



## A THOROUGH ANALYSIS OF 2D MATERIALS: GOING BEYOND GRAPHENE

Priyanshi Singh<sup>1</sup>, Monika Choudhary<sup>1</sup>, Ravindra Kumar<sup>1</sup> and Nitu Singh<sup>2</sup>

<sup>1</sup>Department of Physics, M. M. H. College, Ghaziabad, U.P., India

<sup>2</sup>Department of Physics, Maulana Azad National Institute of Technology, Bhopal, M.P. India

Email: rvndrkmr5@gmail.com



Date of Received

17 August, 2025



Date of Revised

10 September, 2025



Date of Acceptance

29 September, 2025



Date of Publication

30 September, 2025

DOI Link : <https://doi.org/10.51514/JSTR.7.3.2025.7-16>



# JSTR

*"together we can and we will make a difference"*

# A THOROUGH ANALYSIS OF 2D MATERIALS: GOING BEYOND GRAPHENE

Priyanshi Singh<sup>1</sup>, Monika Choudhary<sup>1</sup>, Ravindra Kumar<sup>1</sup> and Nitu Singh<sup>2</sup>

<sup>1</sup>Department of Physics, M. M. H. College, Ghaziabad, U.P., India

<sup>2</sup>Department of Physics, Maulana Azad National Institute of Technology, Bhopal, M.P. India

Email: rvndrkmr5@gmail.com

## ABSTRACT

Two-dimensional (2D) materials are a subclass of nanomaterials that are extremely thin—typically only one atomic layer thick. These materials' two-dimensional electron mobility results in special mechanical, thermal, optical, and electrical characteristics not present in their bulk (3D) counterparts. The discovery of graphene in 2004 sparked the discipline's explosion, which has since grown into a large field of study with enormous potential to transform technology. This review summarizes the current status of 2D materials research, including the ground breaking work of graphene, the wide range of beyond-graphene materials (including M Xenes, transition metal dichalcogenides, and hexagonal boron nitride), their potentially game-changing uses in photonics, electronics, and energy storage, as well as the current obstacles and potential for commercial integration in the future.

**Keywords:** 2D Materials, graphene, technology, photonics, electronics, energy storage

## INTRODUCTION

### The Birth of a New Class of Materials

For decade, it was believed that 2d materials were not thermodynamically stable. This paradigm was shattered in 2004 when Andre Giem and Konstantin Novoselov isolated a single layer of carbon graphene using mechanical exfoliation (Scotch-tape Method) [1,2]. This ground breaking work, which earned Nobel Prize in Physics in 2010, demonstrated that 2d materials are not only stable but also host a plethora of unique physical phenomenon.

### Important Families of 2D Materials:

With the discovery of 0D fullerenes in 1985, 1D carbon nanotubes in 1991, and finally 2D graphene in 2004, the known carbon allotropes have greatly expanded over the past several decades. The final one, graphene, is the building block of all these other graphitic allotropes which makes its recent discovery all the more intriguing. This could be explained by the long-held belief among researchers that it is impossible. In contrast, 2D graphene was believed to be unstable at any finite temperature, unlike fullerenes and nanotubes, which were predicted before they were actually observed. After ignition of graphene a flood has come to explore the 2D Materials similar structure to graphene. In this order many other 2D materials based on electronic structure and their compositions were discovered [3]. The strong leakage current of graphene prompted research into other 2d materials

with a sizable band gap [4,5]. This limitation of graphene led to investigate of additional 2d materials resulting in broad and diverse family.

### 2.0. Graphene: The Prototype

A mono-atom plane of graphite was isolated by Ubbelohde and Lewis (1960), who also noted that graphite is made up of layers, which are a network of hexagonal rings of carbon atoms [6,7]. Consequently, the graphite single-carbon atomic layer may compactly form a two-dimensional (2D) honeycomb lattice called graphene. However, according to Mouras et.al. (1987), the term "graphene" first appeared in 1987 to designate a single sheet of graphite, but Boehm et al. introduced that designation in 1994 [7]. It is zero band gap semiconductor ie. Semi metallic in nature having ultra-high electron mobility ( $\sim 200,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ ), Dirac fermion behaviour, exceptionally strong and stretchable (1TPa Young's modulus). its exhibits very high thermal conductivity ( $\sim 5000 \text{ Wm}^{-1}\text{K}^{-1}$ ).and Transparent ( $\sim 97.7\%$  absorption of white light) [8-11]. Despites of this outstanding performance regarding the in properties graphene carry some limitations ie the lake of a natural band gap is a major hurdle for its use in digital electronics and opto electronics, where a clear on /off state is required creating a band gap in graphene (e.g. via nanoribbons, bilayers or strain) often compromises its other excellent properties.

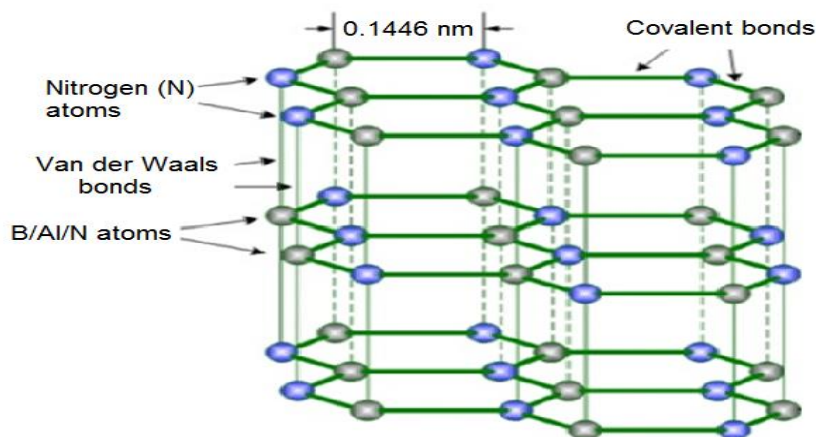
### 2.1. Transition Metal Dichalcogenides (TMDs or TMDCs)

Since the discovery of graphene's special properties, interest in 2D layered materials has grown, including metal chalcogenides, transition metal oxides, and other 2D compounds. Two layers of chalcogen atoms (X) having an  $\text{MX}_2$  stoichiometry are surrounded by hexagonal layers of metal atoms (M) to form transition metal dichalcogenides (TMDs) [13-17]. Depending on the combination of transition metal (often Mo, W, Nb, Re, Ni, or V) and chalcogen (typically S, Se, or Te), TMDs can be classified into about 40 different varieties. Unlike pure graphene, which has a zero-band gap, bilayer graphene, and complexly processed graphene nanoribbons, which have band gaps of several hundred meV, a single-layer  $\text{MoS}_2$  sheet is a direct band gap semiconductor [18]. Consequently,  $\text{MoS}_2$  is a material that shows promise for use in light-emitting diodes and digital circuits [19]. For example, single-layer  $\text{MoS}_2$  transistors have an on/off current ratio greater than at ambient temperature. This is far greater than the graphene transistors. According to existing research, these 2D layered crystals share certain striking changes in their

electrical characteristics as their thickness is decreased to only one or a few layers. Given the distinctiveness of the 2D structure, it seems to reason that these materials would exhibit novel and surprising characteristics, opening up a plethora of creative possibilities. The current state of graphene-like 2D materials, will be covered in this thorough review with an emphasis on theoretical and experimental investigations of their structural and electrical characteristics that have been published thus far.

### III-V Nitride 2D Nanomaterials:

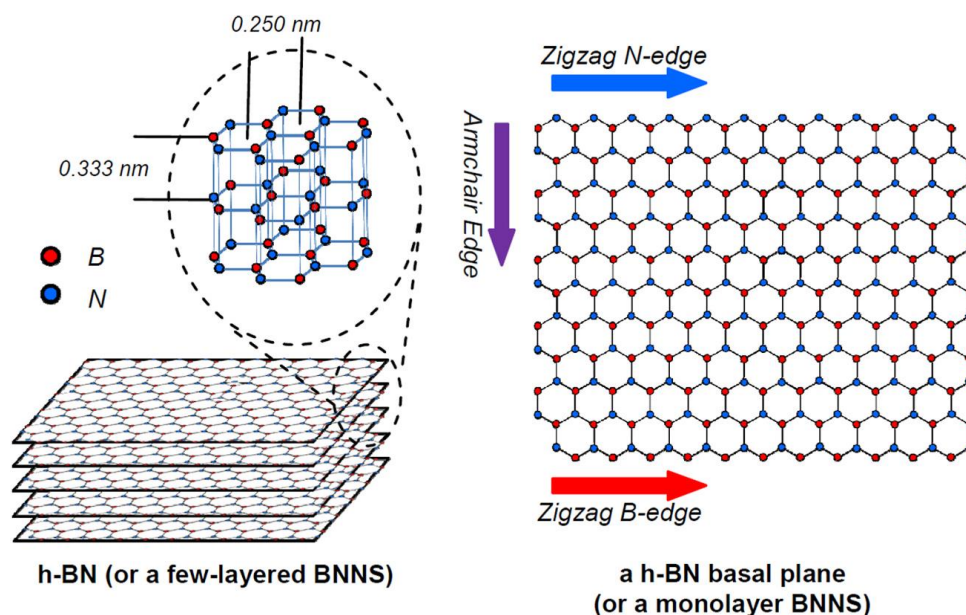
Despite not having layered structures like graphite, it was questioned if group IV elemental and group III-V compound semiconductors might also create stable single layer graphene-like structures after the creation of graphene. According to theoretical research based on total energy minimization, silicon, BN, AlN, GaN, and GaAs may all construct stable single-layer structures in a honeycomb structure using a 2-D hexagonal lattice as early as 2005[20]. h-BN, h-AlN and h-GaN, have motivated several theoretical studies attempting to reveal their mechanical, electrical and optical properties [21-26].



**Fig1.2:** Schematic diagrams of multilayered nitride based 2-D material [27]

**2.2. Hexagonal Boron Nitride (h-BN)** Boron nitride is a synthetic III-V chemical that contains an equal number of nitrogen (N) and boron (B) atoms. For BN, crystalline forms can be hexagonal, cubic, and sometimes even wurtzite. The most common form of BN is h-BN. It is composed of layers of hexagonal lattices of alternating B and N atoms. Covalent bonds connect the B and N within the lattice, but van de Waals forces bind the layers weakly. Between layers, B atoms are located directly above or below N atoms, while for N atoms, the opposite is true. The inter-layer

distance is and the h-BN's in-plane lattice spacing is 2.5 Å. and 3.33 Å is the inter-layer distance [28]. Additionally, h-BN sheets are more thermally stable than graphene. Theoretically, hexagonal boron nitride (h-BN), sometimes known as "white graphene," has a high thermal conductivity of about  $2000 \text{ W m}^{-1} \text{ K}^{-1}$  and is an electrical insulator. Therefore, a polymer composite loaded with h-BN, owing to all these great qualities, h-BN is a promising option to investigate for a range of technical uses.



**Fig. 1.** h-BN nanosheet structure: (Left) Few-layered and (Right) Monolayer. Reproduced with permission from Ref. [8] © 2012, The Royal Society of Chemistry.

### 2.3. MXenes:

The two-dimensional (2D) transition-metal carbides and nitrides known as MXenes have drawn a lot of interest since they were discovered in 2011[29]. They have a distinctive layered structure, a wealth of surface functional groups, complex elemental compositions, and noticeable optical and electrical conductivity characteristics. In the past ten years, about thirty MXenes have been synthesized experimentally, and numerous others have been theoretically anticipated. They have surface terminations such -O, -OH, and -F groups that are inherent and distinct from the parent MAX phase. MXenes is a new family of materials created by Babak Anasori and Yury Gogotsi that has about 30 members [30]. M is an early transition metal, X represents carbon and/or nitrogen, and Tz indicates different terminations like hydroxyl, fluorine, and/or oxygen atoms. The general formula for the MXenes is  $M_{n+1}X_nT_z$  ( $n = 1, 2, \text{ or } 3$ ) or  $M_{1.33}XT_z$ . outstanding mechanical strength, high hydrophilicity, and metallic conductivity. Their highly adjustable surface chemistry makes them especially appealing for electrochemical sensors and energy storage devices like batteries and supercapacitors [31-33].

### 2.4. Xenes (2D Monoelemental Materials):

Motivated by the extensive use of graphene, scientists have discovered numerous other two-

dimensional (2D) atomic materials, such as hexagonal boron nitride (h-BN) [28], transition metal dichalcogenides (TMDs) [16, 17] nitrides and carbonitrides (MXenes) and so forth. Based on their rich physical properties, these materials have all been studied and widely used in optoelectronic devices, energy, catalysis, and other areas. Unfortunately, TMDs' low carrier mobility restricts their usage in sensors; h-BN exhibits insulating qualities; and MXenes' restricted band gaps prevent them from being used efficiently in FETs [34–36]. To address these issues, phosphorene-based 2D monoelemental materials (Xenes), which are also graphene-analogous nanomaterials, have been extensively researched [37-38]. Phosphorene has extremely anisotropic transport and a band gap value that varies with the number of layers, ranging from 0.3 eV in the bulk to 2.0 eV in monolayers. The idea for the module on graphene properties states that flaws, as an unavoidable consequence, can also significantly affect these Xenes materials' electrical characteristics. Notably, these two-dimensional materials with intrinsic flaws can improve the use of thermoelectric, optoelectronic, and lithium battery applications. The ability to manipulate 2D monoelemental materials with exterior flaws, like substitution and adsorption, artificially and carefully can enhance their application prospects in photoelectric, storage, catalysis, and other fields.

Additionally, 2D monoelemental materials from groups IIIA (borophene), IVA (silicene, germanene, and stanine), and VIA (selenene and tellurene nanosheets [39-42]) Because of their diverse range of characteristics, which include semiconductors, metals, and semi-metals, they are all attractive and competitive options for electrical, optoelectronic, spintronic, and thermoelectric applications. Furthermore, in order of silicene, Shiraiishi and Takeda used first principles calculations to study the graphite versions in silicon (Si) and germanium (Ge) in 1994. It was discovered that the two sublattices of silicene are moved perpendicular to the atomic plane, producing a buckled geometry, in contrast to graphene, where the two sub-lattices A and B lie in the same plane. Silica was given this name by Guzmán-Verri and Lew Yan Voon in 2007. They demonstrated that silicene is a zero gap

semiconductor using the unified tight binding (TB) Hamiltonian model. It was established that silicene is dynamically stable. Using phonon dispersion based on density functional theory (DFT) and ab initio molecular dynamics simulations at 1000 K, Ciraci et al. verified this stability. In contrast to graphene, silicene has a buckled structure with a buckling height of 0.44 Å [43]. The band structure of silicene is similar to graphene's, despite this structural difference. The well-known Dirac cone at the k point in the reciprocal space is the result of the  $\pi$  and  $\pi^*$  bands' linear crossing at the Fermi level ( $E_f$ ). Such a band structure causes the charge carriers in silicene to move with a Fermi velocity of about  $10^6$  m s<sup>-1</sup>, similar to that of massless Dirac fermions. Different type graphene family 2D materials shown in Table 1.

**Table 1** Various kinds of 2D material families [44]

Graphene Family	Graphene	hBN 'White graphene'	BCN	Fluorographene	Graphene Oxide
2D Chalcogenides	MoS <sub>2</sub> , WS <sub>2</sub> , MoSe <sub>2</sub> , WSe <sub>2</sub>	Semiconducting dichalcogenides: MoTe <sub>2</sub> , WTe <sub>2</sub> , ZrS <sub>2</sub> , ZrSe <sub>2</sub> and so on	Metallic dichalcogenides: NbSe <sub>2</sub> , NbS <sub>2</sub> , TaS <sub>2</sub> , TiS <sub>2</sub> , NiSe <sub>2</sub> and so on		
			Layered semiconductors: GaSe, GaTe, InSe, Bi <sub>2</sub> Se <sub>3</sub> and so on		
2D Oxides	Micas, BSCCO	MoO <sub>3</sub> , WO <sub>3</sub>	Perovskite-type: LaNb <sub>2</sub> O <sub>7</sub> , (Ca, Sr) <sub>2</sub> Nb <sub>3</sub> O <sub>10</sub> , Bi <sub>4</sub> Ti <sub>3</sub> O <sub>12</sub> , Ca <sub>2</sub> Ta <sub>2</sub> TiO <sub>10</sub> , and so on	Hydroxides: Ni(OH) <sub>2</sub> , Eu(OH) <sub>2</sub> and so on	
	Layered Cu oxides	TiO <sub>2</sub> , MnO <sub>2</sub> , V <sub>2</sub> O <sub>5</sub> , TaO <sub>3</sub> , RuO <sub>2</sub> , and so on		Others	

### 2.5. Other Emerging 2D Materials:

The structures of Perovskites, a large class of compounds, are quite similar to those of CaTiO<sub>3</sub>. The first person to find these structures was Lev Perovski in 1792 [16]. But Wenk and Bulakh were the first to give a thorough account of them in 1926, and it was later published in 1945 [17]. Some of the most significant geological compounds are perovskites and structures developed from them because of their excellent stability and adaptability to incorporate different cations [18]. Perovskites share a similar structure called ABX<sub>3</sub>, in which 'A' and 'B' stand for different-sized cations and 'X' for an anion that forms bonds with both cations. Figure 1 shows the arrangement and configuration of the A, B, and X atoms within the perovskite lattice in the crystal structure of ABX<sub>3</sub> perovskite. Transition metal elements with smaller ionic radii make up the B-site,

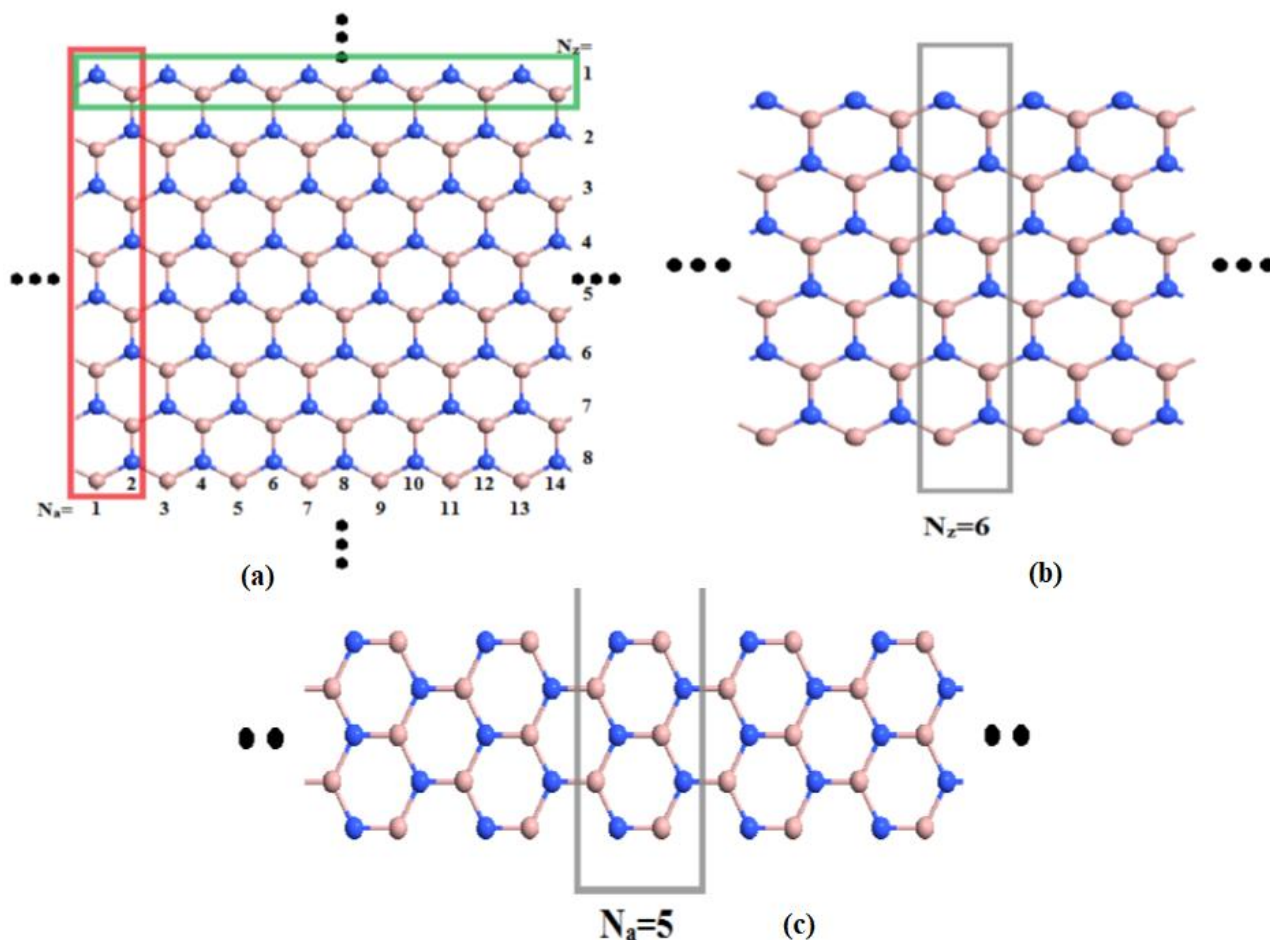
whereas divalent base alkaline, alkaline-earth, or rare-earth metal elements with higher ionic radii usually make up the A-site. Oxygen or other bigger ions, such as halides, sulfides, and nitrides, are frequently represented by X.

### 2.6 Nanoribbons:

Two-dimensional nanosheets cannot be used to directly structure electronic devices. The devices are typically thought to be structured by the thin strips of these two-dimensional materials. A common name for these narrow, finite-width strips is nanoribbon. As single-layered, pseudo-one-dimensional structures, the nanoribbons. They only exhibit periodicity in one dimension, which is parallel to edges. Furthermore, the ribbon's limited width suggests quantum confinement within the nanoribbon, which heightens interactions between the atoms at the edges and their corresponding electron densities. This is primarily

responsible for the difference in the electrical characteristics of the nanoribbon and the nanosheet. The quantum confinement effect is lessened when the nanoribbon's width increases. Consequently, a change in width typically causes a change in the nanoribbon's electrical characteristics. However, the ribbon width is not the sole factor influencing the nanoribbon's

electrical characteristics [45-49]. Three types of nanoribbons are commonly distinguished based on certain periodic patterns at their edges: (1) Zigzag Nanoribbons (Z-ZnONR, Z-GaNNR etc.) (2) Armchair Nanoribbons (A-ZnONR, A-GaNNR, A-BNN) (3) Chiral Nanoribbons.



**Fig. 2** (a) Zigzag and armchair edge directions are represented by green and red boxes (b) Bare Z-GaNNR with width  $N_z=6$  dimers (c) Bare A-GaNNR with width  $N_a=5$  atoms.

**Synthesis Methods: -**

Synthesis methods can be classified into two paradigms

1. **Top-Down:** Exfoliating layers from a bulk crystalline source.
2. **Bottom-Up:** Building the material atom-by-atom from molecular precursors

**Top-Down Synthesis Methods:**

These techniques disrupt the weak van der Waals forces that exist between a bulk crystal's layers.

**Mechanical Exfoliation (The Scotch Tape Method)**

- **Mechanism:** This is how graphene was initially isolated. A bulk crystal (e.g., highly ordered pyrolytic graphite, HOPG) is continuously peeled off in layers using adhesive tape until thin flakes are produced. After that, a substrate (e.g.,  $\text{SiO}_2/\text{Si}$ ) is subsequently exposed to these flakes.
- **Advantages:** Generates the best crystals with the fewest flaws.  
Easy and inexpensive.  
Outstanding for proof-of-concept devices and basic research.

- **Disadvantages:**
- It is not scalable. The flake size is irregular and the output is low.  
Not appropriate for industrial applications and labor-intensive.  
- Limited ability to adjust the thickness and size of flakes  
Ideal for: Research, high-performance single-device demos, and prototyping.

- **B. Liquid-Phase Exfoliation (LPE)**

- To overcome the interlayer binding energy and exfoliate the powder into separate layers, energy is provided (either by sonication, shear mixing, or electrochemical techniques) after the powder has been distributed in a solvent. In order to stabilize the exfoliated sheets and stop re-aggregation, the solvent selection is crucial; its surface energy should be equal to that of the 2D material.

- **Advantages:**

- Generates tiny flakes with a wide range of thickness (several layers).  
Sonication can cause flaws and reduce the quality of crystals.  
To separate few-layer flakes, post-processing is necessary.
- Ideal for: High-volume applications where the final electronic quality is not crucial, such as composites, conductive inks, energy storage electrodes, and sensors [50-56].

- **C. Ion-Intercalation Exfoliation**

- **Mechanism:** Ion-containing solutions, such as  $\text{Li}^+$  ions in butyllithium, are used to soak bulk crystals. These ions weaken the links between the layers by inserting themselves (intercalating). The material exfoliates as a result of the intercalated species vaporizing during subsequent sonication or rapid heating (for example, in water).

- **Advantages:**

More single-layer flakes produced than with LPE.  
Excellent for creating TMD nanosheets (such as  $\text{WS}_2$  and  $\text{MoS}_2$ ).

- **Disadvantages:**

Chemical transformation: Li-intercalation changes semiconducting 2H- $\text{MoS}_2$  to metallic 1T- $\text{MoS}_2$ , demonstrating how the intercalation

process can change the crystal's structure and characteristics. Introduces contaminants and necessitates thorough cleaning. The production of phase-engineered TMDs for electrocatalysis (such as the hydrogen evolution reaction) is its best use.

### 3.0. Bottom-Up Synthesis Methods

These techniques provide far greater control over scale and quality by assembling atoms into a 2D crystalline lattice.

#### A. Chemical Vapor Deposition (CVD)

The most promising approach for high-quality, wide-area electronic applications is this one.

- **Mechanism:** A high-temperature furnace (around  $1000^\circ\text{C}$  for graphene) is used to insert a substrate, usually a metal foil such as Cu or Ni. Gaseous precursors are introduced, such as S powder for  $\text{MoS}_2$ ,  $\text{MoO}_3$  for carbon, and  $\text{CH}_4$  for carbon. The atoms form a two-dimensional crystal lattice as the precursors break down on the catalytic metal surface.

- **Advantages:**

- Large-area, continuous films are produced. scalable to wafer size. Superior command over domain size, quality, and layer count. Excellent crystalline quality, appropriate for electronics with high performance

- **Disadvantages:**

- Expensive and high energy usage. The film must be transferred from the growing substrate to an insulating substrate (like  $\text{SiO}_2/\text{Si}$ ), which may result in wrinkles, cracks, and polymer residues. Generates polycrystalline films with grain boundaries often. Ideal for: Integrated circuit, photodetector, and transistor fabrication. TMD films and graphene's main industrial route.

- **B. Epitaxial Growth on Silicon Carbide (SiC)**

- **Mechanism:** A SiC wafer is vacuum-heated to temperatures above  $1300^\circ\text{C}$ . A carbon-rich layer that reassembles into epitaxial graphene is left behind after the silicon atoms sublime from the surface. High-quality, wafer-scale graphene is produced, which is an advantage. The graphene is already on a semi-insulating substrate, which is perfect for electronics, so no transfer is required.

- Cons: o Very Expensive (SiC wafers are expensive).
- The buffer layer, a strong electronic interaction created by the graphene-SiC contact, has the ability to alter electronic characteristics. Only graphene is allowed. High-frequency electronics, where a solid, non-metallic substrate is crucial, are the best candidates.
- **C. Molecular Beam Epitaxy (MBE)**
- **Mechanism:** In an ultra-high vacuum chamber, atomic or molecule beams are evaporated and then deposited onto a single-crystal substrate, where they condense and grow epitaxially.
- **Advantages:**
- Complete command at the atomic level. o Has the ability to develop incredibly pure and pure interfaces. o Enables complicated heterostructures to form by using alternating beams of material.
- **D. Wet Chemical Synthesis/Colloidal Synthesis**
- **Mechanism:** In a solution with surfactants, molecular precursors containing the desired elements are heated. Atoms nucleate and develop into 2D nanoplatelets as the precursors break down. The growth is restricted to 2D by the surfactant molecules, which regulate it along the vertical axis.
- **Advantages:**
- Scalable process based on a solution. The nanocrystals' size and shape (triangles, hexagons, etc.) may be controlled well. Materials are directly in solution; there is no transfer stage.
- **Disadvantages:**
- Small crystal size, usually in the range of nanometers to a few microns. Defects and surfactants can lower the quality of electronic devices. It frequently needs post-processing to get rid of surfactants.

## REFERENCES

- [1]. Kostya S Novoselov, Andre K Geim, Sergei V Morozov, D Jiang, Y Zhang, Sergey V Dubonos, Irina V Grigorieva, and Alexandr A Firsov. Electric field effect in atomically thin carbon lms. science,306:666-669,2004.
- [2]. Geim, Andre K., and Konstantin S. Novoselov. "The rise of graphene." *Nature materials* 6, no. 3 (2007): 183-191.
- [3]. Kostya S Novoselov, D Jiang, F Schedin, TJ Booth, VV Khotkevich, SV Morozov, and Andre

## Future Directions and Challenges

The field is changing quickly, and research is being done on:

**Scalability & Cost-** The development of roll-to-roll, low-temperature CVD methods

### Transfer-Free Growth

Growing two-dimensional materials directly on insulating, functional substrates to prevent the harmful transfer process

### Vertical & Lateral Heterostructures:

precisely stacking various 2D materials to produce new "designer" materials with on-demand properties (graphene on h-BN on MoS<sub>2</sub>, for example).

**Phase Control-** precisely creating distinct crystalline phases of the same material with radically different electrical characteristics (e.g., 1T vs. 2H phase TMDs).

## CONCLUSION:

The field of two-dimensional materials has advanced significantly since graphene's initial excitement. Rather than being a fleeting scientific trend, 2D materials are a key materials platform that will assist future technological developments in certain, high-impact domains. They will enhance and complement existing technologies and create entirely new applications that standard 3D materials cannot, even if they probably won't replace all silicon electronics. It is anticipated that this "materials-by-design" strategy would unlock previously unattainable functionality. Even though synthesis and integration issues still exist, 2D materials' special qualities make them essential building blocks for the upcoming wave of technological advancement in energy, electronics, and quantum computing. Their journey from the lab to the market will be gradual, with early applications in specialist domains such as next-generation energy storage, enhanced composites, and specialized sensors. Once 2D materials are synthesized and integrated properly, we will be able to build functional systems from the atom up and achieve their full potential.

- K Geim. Two-dimensional atomic crystals. PNAS, 102:10451-10453, 2005.
- [4]. Son, Young-Woo, Marvin L. Cohen, and Steven G. Louie. "Energy gaps in graphene nanoribbons." *Physical review letters* 97, no. 21 (2006): 216803.
- [5]. Melinda Y Han, Barbaros Ozyilmaz, Yuanbo Zhang, and Philip Kim. Energy band-gap engineering of graphene nanoribbons. *Phys. Rev. Lett.*, 98:206805-206805 4, 2007
- [6]. H. Shinohara, A. Tiwari, John Wiley & Sons: Graphene: an introduction to the fundamentals and industrial applications. 2015.
- [7]. S.S. Shams, R. Zhang, J.J.M.S.-P. Zhu, Graphene synthesis: a Review. 2015. 33(3): p. 566-578.
- [8]. Suchismita Ghosh, Wenzhong Bao, Denis L Nika, Samia Subrina, Evghenii P Pokatilov, Chun Ning Lau, and Alexander A Balandin. Dimensional crossover of thermal transport in few-layer graphene. *Nat. Mater.*, 9:555{558, 2010
- [9]. Fang Liu, Pingbing Ming, and Ju Li. Ab initio calculation of ideal strength and phonon instability of graphene under tension. *Phys. Rev. B*, 76:064120-1- 064120-7, 2007.
- [10]. Rahul Raveendran Nair, Peter Blake, Alexander N Grigorenko, Konstantin S Novoselov, Tim J Booth, Tobias Stauber, Nuno MR Peres, and Andre K Geim. Fine structure constant denes visual transparency of graphene. *Science*,320:1308-1308, 2008.
- [11]. Konstantin S Novoselov, VI Falko, L Colombo, PR Gellert, MG Schwab, and K Kim. A roadmap for graphene. *Nature*, 490:192-200, 201.
- [12]. Minoru Osada and Takayoshi Sasaki. Two-dimensional dielectric nanosheets: novel nanoelectronics from nanocrystal building blocks. *Adv. Mater.*, 24:210- 228, 2012.
- [13]. Wang, Q. H., Kalantar-Zadeh, K., Kis, A., Coleman, J. N., & Strano, M. S. Electronics and optoelectronics of two-dimensional transition metal *Nature technology* volume 7, pages 699–712 (2012).
- [14]. Minoru Osada and Takayoshi Sasaki. Two-dimensional dielectric nanosheets: novel nanoelectronics from nanocrystal building blocks. *Adv. Mater.*, 24:210- 228, 2012.
- [15]. Kayci, Lopez-Sanchez O. Lembke D. "M. Radenovic A. Kis A." *Nat. Nanotechnol* 8, no. 497 (2013): 10-1038.
- [16]. Zeng, Hualing, Junfeng Dai, Wang Yao, Di Xiao, and Xiaodong Cui. "Valley polarization in MoS2 monolayers by optical pumping." *Nature nanotechnology* 7, no. 8 (2012): 490-493.
- [17]. Zhang, Wenjing, Chih-Piao Chuu, Jing-Kai Huang, Chang-Hsiao Chen, Meng-Lin Tsai, Yung-Huang Chang, Chi-Te Liang et al. "Ultrahigh-gain photodetectors based on atomically thin graphene-MoS2 heterostructures." *Scientific reports* 4, no. 1 (2014): 3826.
- [18]. Mak, Kin Fai, Changgu Lee, James Hone, Jie Shan, and Tony F. Heinz. "Atomically thin MoS 2: a new direct-gap semiconductor." *Physical review letters* 105, no. 13 (2010): 136805.
- [19]. Zeng, Hualing, Junfeng Dai, Wang Yao, Di Xiao, and Xiaodong Cui. "Valley polarization in MoS2 monolayers by optical pumping." *Nature nanotechnology* 7, no. 8 (2012): 490-493.
- [20]. Engin Durgun, Sefaattin Tongay, and Salim Ciraci. Silicon and III-V compound nanotubes: structural and electronic properties. *Phys. Rev. B*, 72:075420-075431,2005.
- [21]. Colin L Freeman, Frederik Claeyssens, Neil L Allan, and John H Harding. Graphitic nano\_lms as precursors to wurtzite \_lms: theory. *Phys. Rev. Lett.*,96:066102-066106, 2006.
- [22]. Yanli Wang and Siqi Shi. Structural and electronic properties of monolayer hydrogenated honeycomb III-V sheets from \_rst-principles. *Solid State Comm.*,150:1473-1478, 2010.
- [23]. Yandong Ma, Ying Dai, Meng Guo, Chengwang Niu, Lin Yu, and Baibiao Huang. Magnetic properties of the semiuorinated and semi hydrogenated 2D sheets of group-IV and III-V binary compounds. *Appl. Surf. Sci.*, 257:7845-7850, 2011.
- [24]. Arunima K Singh and Richard G Hennig. Computational synthesis of single-layer GaN on refractory materials. *Appl. Phys. Lett.*, 105:051604-051609, 2014.
- [25]. Mehmet Topsakal and Salim Ciraci. Elastic and plastic deformation of graphene, silicene, and boron nitride honeycomb nanoribbons under uniaxial tension: A first-principles density-

- functional theory study. *Phys. Rev. B*, 81:024107-024114,2010.
- [26]. Davoud Vahedi Fakhrrabad, Nasser Shahtahmasebi, and Mojtaba Ashhadi. Optical excitations and quasiparticle energies in the AlN monolayer honeycomb structure. *Superlattices Microstruct.*,79:38-44, 2015.
- [27]. S. Majety, X.K. Cao, R. Dahal, B.N. Pantha, J. Li, J.Y. Lin, and H.X. Jiang. Semiconducting hexagonal boron nitride for deep ultraviolet photonics. In *Quantum Sensing and Nanophotonic Devices IX*, volume 8268, pages 82682R-1-82682R-8. International Society for Optics and Photonics, 2012.
- [28]. E.K. Sichel, R.E. Miller, M.S. Abrahams, and C.J. Buiochi. Heat capacity and thermal conductivity of hexagonal pyrolytic boron nitride. *Phys. Rev. B*,13:4607-4614, 1976.
- [29]. Naguib, M.; Kurtoglu, M.; Presser, V.; Lu, J.; Niu, J.; Heon, M.; Hultman, L.; Gogotsi, Y.; Barsoum, M. W. Two-dimensional nanocrystals produced by exfoliation of Ti<sub>3</sub>AlC<sub>2</sub>. *Advanced materials* 2011, 23 (37), 4248–4253.
- [30]. Gogotsi, Yury, and Babak Anasori. "The rise of MXenes." In *MXenes*, pp. 3-11. Jenny Stanford Publishing, 2023.
- [31]. Chen, L.; Dai, X.; Feng, W.; Chen, Y. Biomedical applications of MXenes: from nanomedicine to biomaterials. *Accounts of Materials Research* 2022, 3 (8), 785–798.
- [32]. Kim, H.; Wang, Z.; Alshareef, H. N. MXetronics: Electronic and photonic applications of MXenes. *Nano Energy* 2019, 60, 179–197
- [33]. Sun, Y.; Li, Y. Potential environmental applications of MXenes: A critical review. *Chemosphere* 2021, 271, 129578.
- [34]. Kong, Xiangkai, Qiangchun Liu, Changlin Zhang, Zhenmeng Peng, and Qianwang Chen. "Elemental two-dimensional nanosheets beyond graphene." *Chemical Society Reviews* 46, no. 8 (2017): 2127-2157.
- [35]. Qiu, Meng, Wen Xiu Ren, Taeho Jeong, Miae Won, Geun Young Park, David Kipkemoi Sang, Li-Ping Liu, Han Zhang, and Jong Seung Kim. "Omnipotent phosphorene: a next-generation, two-dimensional nanoplatfrom for multidisciplinary biomedical applications." *Chemical Society Reviews* 47, no. 15 (2018): 5588-5601.
- [36]. Zhang, Shengli, Shiyong Guo, Zhongfang Chen, Yeliang Wang, Hongjun Gao, Julio Gómez-Herrero, Pablo Ares, Félix Zamora, Zhen Zhu, and Haibo Zeng. "Recent progress in 2D group-VA semiconductors: from theory to experiment." *Chemical Society Reviews* 47, no. 3 (2018): 982-1021.
- [37]. Lu, Lu, Zhiming Liang, Leiming Wu, YunXiang Chen, Yufeng Song, Sathish Chander Dhanabalan, Joice Sophia Ponraj et al. "Few-layer bismuthene: sonochemical exfoliation, nonlinear optics and applications for ultrafast photonics with enhanced stability." *Laser & Photonics Reviews* 12, no. 1 (2018): 1700221.
- [38]. Wang, Yangyang, Pu Huang, Meng Ye, Ruge Quhe, Yuanyuan Pan, Han Zhang, Hongxia Zhong, Junjie Shi, and Jing Lu. "Many-body effect, carrier mobility, and device performance of hexagonal arsenene and antimonene." *Chemistry of Materials* 29, no. 5 (2017): 2191-2201.
- [39]. Xie, Zhongjian, Chenyang Xing, Weichun Huang, Taojian Fan, Zhongjun Li, Jinlai Zhao, Yuanjiang Xiang et al. "Ultrathin 2D nonlayered tellurium nanosheets: facile liquid-phase exfoliation, characterization, and photoresponse with high performance and enhanced stability." *Advanced Functional Materials* 28, no. 16 (2018): 1705833.
- [40]. Feng, Baojie, Jin Zhang, Ro-Ya Liu, Iimori Takushi, Chao Lian, Lan Chen, Kehui Wu et al. "Realization of metallic boron in monolayer structures." *Phys. Rev. B* 94 (2016): 041408.
- [41]. Mannix, Andrew J., Xiang-Feng Zhou, Brian Kiraly, Joshua D. Wood, Diego Alducin, Benjamin D. Myers, Xiaolong Liu et al. "Synthesis of borophenes: Anisotropic, two-dimensional boron polymorphs." *Science* 350, no. 6267 (2015): 1513-1516.
- [42]. Tao, Li, Eugenio Cinquanta, Daniele Chiappe, Carlo Grazianetti, Marco Fanciulli, Madan Dubey, Alessandro Molle, and Deji Akinwande. "Silicene field-effect transistors operating at room temperature." *Nature nanotechnology* 10, no. 3 (2015): 227-231.

- [43]. Mubashir A. Kharadi, Gul Faroz A. Malik, Farooq A. Khanday, z Khurshed A. Shah, Sparsh Mittal,3 and Brajesh Kumar Kaushik; Review—Silicene: From Material to Device Application; 2020, 9, 115031.
- [44]. Geim, Andre K., and Irina V. Grigorieva. "Van der Waals heterostructures." *Nature* 499, no. 7459 (2013): 419-425.
- [45]. Kumar, R., Rakesh, A.K., Govindan, A. and Jaiswal, N.K., 2022, July. Spin dependent electronic properties of NO-adsorbed zigzag ZnO nanoribbons: a DFT study. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1248, No. 1, p. 012030). IOP Publishing.
- [46]. Rakesh, A.K., Kumar, R., Govindan, A., Kharwar, S. and Singh, S., 2023. DFT investigation of hydrogenated cove-edged boron nitride nanoribbons for resonant tunneling diodes application. *Solid State Communications*, 365, p.115119.
- [47]. Rakesh, A.K., Kumar, R., Yogi, R., Govindan, A. and Jaiswal, N.K., 2022. Tuning the Electronic Structure of Zigzag Boron Nitride Nanoribbons via  $sp^2/sp^3$  Edge Functionalization. *Journal of Electronic Materials*, 51(6), pp.3299-3307.
- [48]. Kumar, R., Rakesh, A.K., Govindan, A. and Jaiswal, N.K., 2022. First-principles study of structural and electronic properties of cove-edged zigzag ZnO nanoribbons. *Materials Today: Proceedings*, 67, pp.616-619.
- [49]. Kumar, R., Rakesh, A.K., Yogi, R., Govindan, A. and Jaiswal, N.K., 2022. First-principles study of CO adsorption on zigzag ZnO nanoribbons towards nanosensor application. *Journal of Molecular Graphics and Modelling*, 116, p.108232.
- [50]. S. Nitu, Ahmad Umar, Neha Singh, H. Fouad, Othman Y. Alothman, and Fozia Z. Haque. "Highly sensitive optical ammonia gas sensor based on Sn Doped  $V_2O_5$  Nanoparticles." *Materials Research Bulletin* 108 (2018): 266-274.
- [51]. S. Nitu, Vinita Pandey, Neha Singh, M. M. Malik, and Fozia Z. Haque. "Application of  $TiO_2/SnO_2$  nanoparticles in photoluminescence based fast ammonia gas sensing." *Journal of Optics* 46, no. 3 (2017): 199-203.
- [52]. N. Singh, Jyoti Bamne, K. M. Mishra, Neha Singh, and Fozia Z. Haque. "Photoluminescence and Chemoresistive Gas Sensing: A Comparative Study Using  $V_2O_5$  Nanostructures for  $NH_3$ ." In *Emerging Trends in Nanotechnology*, pp. 279-307. Singapore: Springer Singapore, 2021.
- [53]. Kumar, R., N. Singh, G. K. Tripathi, S. P. Singh, A. Govindan, and M. Chavali. "A Survey on Smart Sensors Drivers and Gas Detection Technologies." *Nanomedicine & Nanotechnology Open Access* 7, no. 1 (2022): 1-8.
- [54]. Raju, A. Singh, S Teotia, and Nitu Singh. "Development In Gas Detection Using  $SNO_2$  Nanoparticles: A Review." *Journal of Science and Technological Researches* 6, no. 1 (March 31, 2024): 21–32.
- [55]. S. Nitu, and S. P Singh. "Advanced Hybrid Nanomaterials For Various Application: A Comprehensive Overview." *Journal of Science and Technological Researches* 5, no. 3 (September 30, 2023): 33–37.
- [56]. N. Singh, R Kumar, Raju Anon, S. P. Singh, A. S. Gautam, and Ram Janma. "Need of Gas Sensors, An Electronic Nose: A Review." *Journal of Science and Technological Researches* 3, no. 4 (December 31, 2021): 32.

