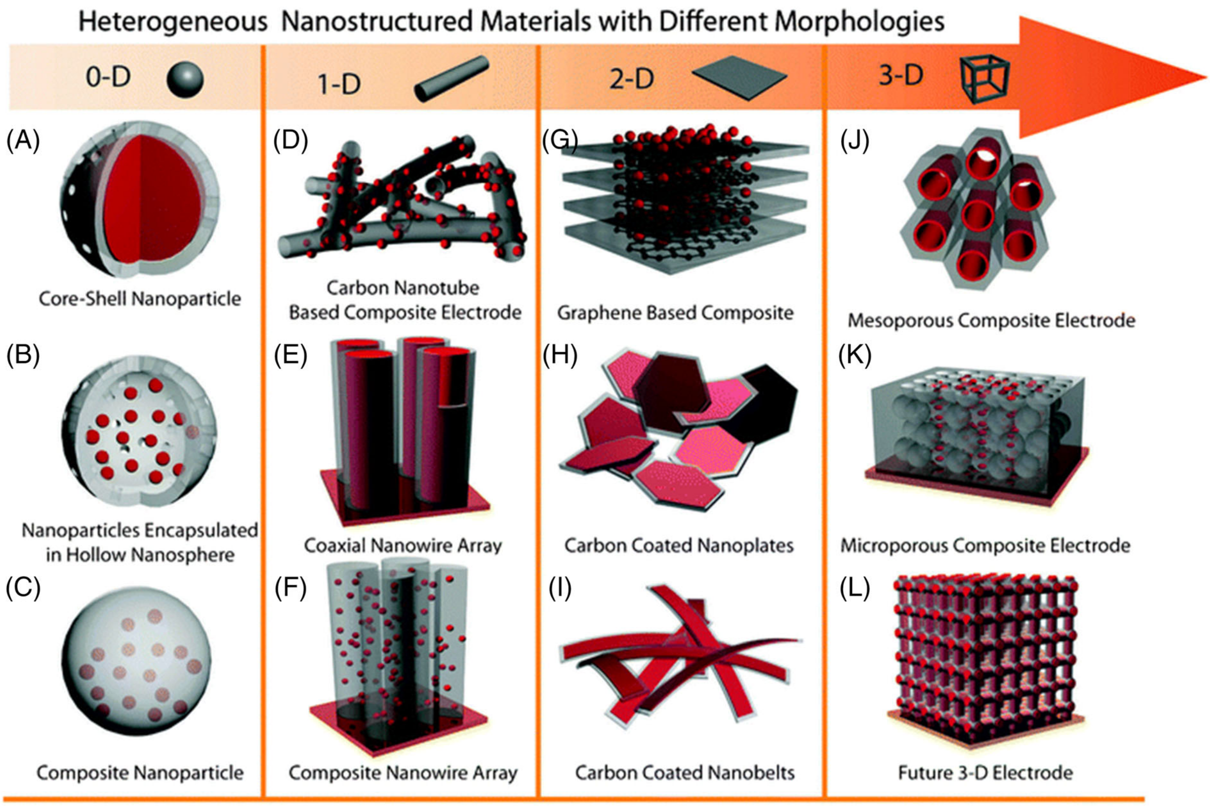

FIGURE 1 Structures of nanomaterials based on dimensions[5]

seen by the naked eye, 3D materials such as a rope or a ball are considered that type of material.

1.2 | 2D materials

If one of the dimensions of any substance is nanosized and two others are not, so 2D materials such as nanosheets are considered that kind of material.

1.3 | 1D materials

When two dimensions of a substance are nanosized, and one dimension of the material is in cm or mm, 1D material such as nanotube or nanowire is considered that type of material.

1.4 | 0D materials

If all three dimensions of a substance are beyond the Micro or Nanoscale the scale then, like a quantum dot, is called 0D material.

Graphene, the first 2D material, was discovered in 2004.[6] Many 2D materials, such as Xenes, phosphorene, germanene, antimonene, borophene, stanene, silicene, tellurene, and tinene, were found after that. The emphasis of this article is on 2D materials, their synthesis processes, the structures of various 2D materials, and their energy applications (2D).

2 | SYNTHESIS OF 2D MATERIALS

Any material may be slimmed down to create a 2D substance (until it has a thickness of just a few atoms). However, because certain materials (such as diamonds) have molecular bonds that are oriented in three dimensions, thinning the substance requires breaking these bonds, leaving them hanging. A 2D material formed in this manner would have a high density of chemically and energetically unstable hanging bonds, causing the material to rearrange its shape to lower its surface energy. Another allotrope of carbon-graphite has solid chemical bonds only along planes within the bulk material. These planes are stacked on top of one another and held together by a weak van der Waals interaction, but they can be removed without leaving any loose bonds. The term graphene refers to a single plane of graphite. As a result, the vast majority of the 2D materials studied are layered materials.[7]

The synthesis of 2D materials can be done in two ways.

- Top-down
- Bottom-up

There are also subbranches of these two main synthesis techniques.

2.1 | Top-down

2.1.1 | Mechanical exfoliation method

For the first time, this process was used to make monolayer graphene. Scotch tape technique is another name for this approach. This approach involves placing a piece of sticky tape on the surface of layered material and peeling it away, leaving flakes behind. By pressing the tape against the substrate, the flakes can be transported to it. The yield of monolayers produced by this method is low, and there is no control over their size or shape. Due to the lack of chemical processing, the size of monolayer flakes that can be made is sufficient, ranging from a few microns to 100 μm, and monolayer quality is excellent, with very few defects. It is also a strategy that can be used with any van der Waals stuff. For these reasons, mechanical exfoliation is widely used in lab experiments, but it is not scalable for use in new technologies (Figure 2).[8]

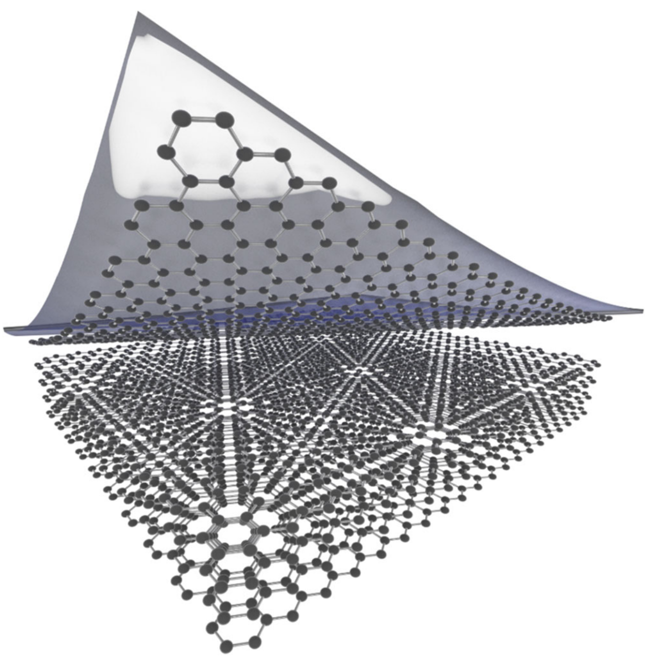

FIGURE 2 A general diagram of the mechanical exfoliation method[8]

2.1.2 | Liquid exfoliation method

This is a kind of 2D material top-down synthesis technique. To transfer mechanical force to the layered material, which is often in the form of a powder suspended in the liquid, an organic solvent is used as a medium. Sonication causes the layers to separate by applying tensile stress to them. Add reactive ions (between the material layers that create hydrogen bubbles) to shove the layers apart, or rapidly mix the solution to increasing shear force on the layers to improve monolayer yield.

This technique is immensely beneficial, but it does have its disadvantages. The yield of monolayers is low, and flakes are usually less than 100 nm in size (due to the applied forces breaking them apart). When the flakes are removed from the solution, they may contain a high density of defects as well as residual solvent, making them unsuitable for many optoelectronic applications (Figure 3).[9]

2.2 | Bottom-up

2.2.1 | Chemical synthesis in solution

A variety of procedures have been developed to synthesized 2D materials using wet chemical methods. Among these are high-temperature chemical reactions in solution, interface-mediated growth (reactions occur only at the liquid's surface), nanoparticle fusion into bigger nanosheets, and a multitude of other processes. Each method is better suited to a particular type of 2D material, and the best method can be used to synthesized everything from graphene and transition metal dichalcogenides (TMDCs) to monolayer metals. These methods produce small flakes (in the hundreds of nanometers), which suffer from the same residual solvent problem as liquid exfoliation. Chemical synthesis, on the other hand, is the most scalable, low-cost, and flexible approach for large-scale production for certain applications.[10]

2.2.2 | Chemical vapor deposition

A heated furnace is used to pass one or more precursor gases (which usually contain the atomic ingredients of the required film) through, where they combine or with a substrate to form a thin layer of the necessary material. With great success, this approach has been used to grow graphene and TMDCs. Several parameters, such as gas pressures and compositions, temperature, and reaction times, must be closely controlled because they affect the

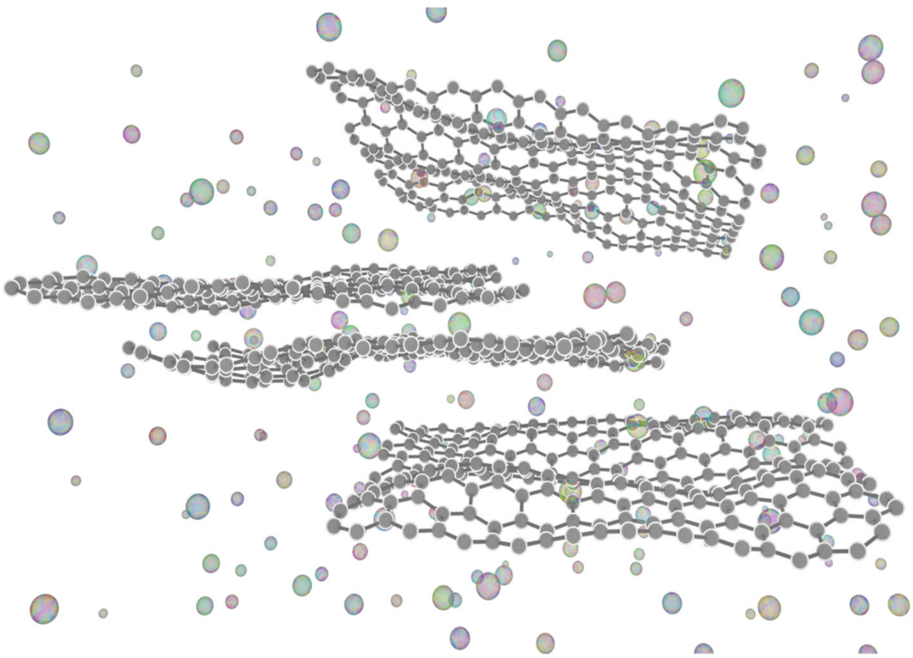

FIGURE 3 A general diagram of liquid exfoliation method

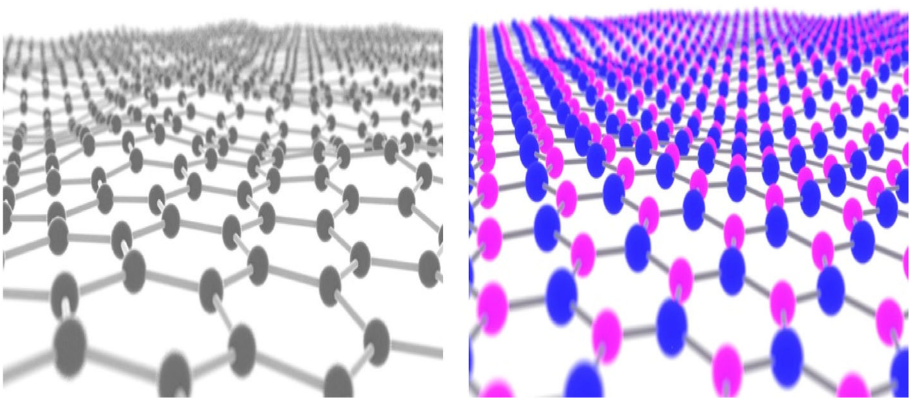

FIGURE 4 A single monolayer of graphene (left side) and a single monolayer of hexagonal boron nitride (right side)[14]

film thickness, quality, and composition. While this method is more complex and expensive than most top-down techniques, it is highly scalable, and the films produced are like mechanically exfoliated layers in quality.[11]

2.3 | Some types of 2D materials

2.3.1 | Graphene

Graphene was the first modern 2D element to be isolated in 2004. Graphene is a covalently bonded hexagonal lattice of carbon atoms that is one atom thick (about 0.14 nm). It is a semimetal of some kind (its conduction and valence bands both touch). Electrons move through graphene at extraordinarily high speeds (roughly 1/300 the speed of light) due to its unique band structure, making it unique properties such as thermal conductivity. Graphene has the highest tensile strength of any material and is optically clear, absorbing only 2% of incident visible light. A single graphene monolayer is just 0.3 nm thick.[12]

2.3.2 | Hexagonal boron nitride

Hexagonal boron nitride is a graphene isomorph (it has the same crystallographic appearance as graphene) with boron and nitrogen atoms instead of carbon. Unlike graphene, it is a wide-bandgap insulator (Figure 4).[13]

2.3.3 | Xenes

Xenes are a group of silicon, germanium, and tin monolayers. Figure 5[15] shows a buckled hexagonal structure of

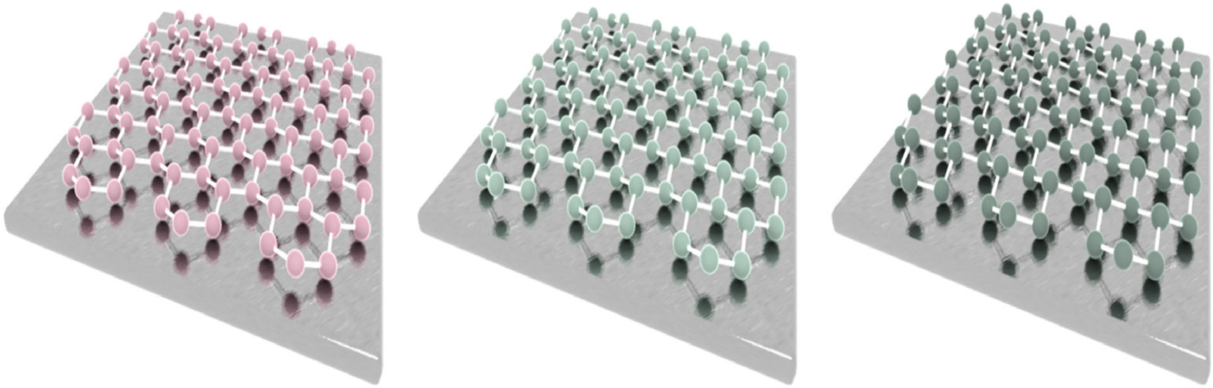

FIGURE 5 Buckled hexagonal structure of tin (right side), silicone (left side), and germanium (middle)[15]

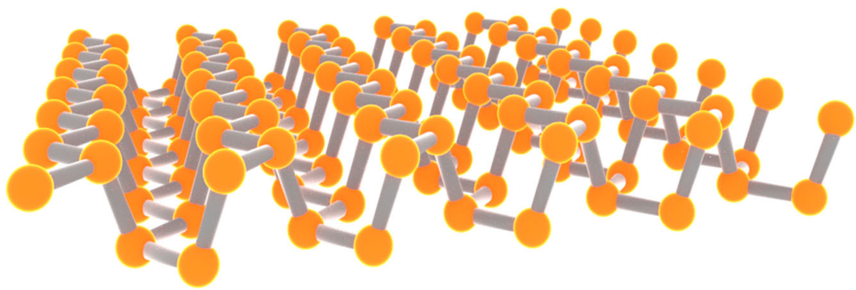

FIGURE 6 Two-dimensional (2D) structure of phosphorene[17]

silicon, germanium, and tin. They have the same hexagonal structure as graphene, but they are buckled to varying degrees. They cannot be exfoliated like graphene from bulk material, but they have to be epitaxially grown on a substrate and have a strong bond with it. Even though they are still in their infancy, potential applications range from field-effect transistors to topological insulators.

2.3.4 | Phosphorene

Phosphorene is a layered, stable elemental phosphorus allotrope with a single layer of black phosphorus. It has a direct bandgap and is puckered honeycomb semiconductor. The bandgap can be adjusted across the visible region by piling layers on top of each other. It is ideal for optoelectronic devices and transistors thanks to its high charge mobility (1000 $cm^2\ V^{-1}\ s^{-1}$). The properties of phosphorus vary enormously depending on which way the material is measured because of its corrugated structure.[16] The 2D structure of phosphorene is shown in Figure 6.

2.3.5 | 2D transition metal dichalcogenides

TMDCs are the common name for 2D TMDCs. TMDCs have the chemical formula MX_2, where X denotes a chalcogen (such as sulfur [S], selenium [Se], or tellurium [Te]), and M denotes a transition metal (such as molybdenum [Mo] or tungsten [W]). The crystal structures of TMDCs should be diverse. The most common 2H-phase with trigonal symmetry produces semiconducting properties such as MoS_2, WS_2, and $MoSe_2$. These semiconductors have an indirect bandgap when they are in bulk. Monolayers are appealing for optoelectronics because they have a direct bandgap in the visible spectrum. Because of their charge mobilities of 100 to 1000 $cm^2\ V^{-1}\ s^{-1}$, they are a popular choice for 2D transistors. The metallic 1T phase, which is the most stable polymorph of WTe_2, is another structure to consider. The 2D structure of WTe_2 and MoS_2 is shown in Figure 7.[18]

2.4 | Energy applications of 2D materials

2D materials are also well-suited to uses where bulk materials would be unsuitable due to the change in properties caused by a reduction in dimensionality.

2.4.1 | 2D material used in sensors and transistors

Field effect transistors have been made from a variety of semiconducting 2D materials, including TMDCs[19] and

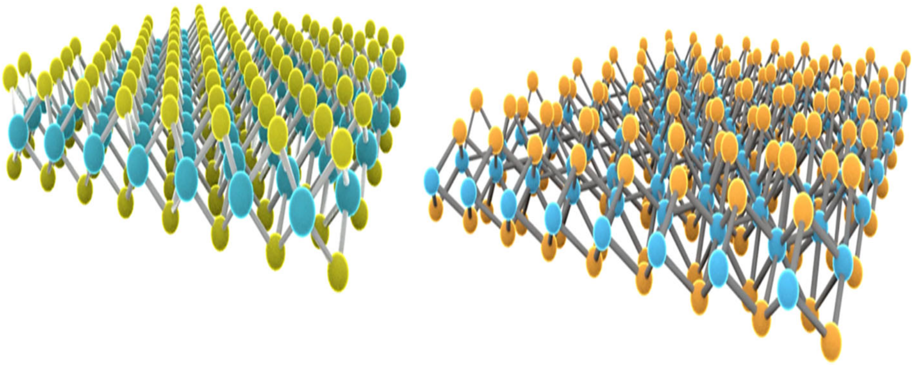

FIGURE 7 Two-dimensional (2D) structures of WTe_2 (right side) and MoS_2 (left side)[18]

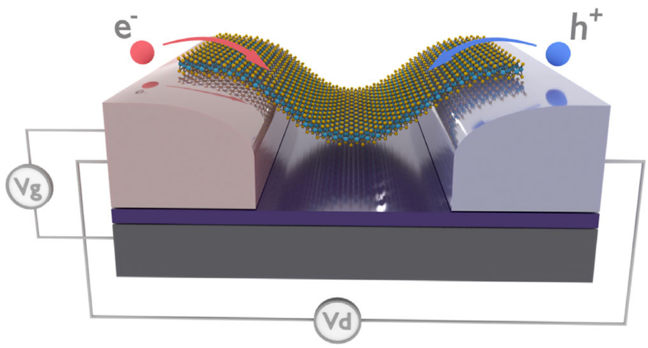

FIGURE 8 A transistor made of a transition metal dichalcogenide (TMDC) monolayer spans metal electrodes[19]

black phosphorus (FETs).[20] Figure 8 shows a transistor made of a TMDC monolayer that spans metal electrodes. Because of their high charge mobility and low bandgaps, they are a good fit for this application. Hexagonal boron nitride is often used as the gate dielectric. Despite its intrinsic lack of bandgap, graphene has been used as the active channel in transistors by using techniques such as designing edge states, chemical doping, and applying electric fields to open a bandgap. One of the benefits of 2D materials is their inherent flexibility over conventional silicon. When combined with the right substrate, 2D materials can be used to create flexible circuits.[21] While large-scale production of high-quality 2D layers, as required by the electronics industry, remains difficult, transistors remain one of the most promising applications. FET-based sensors made from 2D TMDCs can detect a range of chemicals in the parts-per-million range or better by measuring changes in conductance when exposed to these chemicals, such as triethylamine,[22] nitric oxide,[23] ammonia, and nitrogen dioxide,[24] by measuring changes in conductance when exposed to these chemicals.

2.4.2 | 2D materials used in photodetectors

The photodetectors use 2D compounds as well. Many TMDCs, including MoS_2, $MoSe_2$, WS_2, and WSe_2, as well as black phosphorus, have an optical or near-infrared bandgap and good charge transport properties. A single monolayer of TMDC (less than 1 nm thick) can absorb up to 10% of incident visible light, or about 100 nm of silicon.[25] Due to the thinness of the monolayers, this absorption is inadequate for high-efficiency photovoltaics. However, they can be transformed into high-efficiency photodetectors. A device fabricated from a mechanically exfoliated MoS_2 monolayer achieved a sensitivity of 103 A/W over the spectral range 400 to 680 nm[26] while combining MoS_2 with graphene into a heterostructure achieved a sensitivity of 108.[27]

2.4.3 | 2D materials used as battery electrodes

The 2D materials also perform admirably as a battery electrode. Electrodes for ion batteries and supercapacitors require electrically conductive materials with a large surface area to store high densities of ions.[28] Graphene has drawn some interest as a potential successor to graphite electrodes due to its higher surface-to-mass ratio, higher conductivity, greater mechanical strength, and flexibility,[29] which could lead to stronger, lighter batteries with higher power densities and faster charging times.[30] 2D MoS_2 has also garnered a lot of attention as a potential electrode. Even though it is semiconducting in its most stable 2H crystal structure, it can be prepared in such a way (usually by chemical exfoliation) that it adopts a metallic 1 T phase. Graphene-based electrodes had lower power and energy densities than stacked 1 T monolayer electrodes.[31]

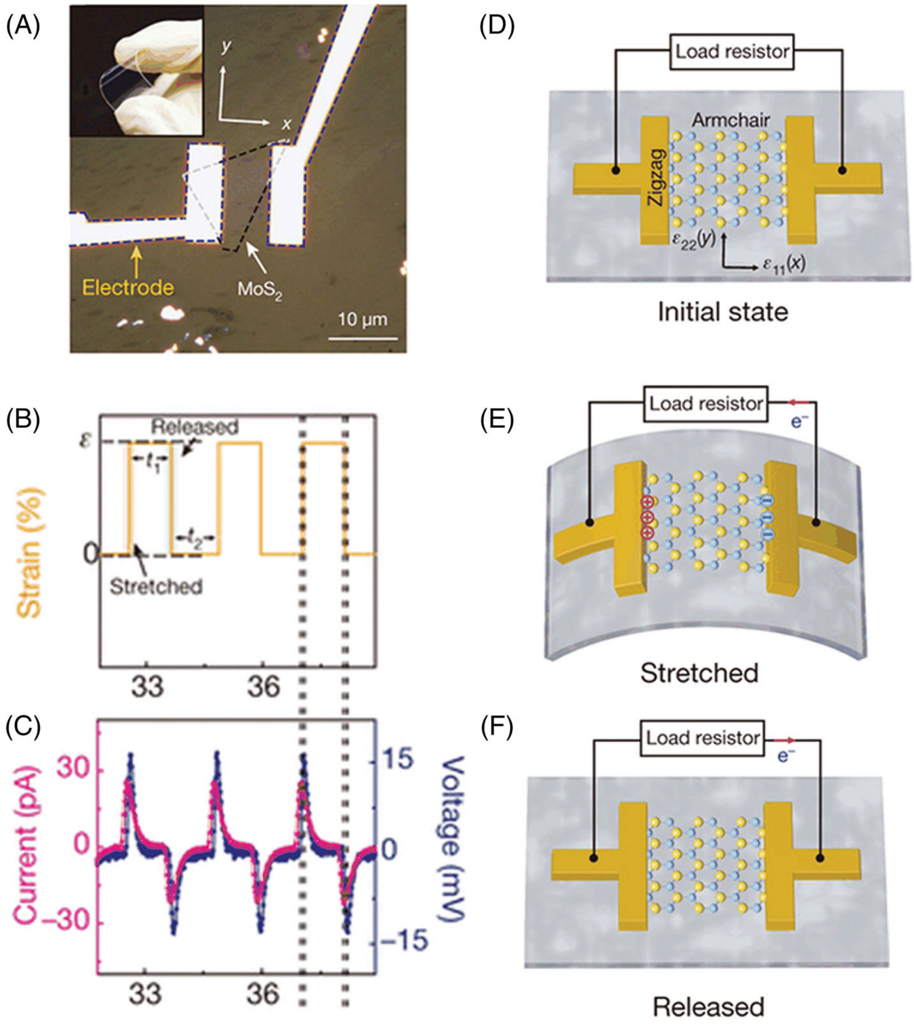

FIGURE 9 A, A flexible device with zigzag metal electrodes and a monolayer MoS_2 flake. B, Strain is applied regularly as a function of time. C, The piezoelectric outputs correspond to strain applied in the armchair direction. The MoS_2-based piezoelectric device's initial state, D, extended state, E, and produced state, F[32]

2.4.4 | 2D materials used in nanogenerators

In nanogenerators, the properties of 2D materials are extraordinary. Odd layer TMDCs have been shown to have piezoelectric properties,[32,33] due to the absence of inversion symmetry, according to the study. A black dashed line highlights the monolayer MoS_2 flake in Figure 9A,[32] which depicts a flexible device. When the substrate is mechanically bent from both ends, the MoS_2 flake will be expanded, causing piezoelectric polarized charges at the zigzag edges, which can drive electron flow in an external circuit, as shown in Figure 9E.

When the substrate is released, electrons flow back in the opposite direction, as shown in Figure 9F. As shown in Figure 9B,C, periodic stretching and releasing of the substrate produces alternating polarity piezoelectric outputs in the external circuit, which convert mechanical energy into electricity (C). The device's mechanical to electrical energy conversion efficiency can be as high as 5.08%.[32] Some 2D materials have piezoelectricity and mechanical flexibility, suggesting they may be used in wearable power-generating nanodevices.

3 | CONCLUSION

This article is based on the 2D materials, synthesis of 2D materials, and the energy applications of 2D materials. In the 21 century, the development in technology is increase day by day. So, the decrease in the size of things also a very attractive point for the researchers. That is why the 2D materials attract a lot of attention after the discovery of graphene in 2004. So, after that many 2D materials have been discovered. Because of the small size and excellent properties, the 2D materials are widely used in different fields. The 2D materials show excellent properties when they are used in energy applications like as an electrode, photodetectors, sensors, transistors, and so forth. To summarize, the novel and multifunctional properties of these novel 2D materials will stimulate further studies and, hopefully, overcome the limitations that have arisen for nanodevice applications. As a result, at this stage of the study, it is highly desirable to undertake additional experimental studies for bulk manufacturing of pure and defect-free 2D materials at a reasonable cost with the appropriate band gap needed for chip functionality. The strong theoretical predictions from various DFT computations of 2D materials with proper electrical composites could be useful in designing device pavements in this way. Indeed, now is the time to look for novel heterostructures other than graphene for fabricating faster, smaller, and smart nanoelectronics devices, which are fundamentally necessary for the next generation.

CONFLICT OF INTEREST

Both authors declare no conflict of interest.

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How to cite this article: Tahir MB, Fatima U. Recent trends and emerging challenges in two-dimensional materials for energy harvesting and storage applications. *Energy Storage*. 2021;e244. https://doi.org/10.1002/est2.244