Scientific Research Publishing

World Journal of Nano Science and Engineering, 2026, 16(3), 139-162
https://www.scirp.org/journal/wjnse
ISSN Online: 2161-4962
ISSN Print: 2161-4954

Two-Dimensional Materials for Next-Generation Nanoelectronic Devices

Arav Rajesh Hinduja[1*], Sananjay Biswas[2]

[1]Oberoi International School, JVLR Campus, Mumbai, Maharashtra, India
[2]Pion Academy and Research Centre, Mumbai, Maharashtra, India
Email: *aravhinduja@gmail.com

How to cite this paper: Hinduja, A.R. and Biswas, S. (2026) Two-Dimensional Materials for Next-Generation Nanoelectronic Devices. *World Journal of Nano Science and Engineering*, **16**, 139-162.
https://doi.org/10.4236/wjnse.2026.163007

Received: July 21, 2026
Accepted: September 21, 2026
Published: September 24, 2026

Abstract

The ongoing expansion of traditional silicon-based electronics is nearing essential physical and performance constraints, prompting the exploration of alternate materials for next-generation nanoelectronic devices. Two-dimensional (2D) materials, such as graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride, have emerged as promising candidates owing to their atomically thin structure, remarkable electrical properties, and superior electrostatic control in ultrathin channels. Semiconducting transition metal dichalcogenides (TMDs) like MoS_2 have significant bandgaps and robust carrier confinement, facilitating the development of high-performance field-effect transistors and other nanoscale electronic devices. The atomic thickness of 2D materials enhances gate control and diminishes short-channel effects, rendering them appealing for energy-efficient electronic devices. This review examines the essential characteristics, synthesis techniques, and primary categories of 2D materials, subsequently addressing their applications in nanoelectronic devices, including field-effect transistors and flexible electronics. Ultimately, significant problems such as large-scale production, contact engineering, and device integration are emphasized, alongside prospective research avenues for the implementation of viable 2D-material-based nanoelectronic devices.

Keywords

Two-Dimensional Materials, Nanoelectronics, Transition Metal Dichalcogenides, Field-Effect Transistors, Flexible Electronics

1. Introduction

The ongoing advancement of contemporary electronic technology has predominantly been propelled by the miniaturization of silicon-based semiconductor de-

vices in alignment with Moore's law. In recent decades, silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) have facilitated significant improvements in computing performance, device density, and energy efficiency. As device diameters near the nanoscale scale, traditional silicon technology faces escalating fundamental physical and technological constraints. These issues encompass significant short-channel effects, elevated leakage currents, excessive power consumption, and diminished electrostatic gate control in ultra-scaled transistors. Moreover, the additional scale of silicon devices results in heightened fabrication complexity and reliability issues, jeopardizing the ongoing advancement of conventional semiconductor technology. Consequently, there is an increasing necessity to investigate alternative materials and device designs capable of supporting the progression of next-generation nanoelectronic systems.

In recent years, two-dimensional (2D) materials have emerged as exceptionally intriguing prospects for future nanoelectronic applications owing to their distinctive structure and electronic features. These materials comprise atomically thin layers where atoms are robustly connected within the plane by covalent interactions, whereas neighboring layers are tenuously held together by van der Waals forces. This stratified configuration enables the materials to be exfoliated into monolayers or few-atom-thick sheets devoid of dangling bonds at the surface, yielding high-quality interfaces and decreased scattering in electronic devices [1] [2]. The atomic thickness of two-dimensional materials offers superior electrostatic control over the channel in transistor devices, mitigating short-channel effects and facilitating aggressive device scaling for nanoscale electronics [3].

The identification of graphene in 2004 was a significant advancement in materials science and initiated comprehensive research into the category of two-dimensional materials. Graphene demonstrates outstanding electrical conductivity, exceptionally high carrier mobility, and significant mechanical strength, rendering it appealing for high-speed electronic and flexible device applications. The lack of an inherent bandgap in graphene restricts its application in digital logic systems that necessitate effective switching performance. As a result, significant focus has transitioned to alternative layered 2D materials with semiconducting characteristics as presented in **Figure 1** [4]. Transition metal dichalcogenides (TMDs), including molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), and tungsten diselenide (WSe_2), have garnered considerable attention owing to their substantial and adjustable bandgaps, facilitating elevated on/off current ratios in field-effect transistors [2]. Moreover, significant 2D materials, such as hexagonal boron nitride (h-BN), black phosphorus, and novel materials like MXenes provide supplementary electrical, insulating, and optoelectronic characteristics.

A primary benefit of 2D materials is their atomic-scale thickness, facilitating superior gate control and diminished short-channel effects in nanoscale transistor channels. Moreover, numerous 2D materials demonstrate adjustable electronic bandgaps, elevated carrier mobility, and exceptional mechanical flexibility, rendering them appropriate for various nanoelectronic applications such as field-effect transistors, flexible electronics, sensors, and nanoelectromechanical systems.

The capability to layer several 2D materials to create van der Waals heterostructures facilitates the development of innovative device topologies with customized electrical and optical characteristics as shown in Figure 2.

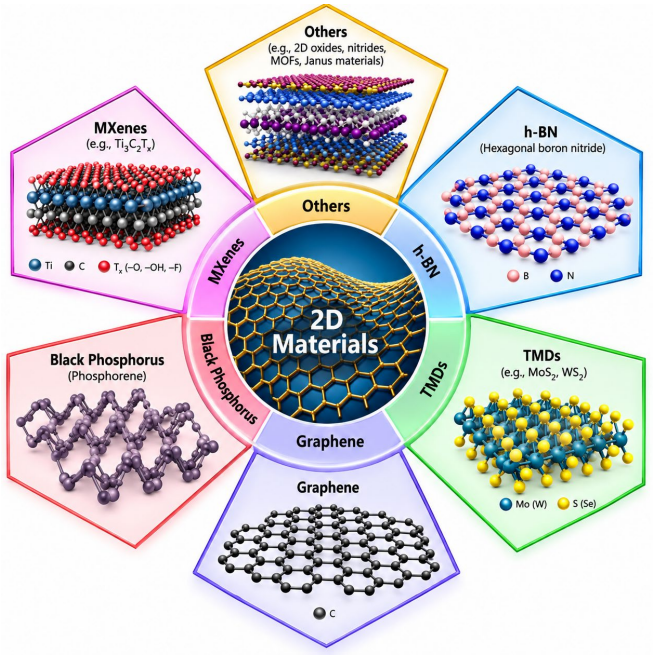

Figure 1. Representative family of two-dimensional (2D) materials and their atomic structures, including graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), black phosphorus (BP), MXenes, and other emerging layered materials [4].

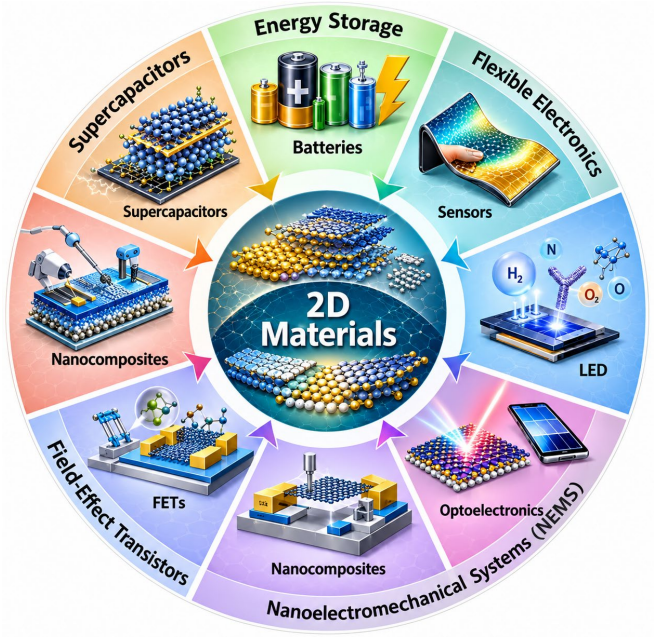

Figure 2. Schematic illustration of the diverse applications of two-dimensional (2D) materials in nanoelectronics and energy technologies, including field-effect transistors (FETs), nanoelectromechanical systems (NEMS), optoelectronic devices, sensors, flexible electronics, supercapacitors, and energy storage systems such as batteries.

Due to the swift advancements in the synthesis, characterisation, and integration of two-dimensional materials into devices, a thorough comprehension of their potential in nanoelectronics is crucial. The current review is centered on 2D materials as active and enabling components in novel nanoelectronic devices. Specifically, the attention will be paid to the electronic and transport properties, fabrication and incorporation methods and applications in field effect transistors, low-power, and tunneling devices, flexible electronics, sensors, nanoelectromechanical systems, and other nanoelectronic architectures. While some of the 2D materials, especially MXenes, show good promise in other applications such as energy storage, shielding against electromagnetic interference, catalysis, etc., they are not within the main scope of this review, but mentioned only in cases where they are important in the context of overall functionality of the materials. Finally, the key problems of large-scale manufacturing, contact formation, performance, and integration with semiconducting electronics will be addressed.

The literature for this review was identified through searches of Web of Science, Scopus, Google Scholar, and ScienceDirect, focusing primarily on peer-reviewed studies published between 2004 and 2026. Relevant studies were selected using combinations of keywords related to 2D materials, synthesis, electronic properties, and nanoelectronic devices. Priority was given to seminal studies, experimental reports, and authoritative reviews directly relevant to material properties, device performance, fabrication, and integration challenges.

2. Fundamental Properties of Two-Dimensional Materials

Two-dimensional (2D) materials exhibit a range of unique physical and electrical features resulting from their atomically thin structure and diminished dimensionality. In contrast to traditional bulk materials, where electrons can travel freely in three dimensions, charge carriers in two-dimensional materials are restricted to a single atomic plane. The diminished dimensionality results in distinctive electrical, mechanical, optical, and thermal properties that render these materials very appealing for nanoscale electronic applications. The essential characteristics of 2D materials are predominantly influenced by their crystalline structure, interlayer interactions, electronic band structure, quantum confinement phenomena, and mechanical and thermal properties. Comprehending these fundamental features is crucial for the design and optimization of nanoelectronic devices utilizing 2D materials.

2.1. Crystal Structure and van der Waals Bonding

Most two-dimensional materials derive from layered bulk crystals, where individual atomic layers exhibit strong in-plane bonding but poor interlayer bonding with adjacent layers. In these materials, atoms in each layer are interconnected by robust covalent bonds, creating very stable and rigid two-dimensional lattices. The interactions between adjacent layers are dictated by weak van der Waals (vdW) forces. The significant disparity in bonding strength facilitates the detachment of individual layers from bulk crystals using methods such as mechanical exfoliation,

liquid-phase exfoliation, or chemical vapor deposition [5].

The inadequate interlayer adhesion produces many distinctive attributes. Firstly, it enables atomically tiny layers to preserve structural integrity even when detached from the bulk crystal. The lack of dangling bonds at the surface results in chemically inert and atomically clean surfaces, thereby substantially diminishing surface scattering and flaws in electrical devices. Third, the feeble van der Waals interactions permit the stacking of various 2D materials without stringent lattice matching prerequisites, resulting in van der Waals heterostructures with customized electrical and optical characteristics [6]. Various categories of 2D materials exhibit distinct crystal formations. Graphene features a hexagonal honeycomb lattice formed by carbon atoms organized in sp^2 hybridization. Transition metal dichalcogenides (TMDs), including MoS_2 and WS_2, generally display a layered architecture including a transition metal layer interposed between two chalcogen layers (S-Mo-S). Hexagonal boron nitride (h-BN) possesses a structure akin to graphene, characterized by alternating boron and nitrogen atoms. These structural differences result in a spectrum of electronic characteristics, encompassing metallic, semiconducting, and insulating behaviors.

2.2. Electronic and Transport Properties

The electrical characteristics of two-dimensional materials are among their most critical attributes for nanoelectronic applications. Due to the confinement of electrons within a narrow atomic layer, two-dimensional materials frequently display distinctive band structures and carrier transport phenomena as shown in **Figure 3** [7]. Graphene exhibits linear energy dispersion close to the Dirac points, leading to massless charge carriers that possess exceptionally high mobility. This characteristic enables graphene-based devices to attain exceptionally high carrier velocities and superior electrical conductivity.

Graphene, however, possesses no intrinsic bandgap, hence constraining its utility in digital circuits that necessitate a substantial on/off current ratio. To address this constraint, extensive research has concentrated on semiconducting two-dimensional materials, particularly transition metal dichalcogenides. These materials have finite bandgaps generally between 1 and 2 eV, rendering them appropriate for transistor applications. Their atomically thin channels offer robust gate control over carrier concentration, facilitating efficient switching behavior in field-effect transistors [8]. The atom-thin nature of the body of 2D semiconductors is also another benefit for transistor scaling in terms of electrostatics. The thinner channel leads to the reduction in electrostatic scaling length, which helps in improving the gate controllability while avoiding the short-channel effect even with nanometer scale of channel lengths. With the use of high-k gate dielectric layers and sub-nanometer equivalent oxide thickness (EOT), 2D channel can have good electrostatic control up to dimensions where traditional planar silicon transistors start to suffer from short-channel effects.

Charge transport in two-dimensional materials is affected by various factors,

including phonon scattering, impurity scattering, and contact resistance at metal-semiconductor interfaces.

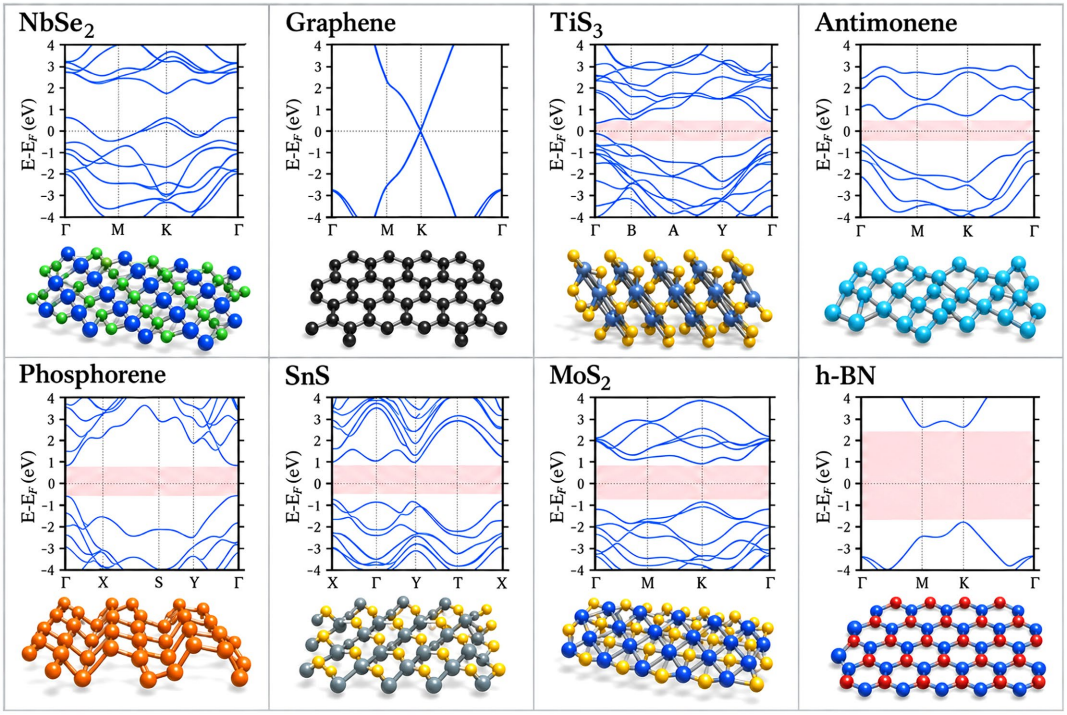

Figure 3. Electronic band structures and atomic crystal structures of representative two-dimensional materials, including $NbSe_2$, graphene, TiS_3, antimonene, phosphorene, SnS, MoS_2, and hexagonal boron nitride (h-BN). The figure highlights the diversity of electronic properties in 2D materials, ranging from metallic and semimetallic to semiconducting and insulating behavior [7].

The electrical characteristics of these materials can be adjusted through methods including strain engineering, chemical doping, electric field modulation, and thickness management. The assembly of heterostructures by the layering of several 2D materials enhances the potential for creating devices with tailored electrical characteristics.

2.3. Quantum Confinement Effects

The lower dimensionality in 2D materials results in pronounced quantum confinement effects. When a material's thickness is diminished to the atomic scale, electron transport becomes restricted in the direction perpendicular to the layer, resulting in the quantization of energy levels. This confinement alters the electronic band structure and frequently results in thickness-dependent electronic characteristics.

An exemplary instance of quantum confinement is evident in transition metal dichalcogenides. Bulk MoS_2 possesses an indirect bandgap, while its monolayer variant features a direct bandgap. This transition markedly augments light-matter interactions and elevates the optical and electrical efficacy of the material. These tunable electronic architectures facilitate the creation of devices with variable op-

tical and electrical characteristics.

Quantum confinement facilitates the creation of low-dimensional nanostructures, including nanoribbons, quantum dots, and quantum wells, originating from two-dimensional materials. These nanostructures demonstrate distinct energy states and exceptional transport phenomena, such as Coulomb blocking and quantized conductance. Experimental investigations have shown that charge carriers can be localized in quantum dots created within two-dimensional semiconductor heterostructures, facilitating the advancement of nanoscale quantum electronic devices [9].

2.4. Mechanical and Thermal Properties

Two-dimensional materials demonstrate exceptional mechanical capabilities owing to their robust in-plane bonding and ultrathin structure. Numerous 2D materials exhibit exceptional tensile strength, flexibility, and elasticity. Graphene exhibits a very high Young's modulus and tensile strength, rendering it one of the strongest materials recognized. Notwithstanding its considerable strength, graphene exhibits significant flexibility and can endure substantial mechanical loads without structural compromise. As per Figure 4 the characteristics of 2D materials render them exceptionally appealing for use in flexible and wearable electrical devices [10].

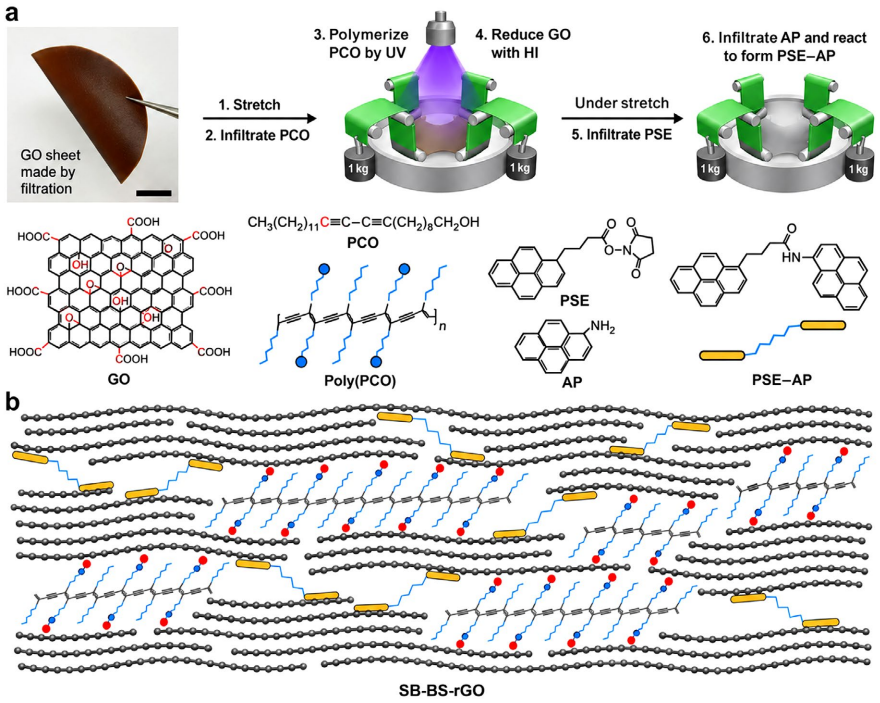

Figure 4. Fabrication methodology and structural framework of the SB-BS-rGO sheet. (a) Schematic representation of the preparation process: a graphene oxide (GO) sheet obtained through filtration was subjected to biaxial stretching and subsequently infiltrated with PCO, followed by UV-induced polymerization. The resultant BS-GO-PCO was chemically reduced with hydrogen iodide (HI). Subsequently, PSE and AP molecules were infiltrated into the sheet and interacted to create PSE-AP complexes while preserving biaxial stretching. Scale bar: 1 centimeter. (b) Structural model illustrating the inter-platelet connectivity within the multilayer architecture via polydiacetylene chains and π-π bridging entities [10].

The mechanical flexibility of two-dimensional materials facilitates strain engineering, wherein mechanical deformation is employed to adjust electrical and optical properties. Strain application can alter a material's band structure, enabling researchers to manipulate carrier mobility, bandgap energy, and optical absorption properties. Besides their mechanical durability, some two-dimensional materials demonstrate outstanding thermal characteristics.

Effective heat dissipation is essential in nanoelectronic systems, as elevated power density may result in overheating. Graphene is recognized for its exceptional thermal conductivity, facilitating efficient heat transfer and enhanced thermal management in electronic devices. Additional 2D materials, such as transition metal dichalcogenides (TMDs) and boron nitride, demonstrate advantageous thermal transport characteristics that enhance device stability and performance [11].

3. Synthesis and Fabrication Techniques

The effective application of two-dimensional (2D) materials in nanoelectronic devices is contingent upon the advancement of dependable synthesis and fabrication methods that can yield high-quality atomically thin layers with regulated thickness, crystallinity, and extensive lateral dimensions. Following the separation of graphene in 2004, considerable efforts have been directed towards the advancement of scalable synthesis methods for a range of two-dimensional materials, including graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), and black phosphorus. Synthesis methods are typically categorized into top-down approaches, which involve the exfoliation of layers from bulk layered crystals, and bottom-up approaches, which entail the synthesis of atomically thin materials via chemical reactions or vapor-phase growth processes [12] [13].

Top-down methods like mechanical exfoliation and liquid-phase exfoliation often provide high-quality nanosheets but are constrained by limited scalability. Conversely, bottom-up methods like chemical vapor deposition (CVD) facilitate the production of extensive monolayer films appropriate for industrial device manufacturing. Consequently, scalable growing techniques are crucial for the incorporation of 2D materials into functional electronic systems and advanced nanoelectronic devices [1] [14].

3.1. Mechanical Exfoliation

Mechanical exfoliation is one of the initial methods employed to isolate two-dimensional materials and was essential in the discovery of graphene. In this method, adhesive tape is used to repeatedly peel thin layers from bulk graphite and transfer them onto a suitable substrate to obtain monolayer or few-layer 2D materials. This approach involves the removal of thin layers from bulk stacked crystals by the use of adhesive tape or mechanical cleavage, as shown in **Figure 5**. The technique utilizes the weak van der Waals interactions between neighboring layers in materials including graphite, MoS_2, and hexagonal boron nitride [15]. The mobility values achieved in mechanically exfoliated graphene are extremely high; however, the

measured mobilities are highly dependent upon the substrate, carrier concentration, temperature, sample purity, and device geometry. Suspended single-layer graphene devices made from ultraclean graphene have yielded low-temperature mobilities higher than 200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at carrier concentrations of about 2×10^{11} cm^{-2}, and the graphene is suspended over the Si/SiO_2 gate stack. The mobility of supported exfoliated graphene devices is lower due to various factors, including substrate disorder, charged impurities, and surface scattering; representative room-temperature mobilities have values of the order of 10,000 - 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$. Therefore, the mobility values obtained from suspended and supported graphene cannot be compared [12] [16]. The exceptional mobility of mechanically exfoliated graphene renders it optimal for fundamental investigations of electrical transport and quantum processes.

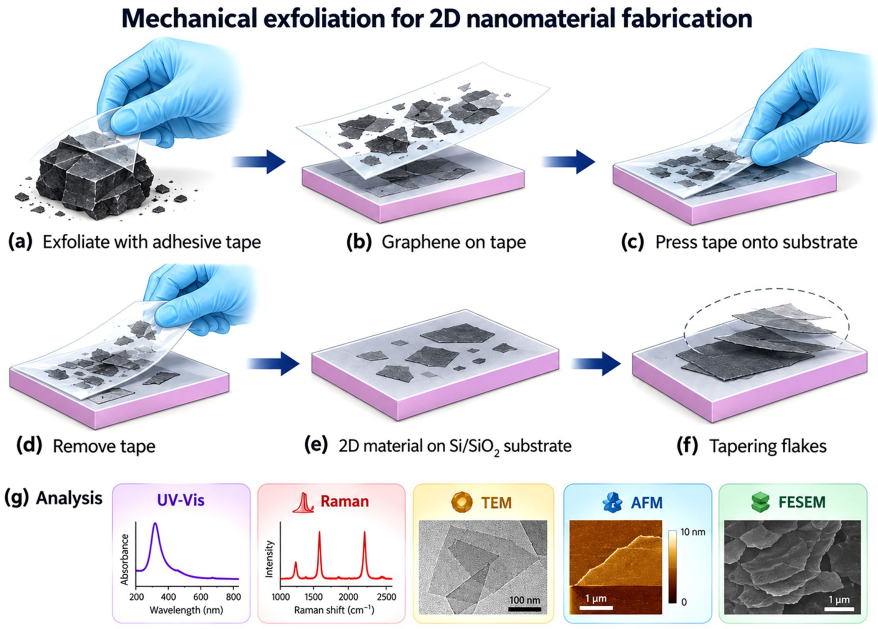

Figure 5. Schematic illustration of the mechanical exfoliation method for fabricating two-dimensional nanomaterials. Bulk graphite is exfoliated using adhesive tape, transferred onto a Si/SiO_2 substrate, and the tape is removed to leave thin 2D material flakes on the surface, which can then be characterized using techniques such as Raman spectroscopy, UV-Vis spectroscopy, AFM, and TEM.

Likewise, mechanically exfoliated MoS_2 monolayers have been extensively investigated for transistor applications. Monolayer MoS_2 field-effect transistors exhibit on/off current ratios surpassing 10^8 and carrier mobility ranging from 10 to 200 $cm^2 \cdot V^{-1} \cdot s^{-1}$, contingent upon substrate and device configuration [17]. Notwithstanding the generation of superior materials, mechanical exfoliation possesses considerable constraints. The resultant flakes often possess lateral diameters varying from a few micrometers to many tens of micrometers, and the yield of monolayer materials is quite low. Thus, this technology is predominantly employed for laboratory-scale investigations rather than industrial manufacturing [13].

3.2. Liquid-Phase Exfoliation

Liquid-phase exfoliation is a prevalent top-down method for generating substantial numbers of 2D nanosheets in liquid suspensions. This process involves dispersing bulk layered materials in liquids and applying ultrasonic energy or shear forces to isolate individual layers. The procedure diminishes the van der Waals forces between neighboring layers, facilitating exfoliation into nanosheets that remain dispersed in the solvent [18]. This method can yield graphene nanosheets with lateral dimensions generally between 100 nm to several micrometers, contingent upon the sonication parameters and solvent employed [19]. Liquid-phase exfoliation may generate gram-scale amounts of graphene and other two-dimensional materials, rendering it appealing for industrial applications including printed electronics, energy storage systems, and composite materials [20]. In this process, graphite is dispersed in suitable solvents and subjected to ultrasonication, which weakens the van der Waals forces between graphene layers. Centrifugation and filtration then separate graphene nanosheets with controlled thickness and size as shown in Figure 6. Graphene films produced via liquid-phase exfoliation exhibit electrical conductivities ranging from roughly 10^3 to 10^4 S·m^{-1}, rendering them appropriate for flexible electrodes and transparent conductive films [19].

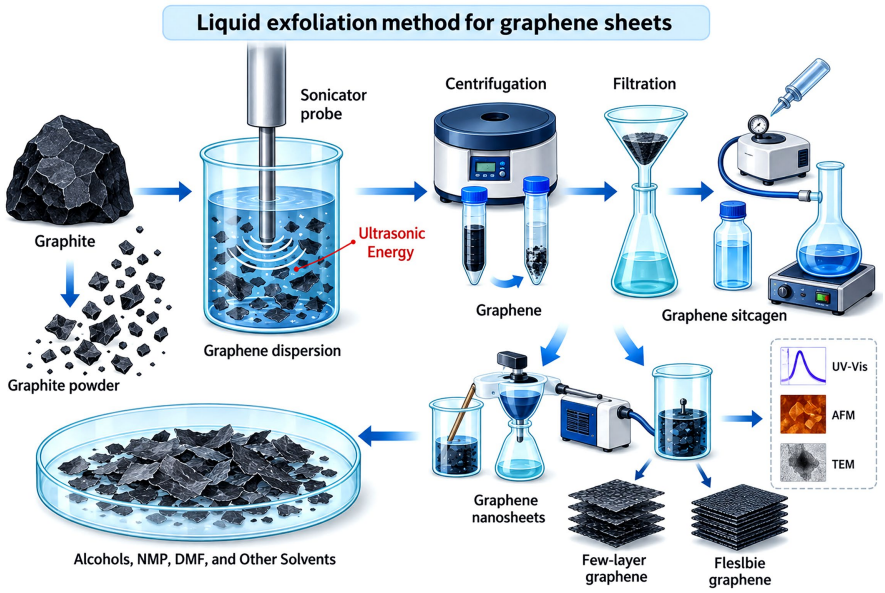

Figure 6. Schematic illustration of the liquid-phase exfoliation process for producing graphene nanosheets. Bulk graphite is first ground into powder and dispersed in a solvent, followed by ultrasonication to exfoliate graphene layers. The resulting dispersion is then subjected to centrifugation and filtration to isolate graphene nanosheets and few-layer graphene suitable for various applications.

Nonetheless, the nanosheets generated by this method generally exhibit reduced lateral dimensions and increased defect density relative to mechanically exfoliated materials. Notwithstanding these constraints, liquid-phase exfoliation continues to be one of the most promising scalable methods for generating sub-

stantial quantities of two-dimensional materials for commercial use.

3.3. Chemical Vapor Deposition (CVD)

Chemical vapor deposition (CVD) is a prevalent bottom-up synthesis method for generating extensive two-dimensional materials. This process involves the introduction of gaseous precursor molecules into a high-temperature reactor, where they undergo chemical reactions or thermal degradation on a substrate surface to produce thin crystalline coatings [21]. Extensive graphene films have been effectively synthesized on copper surfaces utilizing methane as a carbon precursor. This approach has produced graphene films with diameters surpassing 30 inches for industrial purposes [22]. CVD-synthesized graphene generally demonstrates carrier mobility values between 1000 and 5000 $cm^2 \cdot V^{-1} \cdot s^{-1}$, contingent upon growth circumstances and transfer methodologies [21].

Comprehending and enhancing the growth mechanisms of two-dimensional (2D) materials by chemical vapor deposition (CVD) necessitates an integration of theoretical modeling, computational simulations, and experimental analysis. Advanced computational methodologies, including density functional theory (DFT), kinetic Monte Carlo simulations, molecular dynamics, and machine learning models, have emerged as formidable instruments for forecasting growth mechanisms, reaction pathways, and material characteristics. These methodologies assist researchers in examining the impact of reactor parameters, temperature, pressure, and precursor transport on the nucleation and development of high-quality two-dimensional materials as shown in Figure 7.

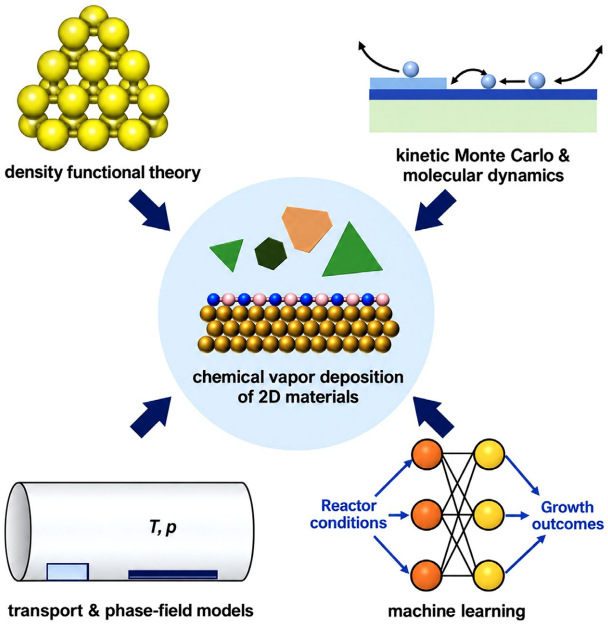

Figure 7. Computational and theoretical approaches used to study the chemical vapor deposition growth of two-dimensional materials, including density functional theory, kinetic Monte Carlo and molecular dynamics simulations, transport and phase-field modeling, and machine learning for predicting growth outcomes and optimizing reactor conditions [23].

CVD techniques have been extensively employed to synthesize transition metal dichalcogenides, including MoS_2 and WS_2. Monolayer MoS_2 films produced via CVD have exhibited field-effect mobilities ranging from 10 to 60 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and on/off current ratios surpassing 10^7 in transistor devices [1] [24]. A primary advantage of CVD is its capacity to generate continuous monolayer films with regulated thickness and exceptional homogeneity over extensive areas. Consequently, scalable growth methodologies like CVD are deemed crucial for the incorporation of 2D materials into nanoelectronic and optoelectronic devices.

3.4. Large Area Growth and Transfer Methods

For practical nanoelectronic applications, it is imperative to transfer extensive 2D materials onto insulating or flexible substrates appropriate for device production. Typically, 2D materials produced using CVD are initially cultivated on metallic substrates like copper or nickel and subsequently require transfer to alternative substrates through polymer-assisted techniques [25]. During a standard transfer procedure, the synthesized graphene film is enveloped with a polymeric support layer, typically polymethyl methacrylate (PMMA). The metal substrate is subsequently chemically etched, facilitating the transfer of the polymer-supported graphene layer onto substrates like SiO_2/Si, glass, or flexible polymer films. Subsequent to the transfer, the polymer layer is eliminated, resulting in the graphene sheet adhering to the new substrate [25]. The transfer of CVD-grown graphene from metallic growth substrates to insulating or flexible substrates is an essential process for the construction of nanoelectronic and optoelectronic devices as shown in **Figure 8**. A widely employed polymer-assisted transfer method utilizing polymethyl methacrylate (PMMA) facilitates the incorporation of graphene sheets onto diverse surfaces.

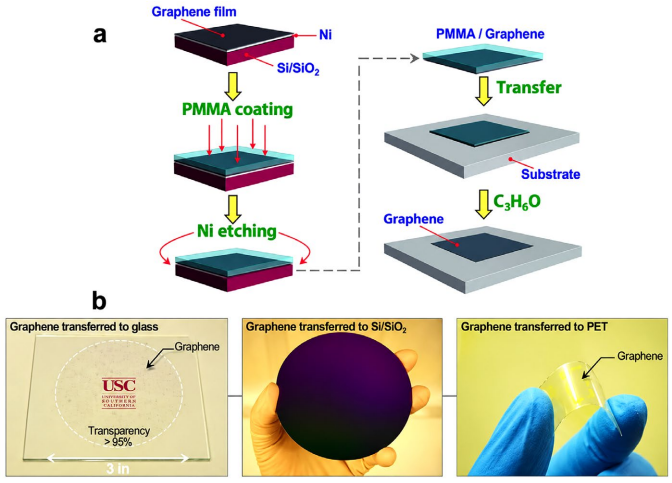

Figure 8. Polymer-assisted transfer of CVD-grown graphene films. (a) Schematic of the PMMA-assisted transfer process from a Ni/Si-SiO_2 growth substrate to a target substrate after metal etching and PMMA removal. (b) Photographs of graphene films transferred onto glass, Si/SiO_2, and flexible PET substrates, demonstrating their high transparency and versatility for electronic applications [26].

Extensive graphene sheets transferred via roll-to-roll techniques have sheet resistances as low as 25 Ω/sq with 97.4% optical transparency, positioning them as viable options for transparent electrodes and flexible electronics [22]. Ongoing enhancements in transfer techniques seek to reduce structural imperfections, contaminants, and creases occurring during the transfer process. These advancements are crucial for enhancing the reliability and performance of nanoelectronic devices based on 2D materials.

Table 1 compares the principal synthesis routes for 2D materials, highlighting their processing approach, advantages, limitations, and representative material properties. Mechanical exfoliation provides high-quality flakes but limited scalability, while liquid-phase exfoliation and CVD offer greater production potential, with trade-offs in defect density, transfer-related contamination, and material quality [12] [13] [15] [18]-[25].

Table 1. Comparative analysis of synthesis techniques for two-dimensional materials.

Synthesis Method	Category	Typical Materials	Process Description	Advantages	Limitations	Reported Properties	References
Mechanical Exfoliation	Top-down	Graphene, MoS_2, h-BN	Thin layers are peeled from bulk layered crystals using adhesive tape and transferred onto substrates such as Si/SiO_2.	Produces high-quality and defect-free monolayers; ideal for fundamental research.	Low yield; small flake sizes (μm scale); not suitable for large-scale production.	Graphene mobility ≈ **10,000 - 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ (RT)** and up to **200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at low temperature**.	[12] [13] [15]
Liquid-Phase Exfoliation	Top-down	Graphene, MoS_2, WS_2	Bulk layered materials are dispersed in solvents and exfoliated using ultrasonication or shear forces, followed by centrifugation.	Scalable and cost-effective; capable of gram-scale production of nanosheets.	Smaller lateral dimensions and higher defect density compared with mechanical exfoliation.	Lateral sizes typically **100 nm - several μm**; conductivity **10^3 - 10^4 $S \cdot m^{-1}$**.	[18]-[20]
Chemical Vapor Deposition (CVD)	Bottom-up	Graphene, MoS_2, WS_2, h-BN	Gaseous precursor molecules react at high temperatures on catalytic substrates (e.g., Cu or Ni) forming thin crystalline films.	Enables wafer-scale growth and high uniformity; compatible with industrial processes.	Requires complex equipment; transfer processes may introduce contamination or defects.	Graphene mobility typically **1000 - 5000 $cm^2 \cdot V^{-1} \cdot s^{-1}$** depending on growth conditions.	[21] [24]
Large-Area Growth and Transfer Methods	Hybrid	Graphene films	CVD-grown films are transferred onto insulating or flexible substrates using polymer-assisted methods (e.g., PMMA).	Enables flexible electronics and transparent conductive films.	Wrinkles, contamination, and structural defects may occur during transfer.	Sheet resistance as low as **25 Ω/sq with ~97.4% transparency**.	[22] [25]

4. Classes of Two-Dimensional Materials

Two-dimensional materials comprise a varied collection of atomically thin crystals exhibiting distinct structural, electrical, and mechanical characteristics. Following the discovery of graphene, extensive research has resulted in the identification of various layered materials that can be exfoliated into monolayers or few-atom-thick sheets. These materials display a diverse array of electronic properties, encompassing metallic, semiconducting, insulating, and superconducting behaviors. This diversity renders them exceptionally promising for applications in nanoelectronics, optoelectronics, sensing, and energy storage devices [12] [13]. The most extensively researched categories of two-dimensional materials encompass graphene and its derivatives, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), and many novel 2D materials including MXenes and black phosphorus. Each class demonstrates unique physical and electrical characteristics that render them appropriate for particular nanoelectronic applications.

4.1. Graphene and Graphene-Derived Materials

Graphene is the most recognized two-dimensional substance, comprising a single sheet of carbon atoms organized in a hexagonal honeycomb lattice. It was initially isolated in 2004 using mechanical exfoliation of graphite, signifying a significant advancement in materials research [15]. Graphene exhibits remarkable physical and electrical characteristics. It demonstrates exceptionally high carrier mobility, attaining values of up to 200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at low temperatures, and around 10,000 - 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at ambient temperature [12] [16]. Moreover, graphene has exceptional heat conductivity surpassing 3000 $W \cdot m^{-1} \cdot K^{-1}$, rendering it one of the most thermally conductive materials recognized [27].

Notwithstanding these benefits, graphene possesses no intrinsic bandgap, as its conduction and valence bands converge at the Dirac points. The zero-bandgap characteristic restricts its direct employment in digital transistors, which necessitate a high on/off switching ratio. To overcome this constraint, other graphene derivatives have been created, such as graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoribbons, which display adjustable bandgaps based on their structural modifications [28]. Graphene and its derivatives have been extensively investigated for use in high-frequency transistors, transparent electrodes, flexible electronics, and sensors, owing to their exceptional electrical conductivity and mechanical flexibility [29]. While graphene is characterized by high carrier mobility, the lack of an intrinsic band gap makes the on/off ratio low, thus limiting its use for digital logic. While some methods, such as nano structuring can increase the band gap, they also reduce carrier mobility.

4.2. Transition Metal Dichalcogenides (TMDs)

Transition metal dichalcogenides (TMDs) are a significant category of two-dimensional materials characterized by the generic chemical formula MX_2, whereby

M denotes a transition metal (such as Mo or W) and X signifies a chalcogen atom (S, Se, or Te). These materials exhibit a stratified architecture with a layer of transition metal atoms interposed between two layers of chalcogens. In contrast to graphene, numerous transition metal dichalcogenides (TMDs) are semiconductors possessing intrinsic bandgaps between 1 and 2 eV, rendering them exceptionally appropriate for nanoelectronic applications. Monolayer molybdenum disulfide (MoS_2) possesses a direct bandgap of roughly 1.8 eV, but its bulk form has an indirect bandgap of around 1.2 eV [30].

However, it was observed that the performance of monolayer MoS_2 FETs is highly sensitive to dielectric environment, contact resistance, channel geometry, and mobility extraction technique. The early monolayer MoS_2 FETs showed lower mobilities; however, high-k HfO_2 gate dielectric in top gated monolayer MoS_2 FET yielded room temperature field effect mobility close to 200 $cm^2 \cdot V^{-1} \cdot s^{-1}$ along with a high on-off current ratio of around 10^8 [17]. This can be viewed in light of the device design and not as a property of monolayer MoS_2. In general, the reported mobilities for MoS_2 are quite diverse. TMDs have robust light-matter interactions, facilitating their application in photodetectors, optoelectronic devices, and valleytronic technologies [1]. One disadvantage of TMD-based transistors is that of metal-semiconductor contact variability. The factors of Schottky barrier formation, Fermi level pinning, interface contamination, and variation in contact geometries can cause significant variation in contact resistances and carrier mobilities measured directly from the device itself.

4.3. Hexagonal Boron Nitride (h-BN)

Hexagonal boron nitride (h-BN) is a significant two-dimensional material that possesses a comparable honeycomb lattice structure to graphene. Nevertheless, the lattice is composed of alternating boron and nitrogen atoms rather than carbon atoms. This configuration produces an insulating material with a broad bandgap of roughly 5.9 eV [31]. Owing to its superior dielectric characteristics, chemical stability, and atomically clean surface, h-BN is frequently employed as an insulating substrate or dielectric layer in devices based on graphene and other two-dimensional materials. The lack of dangling bonds and surface charge traps enables h-BN to markedly enhance the carrier mobility of graphene devices by diminishing scattering effects [31].

Moreover, h-BN is essential in the synthesis of van der Waals heterostructures, wherein several 2D elements are layered to create novel artificial materials with customized electrical characteristics. These heterostructures facilitate the advancement of sophisticated nanoelectronic and optoelectronic devices [32].

4.4. Novel Two-Dimensional Materials

Alongside graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN), other novel two-dimensional materials have garnered considerable interest in recent years. MXenes and black phosphorus have notably ad-

vantageous characteristics for nanoelectronic applications. MXenes constitute a class of two-dimensional transition metal carbides or nitrides, generally denoted by the formula $M_{n+1}X_nT_x$, where M signifies a transition metal, X denotes carbon or nitrogen, and T_x indicates surface functional groups such as hydroxyl or oxygen. An MXene is a kind of 2D material that is a transition-metal carbide or nitride, typically represented by the chemical formula $M_{n+1}X_nT_x$, in which M stands for a transition metal, X represents either carbon or nitrogen, and T_x stands for surface functional groups. High electrical conductivity, ability to adjust the surface chemistry, hydrophilicity, and suitability for solution-based processing make them a candidate for many applications in the field of electronics, including sensors, conductors, flexible electronics, and novel device structures. MXenes have been widely explored in the areas of energy storage and electromagnetic interference shielding. Yet these applications are not the main topics of the current review and are mentioned merely for illustrating the overall multifunctionality of MXenes [33].

Table 2 summarizes the major classes of 2D materials used in nanoelectronics, comparing their crystal structures, bandgaps, carrier mobilities, key advantages, and typical applications. Graphene, TMDs, h-BN, MXenes, and black phosphorus exhibit distinctly different electronic characteristics, enabling their use in transistors, optoelectronics, flexible electronics, sensing, and heterostructure-based devices [1] [12] [16] [17] [27] [30]-[34].

Table 2. Comparison of major classes of two-dimensional materials for nanoelectronics.

Material Class	Crystal Structure	Bandgap	Carrier Mobility	Key Advantages	Typical Applications	References
Graphene	Hexagonal honeycomb lattice of carbon atoms	0 eV	Up to **200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ (low T)**; **10,000 - 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ (RT)**	Exceptional electrical conductivity, high thermal conductivity (>3000 $W \cdot m^{-1} \cdot K^{-1}$), excellent mechanical strength	High-frequency transistors, transparent electrodes, flexible electronics, sensors	[12] [16] [27]
Transition Metal Dichalcogenides (TMDs)	MX_2 layered structure (transition metal between two chalcogen layers)	**1 - 2 eV**	**10 - 200 $cm^2 \cdot V^{-1} \cdot s^{-1}$**	Intrinsic bandgap suitable for transistor switching; strong light-matter interaction	Field-effect transistors, photodetectors, optoelectronics	[1] [17] [30]
Hexagonal Boron Nitride (h-BN)	Honeycomb lattice of alternating boron and nitrogen atoms	**~5.9 eV**	Insulating material	Excellent dielectric properties, chemically stable, atomically smooth surface	Gate dielectrics, substrates for graphene devices, van der Waals heterostructures	[31] [32]

Continued

MXenes	Layered transition metal carbides/ nitrides ($M_{n+1}X_nT_x$)	Metallic/small bandgap	High electrical conductivity	Large surface area, hydrophilic surface chemistry, tunable functional groups	Energy storage devices, sensors, electromagnetic shielding	[33]
Black Phosphorus (Phosphorene)	Layered puckered orthorhombic structure	**0.3 - 2.0 eV (thickness dependent)**	Up to **~1000 $cm^2 \cdot V^{-1} \cdot s^{-1}$**	Tunable bandgap, anisotropic transport properties	High-performance transistors, photodetectors, optoelectronic devices	[34]

Another new two-dimensional substance is black phosphorus, which can be exfoliated into thin layers referred to as phosphorene. Phosphorene demonstrates a bandgap that varies with thickness, spanning from 0.3 eV in bulk form to around 2.0 eV in monolayer form. It exhibits a notable carrier mobility of up to 1000 $cm^2 \cdot V^{-1} \cdot s^{-1}$, rendering it appealing for high-performance electrical and optoelectronic applications [34]. As research advances, these novel materials are anticipated to have a progressively significant role in the evolution of next-generation nanoelectronic technology. The main drawback of black phosphorous is its instability in the environment. The presence of oxygen and water will quickly oxidize black phosphorous. Thus, it needs to be encapsulated to stabilize its properties in any application. The swift identification of novel two-dimensional materials perpetuates the diversification of accessible electronic characteristics and device potentialities.

5. Nanoelectronic Devices Based on Two-Dimensional Materials

Two-dimensional (2D) materials have created novel opportunities for nanoelectronic device architectures owing to their atomically thin structure, adjustable bandgaps, elevated carrier mobility, and superior electrostatic gate control. These attributes facilitate device scalability beyond the constraints of traditional bulk semiconductors, concurrently diminishing short-channel effects and power consumption. Consequently, 2D materials have been extensively studied for numerous nanoelectronic applications, including field-effect transistors (FETs), tunneling and low-power devices, flexible and wearable electronics, and nanoelectromechanical systems (NEMS). The ultrathin characteristics of these materials enable effective control of charge carrier density and support the production of nanoscale devices with enhanced performance and functionality.

Field-effect transistors represent one of the most thoroughly researched applications of 2D materials. Graphene-based transistors garnered significant interest owing to graphene's remarkable carrier mobility, which can surpass 10,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ at ambient temperature and attain 200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ under optimal

conditions [12] [29]. The lack of an intrinsic bandgap in graphene restricts its application in digital logic systems that necessitate high switching ratios. To address this constraint, semiconducting two-dimensional materials, specifically transition metal dichalcogenides (TMDs), have been extensively investigated. Monolayer MoS_2 transistors exhibit on/off current ratios surpassing 10^8 and carrier mobility between 10 and 200 $cm^2 \cdot V^{-1} \cdot s^{-1}$, rendering them exceptionally appropriate for low-power electronic applications [1] [17]. The inherent bandgaps of transition metal dichalcogenides (TMDs), often between 1 and 2 eV, provide effective switching and enhance device performance relative to graphene-based transistors.

In addition to traditional FETs, 2D materials have facilitated the advancement of tunneling field-effect transistors (TFETs) and various low-power devices. In these devices, charge transport transpires via quantum tunneling instead of thermionic emission, enabling the potential to attain subthreshold swings beneath the theoretical threshold of 60 mV per decade established by traditional transistor functionality. Stacking various 2D materials to create van der Waals heterostructures enables the precise engineering of band alignments and tunneling barriers at the atomic level. Devices utilizing graphene and hexagonal boron nitride heterostructures exhibit effective tunneling characteristics and elevated switching velocities [32].

A significant benefit of 2D materials is their mechanical flexibility, facilitating the production of flexible and wearable electrical devices. In contrast to conventional semiconductors that are fragile and susceptible to breakage, atomically thin materials can endure substantial mechanical stress without compromising electrical performance. Graphene can endure mechanical strains of 20% while preserving good electrical conductivity [35]. This characteristic has facilitated the creation of graphene-based transparent conductive electrodes exhibiting optical transparency exceeding 97% and a sheet resistance of approximately 125 Ω/square, positioning them as viable substitutes for indium tin oxide in flexible electronic devices [22]. Likewise, flexible transistors and sensors utilizing MoS_2 and other transition metal dichalcogenides (TMDs) have been exhibited on polymer substrates for wearable electronics and biomedical applications.

Besides electrical and flexible devices, 2D materials have facilitated the advancement of nanoelectromechanical systems (NEMS). Materials like graphene are optimal for fabricating nanoscale resonators, sensors, and actuators due to their remarkably low mass density, elevated Young's modulus, and outstanding mechanical strength. Graphene-based NEMS resonators have resonance frequencies spanning the MHz to GHz range, facilitating ultra-sensitive detection of variations in mass, force, and pressure [36]. The elevated Young's modulus of graphene, around 1TPa, along with its atomic thickness, facilitates the development of very sensitive electromechanical devices with prospective applications in sensing, signal processing, and quantum technologies [35]. The distinctive amalgamation of electrical, optical, and mechanical capabilities renders two-dimensional materials

an exceptional foundation for next-generation nanoelectronic devices. Their capacity to create heterostructures, along with advancements in synthesis and device fabrication methods, persists in propelling the evolution of high-performance nanoscale electrical and electromechanical systems [37]. Although considerable advancements have been made in the development of prototypes, the majority of nanoelectronics based on 2D materials are still quite low-to-intermediate TRL, with significant differences existing between laboratory demonstrators and commercial large-scale production. The individual FETs, sensors, flexible devices, and other heterostructure-based devices have shown good results, yet reproducible wafer-scale processing, low resistance contacts, quality and consistency of material, durability and compatibility with CMOS production are still significant hurdles that need to be overcome. Technologies utilizing graphene as a conductive and sensing material have come much further down the path toward actual implementation compared to the logic devices utilizing TMDs, black phosphorus, and heterostructures.

6. Challenges and Future Perspectives

Notwithstanding the significant advancements made in the creation of two-dimensional (2D) materials for nanoelectronic applications, some major difficulties persist before these materials may be extensively adopted in commercial electronic technology. Challenges of large-scale manufacture, contact resistance, device reliability, and integration with current semiconductor technologies must be resolved to fully use the potential of 2D materials in next-generation electronic systems. Ongoing research endeavors are thus concentrated on surmounting these constraints via enhanced synthesis methodologies, sophisticated device engineering, and the establishment of scalable manufacturing processes [13] [24].

A key problem is the large-scale production and consistency of high-quality 2D materials. While mechanical exfoliation yields high-quality crystals appropriate for fundamental research, it is incompatible with large-scale industrial production. Chemical vapor deposition (CVD) has become a leading method for the scalable synthesis of graphene and other two-dimensional materials. Nonetheless, attaining uniform monolayer development over wafer-scale substrates is challenging due to complications such as grain boundaries, domain mismatches, and thickness discrepancies. These structural nonuniformities can markedly affect the electrical characteristics of devices and diminish repeatability in large-scale production [1] [21]. Consequently, enhancing growth regulation and advancing wafer-scale synthesis methods are critical obstacles to the commercialization of 2D material-based nanoelectronics.

One of the major difficulties in designing devices based on 2D materials is establishing the low contact resistance. In traditional metal-semiconductor contacts, a Schottky barrier limits carrier injection while interface states and metal-induced gap states could lead to the Fermi-level pinning, and thus to inability to control the contact barrier. Different methods of contact engineering have thus been stud-

ied. The edge contacts, which allow carrier injection using the edges of the 2D material, have a better electronic coupling than regular top contacts. Phase-engineered contacts modify locally the semiconducting regions, especially in TMDs like MoS_2, to the conductive phase, decreasing injection barrier and contact resistance. The van der Waals contacts use weakly bound metals or semimetals as electrodes to avoid disorder, chemical bonding, and metal-induced gap states at the interface, thus preventing Fermi-level pinning and maintaining the intrinsic electronic properties of the 2D semiconductor. Thus, it has been shown that not only the work function of the metal determines the contact resistance but also the interface chemistry, the contact geometry, the electronic phase, and the interfacial coupling, making contact engineering an important prerequisite for nanoelectronics based on 2D materials [17] [38].

Device dependability and long-term stability constitute significant obstacles for practical applications. Certain 2D materials exhibit sensitivity to environmental influences, including oxygen, moisture, and temperature, resulting in the deterioration of their structural and electrical properties. Black phosphorus is recognized for its quick oxidation upon exposure to air, resulting in diminished device performance [39]. Likewise, extended electrical operation may cause charge trapping and structural deterioration in specific 2D materials. Researchers are developing encapsulation approaches utilizing materials like hexagonal boron nitride (h-BN) or protective polymer coatings to enhance environmental stability and prolong device lifespan [31].

The amalgamation of 2D materials with traditional complementary metal-oxide-semiconductor (CMOS) technology poses both obstacles and prospects. For effective implementation in electronic circuits, 2D materials must align with established semiconductor fabrication procedures, encompassing lithography, deposition, and etching methods. However incorporating atomically thin materials into silicon-based manufacturing processes while preserving their structural integrity, we face significant challenges. Moreover, extensive transfer methods may result in contamination or mechanical damage that compromises device performance. The advancement of wafer-scale integration techniques and hybrid device architectures that merge 2D materials with traditional silicon electronics is currently a prominent research focus [32] [37]. Several avenues of development can contribute to the advancement of 2D materials from lab-scale demonstrations to actual nanoelectronics applications. The application of artificial intelligence and machine learning techniques to materials discovery, predicting material properties, optimizing synthesis parameters, and discovering suitable heterostructures is gaining increasing popularity. Simultaneously, the wafer-scale growth and integration of the materials is a necessary step for ensuring uniformity of material quality and consistent device operation. An additional avenue of development involves heterogeneous integration of 2D materials along with well-known CMOS technologies, thus leveraging the unique electronic, optical, and sensing properties of 2D materials while not necessarily replacing silicon-based technology.

Future advancements in scalable synthesis methods, defect engineering, and heterostructure manufacturing are anticipated to be pivotal in addressing these difficulties. Current research avenues encompass the creation of van der Waals heterostructures, machine-learning-enhanced materials discovery, and innovative device architectures that leverage the distinctive features of two-dimensional materials. Ongoing advancements in these domains suggest that two-dimensional materials will emerge as essential elements in next-generation nanoelectronic technologies, facilitating quicker, more energy-efficient, and highly adaptable electronic systems [37].

7. Conclusions

Two-dimensional (2D) materials have emerged as a revolutionary category of materials for next-generation nanoelectronic devices owing to their distinctive structural, electrical, and mechanical characteristics. Their atomically thin architecture facilitates superior electrostatic gate regulation, diminishes short-channel phenomena, and improves carrier mobility, which are crucial for advancing device miniaturization beyond the constraints of traditional silicon technology. Materials including graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), MXenes, and black phosphorus exhibit a variety of electronic properties, encompassing metallic, semiconducting, and insulating behaviors, thereby offering a flexible foundation for the development of sophisticated nanoelectronic systems.

Substantial advancements have been achieved in comprehending the essential characteristics, synthesis methodologies, and device applications of two-dimensional materials. Diverse manufacturing techniques, such as mechanical exfoliation, liquid-phase exfoliation, and chemical vapor deposition, have facilitated the generation of atomically thin layers with regulated thickness and enhanced crystallinity. Among these processes, scalable growth techniques like CVD are especially significant for the production of large-area films appropriate for industrial applications. The incorporation of 2D materials into field-effect transistors, tunneling devices, flexible electronics, and nanoelectromechanical systems has exhibited their capability for high-performance and energy-efficient nanoelectronic technologies.

Notwithstanding these advancements, numerous hurdles persist before 2D materials may be extensively utilized in commercial electronic gadgets. Challenges pertaining to large-scale synthesis, defect management, contact resistance, device stability, and integration with current CMOS technology must be resolved to ensure dependable and consistent device performance. Ongoing research in interface engineering, heterostructure fabrication, and sophisticated device topologies is anticipated to be essential in addressing these constraints. The swift advancement in the synthesis, characterisation, and use of two-dimensional materials suggests they will be crucial in the evolution of future nanoelectronic technologies. Ongoing advancements in scalable manufacturing and device integration are an-

ticipated to facilitate the development of quicker, smaller, more energy-efficient, and flexible electronic systems using 2D materials, thereby fostering creative applications in computing, sensing, communication, and wearable technology.

Author Contributions

Arav Rajesh Hinduja: Conceptualization, literature review, manuscript preparation, and visualization. Sananjay Biswas: Supervision, methodology, critical review, editing, and overall guidance. Both authors reviewed and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Wang, Q.H., Kalantar-Zadeh, K., Kis, A., Coleman, J.N. and Strano, M.S. (2012) Electronics and Optoelectronics of Two-Dimensional Transition Metal Dichalcogenides. *Nature Nanotechnology*, **7**, 699-712. https://doi.org/10.1038/nnano.2012.193

[2] Rai, A., Movva, H., Roy, A., Taneja, D., Chowdhury, S. and Banerjee, S. (2018) Progress in Contact, Doping and Mobility Engineering of MoS_2: An Atomically Thin 2D Semiconductor. *Crystals*, **8**, Article 316. https://doi.org/10.3390/cryst8080316

[3] Mitta, S.B., Choi, M.S., Nipane, A., Ali, F., Kim, C., Teherani, J.T., *et al.* (2021) Electrical Characterization of 2D Materials-Based Field-Effect Transistors. 2*D Materials*, **8**, Article 012002. https://doi.org/10.1088/2053-1583/abc187

[4] Ma, B., Martín, C., Kurapati, R. and Bianco, A. (2020) Degradation-by-Design: How Chemical Functionalization Enhances the Biodegradability and Safety of 2D Materials. *Chemical Society Reviews*, **49**, 6224-6247. https://doi.org/10.1039/c9cs00822e

[5] Bian, R., Li, C., Liu, Q., Cao, G., Fu, Q., Meng, P., *et al.* (2022) Recent Progress in the Synthesis of Novel Two-Dimensional van der Waals Materials. *National Science Review*, **9**, nwab164. https://doi.org/10.1093/nsr/nwab164

[6] Liu, Y., Huang, Y. and Duan, X. (2019) Van Der Waals Integration before and beyond Two-Dimensional Materials. *Nature*, **567**, 323-333. https://doi.org/10.1038/s41586-019-1013-x

[7] Roldán, R., Chirolli, L., Prada, E., Silva-Guillén, J.A., San-Jose, P. and Guinea, F. (2017) Theory of 2D Crystals: Graphene and Beyond. *Chemical Society Reviews*, **46**, 4387-4399. https://doi.org/10.1039/c7cs00210f

[8] Sangwan, V.K. and Hersam, M.C. (2018) Electronic Transport in Two-Dimensional Materials. *Annual Review of Physical Chemistry*, **69**, 299-325. https://doi.org/10.1146/annurev-physchem-050317-021353

[9] Hamer, M., Tóvári, E., Zhu, M., Thompson, M.D., Mayorov, A., Prance, J., *et al.* (2018) Gate-Defined Quantum Confinement in Inse-Based van der Waals Heterostructures. *Nano Letters*, **18**, 3950-3955. https://doi.org/10.1021/acs.nanolett.8b01376

[10] Wan, S., Chen, Y., Fang, S., Wang, S., Xu, Z., Jiang, L., *et al.* (2021) High-Strength Scalable Graphene Sheets by Freezing Stretch-Induced Alignment. *Nature Materials*, **20**, 624-631. https://doi.org/10.1038/s41563-020-00892-2

[11] Buscema, M., Island, J.O., Groenendijk, D.J., Blanter, S.I., Steele, G.A., van der Zant,

H.S.J., *et al.* (2015) Photocurrent Generation with Two-Dimensional van der Waals Semiconductors. *Chemical Society Reviews*, **44**, 3691-3718. https://doi.org/10.1039/c5cs00106d

[12] Novoselov, K.S., Geim, A.K., Morozov, S.V., Jiang, D., Katsnelson, M.I., Grigorieva, I.V., *et al.* (2005) Two-Dimensional Gas of Massless Dirac Fermions in Graphene. *Nature*, **438**, 197-200. https://doi.org/10.1038/nature04233

[13] Butler, S.Z., Hollen, S.M., Cao, L., Cui, Y., Gupta, J.A., Gutiérrez, H.R., *et al.* (2013) Progress, Challenges, and Opportunities in Two-Dimensional Materials beyond Graphene. *ACS Nano*, **7**, 2898-2926. https://doi.org/10.1021/nn400280c

[14] Chakroborty, S. and Pal, K. (2024) 2D Nanomaterials: Synthesis, Properties, and Applications. John Wiley & Sons.

[15] Novoselov, K.S., Geim, A.K., Morozov, S.V., Jiang, D., Zhang, Y., Dubonos, S.V., *et al.* (2004) Electric Field Effect in Atomically Thin Carbon Films. *Science*, **306**, 666-669. https://doi.org/10.1126/science.1102896

[16] Castro Neto, A.H., Guinea, F., Peres, N.M.R., Novoselov, K.S. and Geim, A.K. (2009) The Electronic Properties of Graphene. *Reviews of Modern Physics*, **81**, 109-162. https://doi.org/10.1103/revmodphys.81.109

[17] Radisavljevic, B., Radenovic, A., Brivio, J., Giacometti, V. and Kis, A. (2011) Single-layer MoS_2 Transistors. *Nature Nanotechnology*, **6**, 147-150. https://doi.org/10.1038/nnano.2010.279

[18] Hernandez, Y., Nicolosi, V., Lotya, M., Blighe, F.M., Sun, Z., De, S., *et al.* (2008) High-Yield Production of Graphene by Liquid-Phase Exfoliation of Graphite. *Nature Nanotechnology*, **3**, 563-568. https://doi.org/10.1038/nnano.2008.215

[19] Coleman, J.N., Lotya, M., O'Neill, A., Bergin, S.D., King, P.J., Khan, U., *et al.* (2011) Two-Dimensional Nanosheets Produced by Liquid Exfoliation of Layered Materials. *Science*, **331**, 568-571. https://doi.org/10.1126/science.1194975

[20] Nicolosi, V., Chhowalla, M., Kanatzidis, M.G., Strano, M.S. and Coleman, J.N. (2013) Liquid Exfoliation of Layered Materials. *Science*, **340**, Article 1226419. https://doi.org/10.1126/science.1226419

[21] Li, X., Cai, W., An, J., Kim, S., Nah, J., Yang, D., *et al.* (2009) Large-Area Synthesis of High-Quality and Uniform Graphene Films on Copper Foils. *Science*, **324**, 1312-1314. https://doi.org/10.1126/science.1171245

[22] Bae, S., Kim, H., Lee, Y., Xu, X., Park, J., Zheng, Y., *et al.* (2010) Roll-to-Roll Production of 30-Inch Graphene Films for Transparent Electrodes. *Nature Nanotechnology*, **5**, 574-578. https://doi.org/10.1038/nnano.2010.132

[23] Bhowmik, S. and Govind Rajan, A. (2022) Chemical Vapor Deposition of 2D Materials: A Review of Modeling, Simulation, and Machine Learning Studies. *iScience*, **25**, Article 103832. https://doi.org/10.1016/j.isci.2022.103832

[24] Manzeli, S., Ovchinnikov, D., Pasquier, D., Yazyev, O.V. and Kis, A. (2017) 2D Transition Metal Dichalcogenides. *Nature Reviews Materials*, **2**, Article 17033. https://doi.org/10.1038/natrevmats.2017.33

[25] Reina, A., Jia, X., Ho, J., Nezich, D., Son, H., Bulovic, V., *et al.* (2009) Large Area, Few-Layer Graphene Films on Arbitrary Substrates by Chemical Vapor Deposition. *Nano Letters*, **9**, 30-35. https://doi.org/10.1021/nl801827v

[26] De Arco, L.G., Zhang, Y. and Zhou, C. (2011) Large Scale Graphene by Chemical Vapor Deposition: Synthesis, Characterization and Applications. In: Gomez De Arco, L., Zhang, Y. and Zhou, C., Eds., *Graphene-Synthesis*, *Characterization*, *Properties and Applications*, InTech, 161-184. https://doi.org/10.5772/22358

[27] Balandin, A.A., Ghosh, S., Bao, W., Calizo, I., Teweldebrhan, D., Miao, F., *et al.* (2008) Superior Thermal Conductivity of Single-Layer Graphene. *Nano Letters*, **8**, 902-907. https://doi.org/10.1021/nl0731872

[28] Dreyer, D.R., Park, S., Bielawski, C.W. and Ruoff, R.S. (2010) The Chemistry of Graphene Oxide. *Chemical Society Reviews*, **39**, 228-240. https://doi.org/10.1039/b917103g

[29] Schwierz, F. (2010) Graphene Transistors. *Nature Nanotechnology*, **5**, 487-496. https://doi.org/10.1038/nnano.2010.89

[30] Mak, K.F., Lee, C., Hone, J., Shan, J. and Heinz, T.F. (2010) Atomically Thin MoS_2: A New Direct-Gap Semiconductor. *Physical Review Letters*, **105**, Article 136805. https://doi.org/10.1103/physrevlett.105.136805

[31] Dean, C.R., Young, A.F., Meric, I., Lee, C., Wang, L., Sorgenfrei, S., *et al.* (2010) Boron Nitride Substrates for High-Quality Graphene Electronics. *Nature Nanotechnology*, **5**, 722-726. https://doi.org/10.1038/nnano.2010.172

[32] Geim, A.K. and Grigorieva, I.V. (2013) Van der Waals Heterostructures. *Nature*, **499**, 419-425. https://doi.org/10.1038/nature12385

[33] Naguib, M., Kurtoglu, M., Presser, V., Lu, J., Niu, J., Heon, M., *et al.* (2023) Two-Dimensional Nanocrystals Produced by Exfoliation of Ti_3AlC_2. In: Gogotsi, Y., Ed., *MXenes*, Jenny Stanford Publishing, 15-29. https://doi.org/10.1201/9781003306511-4

[34] Li, L., Yu, Y., Ye, G.J., Ge, Q., Ou, X., Wu, H., *et al.* (2014) Black Phosphorus Field-Effect Transistors. *Nature Nanotechnology*, **9**, 372-377. https://doi.org/10.1038/nnano.2014.35

[35] Lee, C., Wei, X., Kysar, J.W. and Hone, J. (2008) Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene. *Science*, **321**, 385-388. https://doi.org/10.1126/science.1157996

[36] Bunch, J.S., van der Zande, A.M., Verbridge, S.S., Frank, I.W., Tanenbaum, D.M., Parpia, J.M., *et al.* (2007) Electromechanical Resonators from Graphene Sheets. *Science*, **315**, 490-493. https://doi.org/10.1126/science.1136836

[37] Ferrari, A.C., Bonaccorso, F., Fal'ko, V., Novoselov, K.S., Roche, S., Bøggild, P., *et al.* (2015) Science and Technology Roadmap for Graphene, Related Two-Dimensional Crystals, and Hybrid Systems. *Nanoscale*, **7**, 4598-4810. https://doi.org/10.1039/c4nr01600a

[38] Allain, A., Kang, J., Banerjee, K. and Kis, A. (2015) Electrical Contacts to Two-Dimensional Semiconductors. *Nature Materials*, **14**, 1195-1205. https://doi.org/10.1038/nmat4452

[39] Wood, J.D., Wells, S.A., Jariwala, D., Chen, K., Cho, E., Sangwan, V.K., *et al.* (2014) Effective Passivation of Exfoliated Black Phosphorus Transistors against Ambient Degradation. *Nano Letters*, **14**, 6964-6970. https://doi.org/10.1021/nl5032293