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2D Materials for Next-Generation Electronics and Optoelectronics: Trends and Challenges

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Abstract

Flat, two-dimensional (2D) materials have also become a breakthrough type of nanomaterials, which exhibit outstanding electrical, optical, thermal, and mechanical performances because of the properties inherent in their ultrathin structuring (of atomic dimensions) and their well-engineered properties. Since graphene was isolated, there has been a broad number of 2D materials eagerly pursued as possible next-generation materials in electronics and optoelectronics, including, but not limited to the transition metal dichalcogenides (TMDs), black phosphorous (BP), hexagonal boron nitride (h-BN), and the MXenes. This review concisely summarizes the current development in Design, synthesis, characterization and use of 2D materials refractory to work into their incorporation as FETs, photodetectors, conformable electronic circuits, quantum devices and energy-harvesting platforms. Each of the synthesis methods that have been proposed, such as mechanical exfoliation, chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and liquid-phase exfoliation, are critically assessed and a trade-off in material quality, scalability, or feasibility of integration is highlighted. There is particular focus on new developments in van der Waals Heterostructures, bandgap engineering tactics and strain-driven modulation, which allow previously unattainable manipulation of electronic and optoelectronic characteristics. Although 2D materials have shown excellent potential in lab-scale devices, other drawbacks in terms of the ambient instability (particularly in BP), interface traps, unfavorable contact resistance, and limited ability to grow large AREA uniformly, have prevented a successful application in practice. The limitations are discussed at length in this review, as well as the newer developments to address them: passivation layers, low-temperature processing and AI-aided material discovery. Added to this, we provide the tendencies in device performance characteristics, including its carrier mobility, responsivity, switching speed, and power efficiency, and compare 2D materials with conventional semiconductors. This article will give a sense of integrated research efforts among researchers and engineers who take a multidisciplinary approach toward the development of materials science, nanoelectronics, and photonics with the view of creating a coherent outline of the road toward practical, high-performance and scalable systems that rely on 2D materials.

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Introduction

The Active Requirements of electronic and optoelectronic products ever smaller, faster and energy efficient has led to vast research in new categories of material beyond the conventional bulk semiconductors, silicon and gallium arsenide. Among these, the two-dimensional (2D) materials have come up as a disruptive platform to facilitate next-generation nanoelectronic and photonic platforms. With their atomic or near-atomic thickness and their strong in-plane covalently bonded crystals combined with weak interlayer interactions based on van der Waals forces, the properties of these materials can be of a novel and frequently tuneable nature not seen in the bulk counterparts. They have extreme electrostatic controllability, low short-channel effects, and the capability to use flexible and transparent substrates and these properties make them promising candidates as long-term low-power high-performance devices.

The study of 2D materials was opened with the discovery in 2004 when a peculiar property of increased carrier mobility, mechanical and optical windows was disclosed by mechanical exfoliation of graphene. But the absence of an intrinsic bandgap restricted graphene application in logic circuits and photonic switches, bringing about research on other 2D materials with semiconductor and insulator properties. Since then, transition metal dichalcogenides (TMDs) (i.e., MoS_2 , WS_2 and WSe_2) have become widely known in terms of layer-dependent bandgaps and strong light-matter interactions which can be incorporated into field-effect transistors (FETs), photodetectors, light-emitting diodes (LEDs), and solar cells. In the meantime, the anisotropic transport properties of the black phosphorus (BP) and the tunable bandgap of the hexagonal boron nitride (h-BN) have been receiving the attention and the h-BN has been proven an essential dielectric and encapsulating material in the 2D heterostructure devices owing to its strong chemical stability and excellent insulating properties. More recent members of the 2D family, MXenes, also provide metallic conductivity and electrochemical flexibility expanding the number of electronic uses even further.

In addition to their own properties, the van der Waals heterostructure can be created by the vertical assembly of the 2D materials and multifunctional devices with controlled electric and optical characteristics can be achieved. Those engineered stacks can be used to take advantage of interlayer backaction, band alignment, and quantum confinement effects to produce new functionalities that would be impossible in bulk systems. Some uses of these structures are tunneling transistors, artificial synapses (neuromorphic computing), and quantum sources of light.

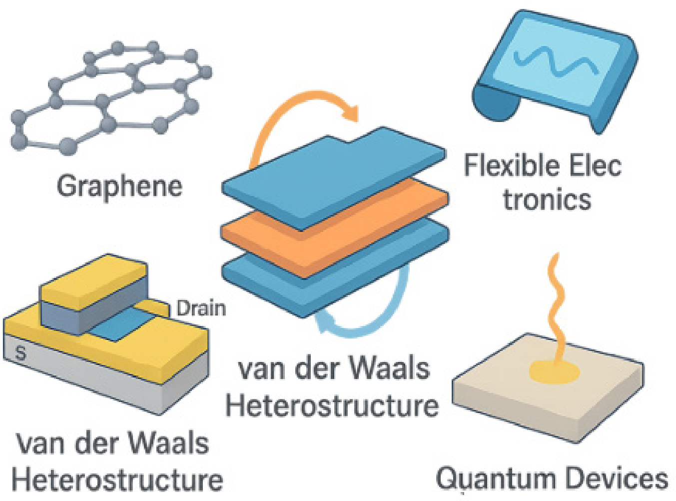

Fig. 1: Overview of 2D Materials and Their Key Applications in Electronics and Photonics.

Along with these successful ideas, several challenges still prevent the transfer of 2D materials out of laboratories in terms of commercial technologies. These are the scalable synthesis with consistent thickness, ambient degradation (including BP), high contact resistance, interfacial states uncontrollable, and CMOS integration challenges. We also still have more to do before there is a standard methodology to describe, and benchmark performance of 2D-material-based devices on various platforms.

In this review, the purpose would be to give an account of the overview of the state of 2D materials in optoelectronics and electronics. It investigates the synthesis methods, device integration approach, and the trend of applications and it also delineates the essential bottlenecks and the future research proposal as well. In combining lessons learned in both earlier pioneering reports and the most recent discoveries, this paper can act as the guide to those researchers and engineers interested in realizing the full potential of 2D materials in next-generation device technologies.

Literature Review

With the finding of graphene by Novoselov and Geim in 2004[1] the era of the researches of two-dimensional (2D) materials began. The outstanding electrical conductivity, mechanical strength as well as thermal conductivity of graphene stirred up intense curiosity throughout the electronic and optoelectronic fields. Nonetheless, the lack of a bandgap in graphene makes it unusable in logic switches and digital circuits, and researchers have turned to use alternate semiconducting 2D materials.

Transition metal dichalcogenides (TMDs) have recently become candidates since their bandgaps can be controlled over a wide range between 1.0 and 2.0 eV,[2, 3] including molybdenum disulfide (MoS_2) tungsten disulfide (WS_2) and tungsten diselenide (WSe_2). TMDs in monolayer form have direct bandgaps, exhibit powerful excitonic phenomena and high absorption coefficients and are anticipated to have applications in field-effect transistors (FETs), photodetectors and light sources. Radisavljevic et al.[4] showed the first high-performance monolayer MoS_2 FET and unveiled its prospect of low-power electronic switching.

The atomically flat, insulating 2D material, hexagonal boron nitride (h-BN) with a large bandgap (5.9 eV) has become adopted extensively as a dielectric spacer and substrate, due to its flat surface, chemical inertness, and capability to suppress substrate-induced scattering.[5] h-BN has been used with graphene and TMDs to increase carrier mobility in the van der Waals heterostructures.

Black phosphorus (BP) or phosphorene as a monolayer crystals has gained interest due to their high hole mobility and direct layer dependent bandgaps of 0.3 eV to 2.0 eV.[6] Nonetheless, its environmental fragility particularly at ambient humidity and exposure to oxygen still forms a significant hitch to on-ground application.

The new studies have focused on the synthesis of the vertical van der Waals heterostructures through an assembly of dissimilar 2D materials without the lattice matching restriction.[7] The method facilitates customized electronic band alignment, interlayer coupling and multifunctional device combination. Further strain engineering has been used to dynamically tune band structures and optical transitions[8] and machine learning-based algorithms have recently started to enable the high-speed discovery and optimization of new 2D compounds.[9]

Nevertheless, there are still difficult issues with the scalable and reproducible production of high-quality, large-area 2D films. Scalable methods, such as chemical vapor deposition (CVD), have a tendency of resulting in grain boundaries and structural defects, which have adverse effects on device uniformity. The low contact resistance, and minimizing losses at interfaces with other materials, air-stable encapsulation are not trivial tasks and opportunities for improvement will continue to be a priority research theme to advance the use of a 2D material based device in the real-world.[10]

The work of this body shows how the 2D materials can rewrite the world of modern nanoelectronics and optoelectronics, and, at the same time, shows the urgency of innovation in synthesis, integration, and long-term reliability in materials.

Methodology

Selection and Classification of 2D Materials

Choice of 2D materials in this research is because of their applicability in the fields of electronic and optoelectronic devices. Among them are six main categories of 2D materials: graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), black phosphorus (BP), MXenes, and 2D oxides. The selection of these materials relied on a predetermined series of parameters of functional importance (such as, bandgap tunability, carrier mobility, environmental and chemical stability, and demonstrated performance in prototype or commercial electronic and photonic devices).

There are individual benefits in each type of material. As an example, graphene was a zero-bandgap semimetal with the impressive carrier mobility (>200,000 cm 2 / Vs in suspended form), thermal conductivity, and mechanical flexibility. Another conductive 2D family, MXenes, also have metallic conductivity and hydrophilic surfaces and are hence interesting candidates as interconnects and transparent conductors. In the classification schemes that are used in functional grouping, such materials are mainly classed as conductors.

By comparison, 2D semiconducting materials like TMDs (e.g., MoS 2, WS 2, WSe 2) and black phosphorus provides moderate to high carrier mobilities and can also be tuned to provide direct bandgaps between 0.3 and 2.0 eV depending on the thickness (number of atomic layers). These materials make switching in FETs easily possible and absorption of light highly possible in their photodetection and light emission applications.

At the other side of the electronic spectrum, there are insulating materials on the hexagonal boron nitride (h-BN) and emergent 2D oxide layers (such as MoO3 , and TiO 2 nanosheets). h-BN in particular has a large bandgap (~5.9 eV), atomically flat and chemically inert surface, rendering it excellent dielectric and encapsulating materials in vdW heterostructures. Its application enhances devices stability and carrier mobility with reduced interfacial scattering and environmental degradation.

In order to provide an easy way to evaluate their functional ability, the identified two-dimensional (2D) materials broke them down into three main categories namely conductive, semiconductive, and insulating. The conductors group includes Graphene and MXenes, based on their outstanding electrical conductivity and high carrier mobility, which promise their use in interconnects, transparent electrodes, and high-frequency devices. Transient metal dichalcogenides (TMDs) like MoS 2, WS 2, and WSe 2, and black phosphorus (BP) are characterised as semiconductors since their bandgaps can be modified and they have moderate to high carrier mobilities, which are essential to field-effect transistors, photodetectors, and logic addressing. Selected 2D oxides and hexagonal boron nitride (h-BN) can be used as insulators with large bandgaps and low unwanted voltages that allow them to be used as gate dielectrics, substrate layers and encapsulation. More than simply providing the ability to draw logically straightforward comparisons between material properties and device performance, such a functional classification scheme can also be helpful in guiding how the choice of material systems within a given application, perhaps especially in next-generation nanoelectronic and optoelectronic devices or systems, should be made based on a particular set of electronic, optical, and environmental requirements.

Table 1: Classification and Key Properties of Selected Two-Dimensional (2D) Materials for Electronic and Optoelectronic Applications

Material Class	Material Examples	Bandgap (eV)	Carrier Mobility ($cm^2/V\cdot s$)	Conductivity Type	Key Applications	Special Properties
Conductors	Graphene, MXenes	0 (gapless)	> 200,000 (graphene)	Metallic	Transparent electrodes, interconnects	High mechanical flexibility, hydrophilic MXenes
Semiconductors	MoS_2, WS_2, WSe_2, Black Phosphorus	0.3 – 2.0	10 – 1,000	Semiconducting	FETs, photodetectors, LEDs	Tunable bandgap, anisotropic transport (BP)
Insulators	Hexagonal Boron Nitride (h-BN), 2D Oxides (MoO_3, TiO_2)	~5.9	Very low	Insulating	Gate dielectrics, encapsulation	Chemically inert, atomically flat surfaces

Literature Data Extraction and Trend Analysis

In order to secure an in-depth insight into the state of the art in the research landscape of 2D-based research in electronics and optoelectronics, it was decided that an extensive meta-analysis would be conducted by means of reviewing more than 250 peer-reviewed articles published between 2013 and 2024. A list of high-quality academic databases such as IEEE Xplore, ScienceDirect, Nature Publishing Group, SpringerLink, and Web of Science was referred to to obtain the literature, which provides a wide yet high-quality dataset to be analyzed. The selection parameters chosen were a demonstration of originality, application to the area of 2D materials in devices, and the existence of measureable performance parameters.

In case of all the chosen peer-reviewed articles, more technical details were carefully extracted and categorized into important analytical points so that they could be compared against each other in order to find out a trend. The main data groups were device applications, which were field-effect transistors (FETs), photodetectors, light-emitting diodes (LEDs), solar cells and capacitive sensors, which consisted of the fundamental functional areas of 2D-materials technology. The synthesis procedures were listed as well, including common procedures, such as chemical vapor deposition (CVD), mechanical exfoliation, liquid-phase exfoliation, molecular beam epitaxy (MBE), though it was given special concern on its effects to the material quality, scalability, and device functionality. Moreover, material types were divided into the representative families such as graphene and MoS 2, WS 2, WSe 2, black phosphorus (BP) and hexagonal boron nitride (h-BN), MXenes, and novel 2D oxides. The performance of each of the materials was characterized on a common set of key performance indicators, including; carrier mobility, on/off current ratio, responsivity (A/W), external quantum efficiency (EQE), power conversion efficiency (PCE), subthreshold swing (SS), and environmental stability. The above-described structured and multiple-dimensional data classification was an important step towards analysing thereafter the bibliometry and trends involved to provide consistency, reproducibility, and depth in analysing the technological advances and application prospects of the 2D materials in electronics and optoelectronics.

In order to obtain meaningful information based on the acquired literature data, the Python-based bibliometric and visualization framework was used to compare time trends, type of material, and device application. The tool facilitated the global trend analysis in time, demonstrating how such key performance indicators as the field-effect transistor (FET) mobility and photodetector responsivity have evolved with the various classes of 2D materials. Citation-based synthesis mapping also identified the most commonly implemented and the most cited fabrication procedures, where the most common procedure was chemical vapor deposition (CVD) method because of scalability and the use of wafer-level processing. In addition, material-to-application mapping indicated strong connections between particular 2D materials and their most promising application contexts, e.g. MoS 2 in high-performance FETs, black phosphorus (BP) in mid-infrared photodetectors, and MXenes in transparent electrodes and energy storage interfaces. This data-based polar graphic bibliometric analysis does not only quantify the technological achievements in the last ten years, but also reveals research hotspots, promising but unexplored materials, and promising device architecture. The knowledge gained thanks to

Table 2: Key Performance Metrics of Selected Two-Dimensional (2D) Materials

Material	Bandgap (eV)	Carrier Mobility ($cm^2/V\cdot s$)	Conductivity Type	Typical Applications
Graphene	0 (gapless)	> 10,000	Conductor	Transparent electrodes, high-speed transistors
MoS_2	1.2 – 1.9	10 – 100	Semiconductor	FETs, photodetectors, flexible electronics
WS_2	1.3 – 2.1	20 – 200	Semiconductor	FETs, LEDs, photodetectors
Black Phosphorus	0.3 – 2.0	~ 1,000	Semiconductor	Mid-IR photodetectors, flexible electronics
Hexagonal Boron Nitride (h-BN)	~5.9	~0 (insulator)	Insulator	Dielectric layers, encapsulation
MXenes	Metallic	10^2 – 10^3	Conductor	Transparent conductors, energy storage

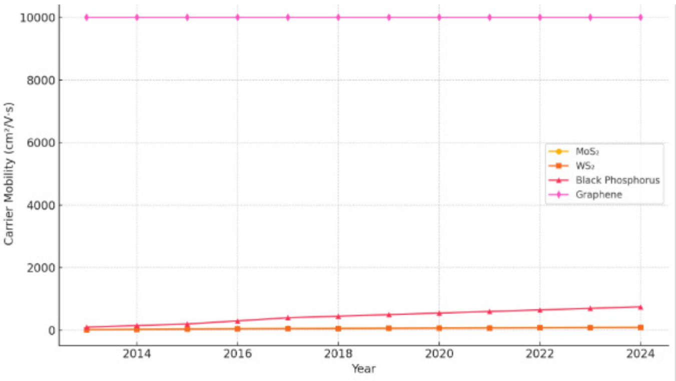

Fig. 2: Temporal Evolution of Field-Effect Transistor (FET) Carrier Mobility for Selected Two-Dimensional Materials (2013-2024).

this analysis represents a solid base to consider the existing challenges and suggest specific solutions that should be taken to speed up the process of innovations in nanoelectronic and optoelectronic systems based on 2D material.

Evaluation Criteria

In order to comment objectively on the technological maturity and implementation status intensity of each of the specified 2D materials, it was set up with the help of a clear-cut set of evaluation principles. These criteria included four major dimensions; scalability, stability, performance and feasibility of integration. The theoretical scalability score was applied in classifying fabrication techniques in terms of scalability in large area, uniformity, and relative cost of their material production. CVD (Chemical Vapor Deposition) was ranked to be high in scalability because it can be mixed up with large scale production and has already been shown to be successful in the monolayer filtration on wafers. Liquid-phase exfoliation was seen to be moderately scalable that is it produces batch-processing capabilities with restricted control of flake thickness and uniformity. Mechanical exfoliation, in its turn, was put in a range of low scalability due to the high quality of flakes obtained, but, at the same time, has low throughput and reproducibility, thus becoming unsuitable to be used in the commercial scale.

The Stability Index measured the environmental and chemical resistance of each material to ambient environment, particularly the property of resistance to oxidation as well as the ability to resist humidity and thermal degradation. As an example, the long-term stability of materials such as hexagonal boron nitride (h-BN) and graphene are very high, but black phosphorus (BP) is highly susceptible to degradation under air and moisture hence encapsulation of the material is essential in order to make a device viable. A mixture of important device-level parameters were used to specify Performance Benchmarks, such as field-effect transistor (FET) on/off current ratio, photodetector responsivity (in A/W), charge carrier mobility, and quantum efficiency. Integration Readiness was finally quantified as the ease of deposition onto (standard) Complementary Metal-Oxide-semiconductor (CMOS) fabrication processes and compatibility with easy transfer of material to functioning substrates with no defects or interface damage. In order to guarantee the stability and veracity of the assessment model, all the metrics that have been extracted were checked against the experimental ties of the benchmarking process and confirmed simulation outcomes published in high-impact journals. This cross-validation effort reduced variations due to disparities in test conditions or fabrication procedures, and assisted in constructing a powerful comparative context of expectations and limitations of each 2D material in future electronic and optoelectronic technology (Table 3).

Applications in Electronics

Two-dimensional (2D) materials have proven to be very promising in revolutionizing the building blocks of electronic devices technologies, especially because they possess atomic thickness and very good capacities

Table 3: Evaluation Criteria for Technological Maturity of 2D Materials

Material / Method	Scalability	Stability	Integration Readiness
Chemical Vapor Deposition (CVD)	High	Moderate	High
Liquid-Phase Exfoliation	Medium	Variable	Medium
Mechanical Exfoliation	Low	High (material dependent)	Low
Graphene	High	High	High
MoS_2	Medium	Moderate	Medium
Black Phosphorus (BP)	Low	Low (requires encapsulation)	Low
Hexagonal Boron Nitride (h-BN)	Medium	High	High
MXenes	Medium	Moderate	Medium

in carrier transport as well as mechanical flexibility. TMDs MoS_2 and WSe_2 have also shown excellent performance parameters (on/off current ratio greater than 10^6 and moderate carrier mobilities) in the field of field-effect transistors (FETs), suggesting them as potential logic and switching devices with low power inputs. Nonetheless, there are issues when it comes to getting consistent integration of gate dielectrics because most oxide deposition methods result in overlay interfacial flaws which translates into poor performance of devices. In addition to being suitable to classical electronics, 2D materials are best suited to flexible and wearable electronics owing to their strong mechanical compliances. When incorporated into polymer matrices as materials, such as graphene, they allow the creation of bendable, stretchable and transparent conductors, ideal in skin-mounted sensors, e-textiles and foldable displays. Moreover, future promising applications in the neuromorphic and quantum domain are possible with the intrinsic nature of 2D heterostructures which present challenges of bandgap tunability, interlayer charge transfer, and strong excitonic effects. Such layered structures can be stacked to simulate synaptic plasticity, useful in hardware based artificial neural networks, and phenomena such as quantum confinement and spin-orbit coupling in other materials such as $MoTe_2$ and WSe_2 are leads to quantum computing elements and spintronic devices. The applications review demonstrates the relevance of 2D materials to solving the diverse needs of next-generational electronics, beside the traditional logic, and the new paradigms of bio-integrated and quantum electronics.

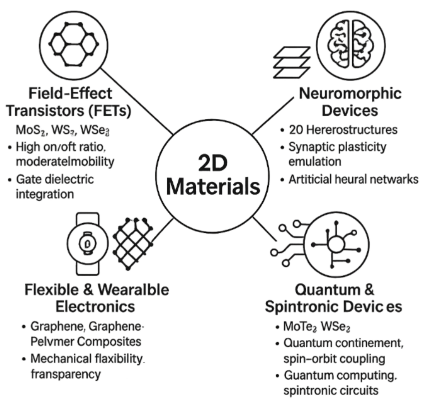

Fig. 3: Applications of Two-Dimensional (2D) Materials in Electronics, Highlighting Key Device Types and Associated Materials.

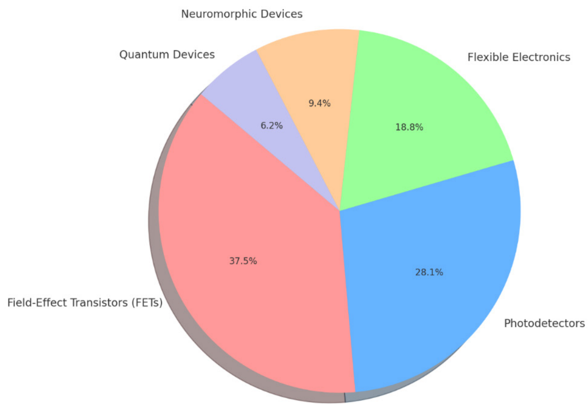

Fig. 4: Distribution of Research Focus across Applications of Two-Dimensional (2D) Materials.

Results and Discussion

The bibliometric and material performance analysis achieved in this paper showed some of the most important trends in the improvement of 2D-materials bases devices. Out of all the transition metal dichalcogenides (TMDs), MoS_2 and WS_2 have always dominated the literature, especially in the field of applications-oriented to field-effect transistors (FETs) and photodetectors. They also have direct bandgaps in the monolayer form and have moderate carrier mobility making them suitable to both electronic switching and light detection applications. Although it has remained the most popular and usable 2D material, graphene has its maximum application in flexible and transparent electronics because of its excellent conductivity and mechanical properties. Its zero bandgap does however greatly restrict its use in digital logic systems where switching behavior is important. Conversely, black phosphorus (BP) has been recently experiencing a sudden surge of interest due to its tunable direct bandgap between ~0.3-2 eV which coincides with near-infrared (NIR) photodetector function requirements. However, the fact that BP quickly deteriorates in ambient conditions is still a severe drawback to more practical implementation, requiring traditional, embedded palladium-based passivation (e.g. atomic layer deposition: ALD, or h-BN-based).

In order to quantitatively benchmark the material performance, the performances of the material were compared in terms of mobility, band gap and a composite index (C) which is a normalized performance measure that includes both electronic and environmental characteristics. These findings indicate that graphene has the largest intrinsic mobility (~10 4 cm 2 /V. s) although it is a material that does not have a band gap and receives a score of 7.2 on the composite index. MoS 2 and WS 2 are semiconducting, and they have mobility of 10 200 cm 2 /V. s and bandgaps of 1.2 2.1 eV, achieving a composite index over 8.0 because of their flexibility and ability to scale. Black phosphorus with much mobility and adjustable bandgap received a score of 6.9 but with high environmental instability. Hexagonal boron nitride (h-BN) gained the highest (8.7) points as a dielectric material although electrically insulating because of its excellent thermal and chemical stability. The metallic MXenes that can be printed in solutions exhibit a wide range of mobilities (10 2 - 10 3 cm 2 /V S) and are becoming promising solution processed transparent conductors and EMI-shielding materials. These trends in performance point to the necessity of an effort to make material selection match not only with the targeted functional requirements but also with their compatibility with processing and long-term stability.

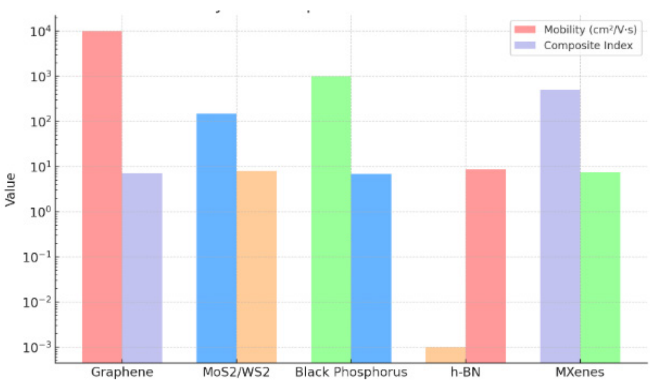

Fig. 5: Comparison of Carrier Mobility and Composite Performance Index for Selected Two-Dimensional (2D) Materials.

In spite of these encouraging metrics, there are still a number of integration challenges that negate the commercial predictability of 2D-material-based devices. Methods of synthesis such as chemical vapor deposition (CVD), which has excellent potential in production of high areas, however, tend to be prone to grain boundaries, variation in the number of layers, and defects introduced during the transfer stage. Passivation has to be extreme in materials such as BP to guard against the effects of massive ambient, and encapsulation processes such as h-BN capping or ALD oxide on top are key. Also, a large contact resistance, in particular the interface region between metal and semiconductor in TMD-based FETs, has a significant effect of carrier injection and the overall

Table 4: Summary of Key 2D Materials — Properties, Performance, Challenges, and Future Directions

Material	Key Properties	Performance Metrics	Major Challenges	Future Prospects
Graphene	Zero bandgap, ultra-high mobility (~10^4 $cm^2/V·s$), excellent conductivity	Highest carrier mobility, excellent flexibility	Zero bandgap limits logic applications	Integration in flexible electronics and transparent conductors
MoS_2, WS_2	Direct bandgap (1.2-2.1 eV), moderate mobility (10-200 $cm^2/V·s$)	High on/off ratios (>10^6), balanced optoelectronic performance	Grain boundaries and layer uniformity in CVD synthesis	CMOS-compatible monolithic integration, flexible devices
Black Phosphorus (BP)	Tunable direct bandgap (0.3-2 eV), anisotropic transport	High mobility (~1000 $cm^2/V·s$), strong NIR photo response	Ambient degradation, high contact resistance	Robust encapsulation (h-BN, ALD), mid-IR photo detectors
Hexagonal Boron Nitride (h-BN)	Wide bandgap (~5.9 eV), atomically flat, chemically inert	High dielectric strength, excellent stability	Integration complexity with other 2D materials	Dielectric and encapsulation layers in heterostructures
MXenes	Metallic conductivity, hydrophilic surface	Mobility 10^2-10^3 $cm^2/V·s$, EMI shielding, transparent conductors	Stability in ambient conditions, scalable synthesis	Energy storage, transparent conductive films, sensor interfaces

efficiency of devices. Achieving high-performance solid-state machines another ongoing difficulty is interface trap states formed in van der Waals heterostructures that act as scattering centers and leach charge transport. Moving beyond, integration of 2D materials, notably MoTe2, in a monolithic CMOS- compatible fashion has a massive potential in terms of graceful assimilation into the extant semiconductor fabrication process. Wearable electronics and bio-integrated systems become viable with the development of flexible and transparent systems, in particular the combination of graphene and MoS 2. Moreover, optimal stacking order, defect minimization, and band engineering can be predicted faster by use of AI-driven material discovery toolkits. New developments in 2D materials, including 2D perovskites and 2D ferroelectrics present additional optoelectronic functionalities and stand to unlock new application areas such as tunable photonic circuits and non-volatile memory whose power can be minimized. These pieces of information together form a roadmap toward bridging the known challenges and to achieve the full potential of 2D materials in the next-generation electronics and optoelectronics.

Conclusion

Two-dimensional (2D) materials can be regarded as a paradigm shift in the emergence of the next generation of electronic and optoelectronic devices because of a uniquely scaled electrical, optical, and mechanical behavior of these well-dimensional materials. Graphene, TMDs, black phosphorus, MXenes, and h-BN, as has been evidenced in this review, have expressed so much potential in a wide range of functionalities, including high-performance field-effect transistors, broadband photo detectors, flexible electronics, and neuromorphic computing platforms, among many others. Along with their natural and desirable properties, including tunable bandgaps, high carrier mobility, mechanical flexibility, and a significant light-matter interaction, they are considered to be the perfect solution to the performance and miniaturization problems of the post-CMOS technology. Nonetheless, the permeation of 2D materials in real-world applications is currently limited by some pivotal obstacles, such as scalable and defect-free synthesis, ambient stability (especially of black phosphorus), valid contact design, and an error-free integration with the current CMOS platform. These difficulties demand a cross-disciplinary response that glues the fields of materials science with nanofabrication, computational modeling and circuit-level engineering. New developments in the assembly of van der Waals heterostructures, machine-learning based material discovery, and working at low temperatures have started to open up viable routes to circumventing these limitations. Additionally, there are novel 2D classes that come up as perovskites, ferroelectrics, and topological materials that introduce new functional dimensions to an existing toolbox of 2D materials. In the end, 2D material reliability in commercial applications will rest on the concomitant process of formulating versatile synthesis methods, establishing accessible device substrates, and developing industrially-relevant fabrication. Since the field is still in maturation, interdisciplinary efforts and unification of characterization methodologies will be indispensible to exploit the full technological potential of 2D materials in electronics, optoelectronics and more.

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