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ORIGINAL ARTICLE

Recent Advances in Two-Dimensional Quantum Materials for Next-Generation Electronic and Optoelectronic Devices: A Critical Review

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ABSTRACT

Two-dimensional (2D) quantum materials have emerged as one of the most promising classes of materials for future electronic and optoelectronic technologies. Their atomically thin structure, tunable electronic properties, high carrier mobility, and strong light–matter interaction have created new opportunities for device innovation. Over the past decade, rapid progress in material synthesis, characterization, and device engineering has expanded their potential across a wide range of applications. Despite these advances, several challenges continue to limit large-scale commercialization, including material stability, defect control, scalable fabrication, and seamless integration with existing semiconductor technologies. This study critically examines recent developments in major families of 2D quantum materials, including graphene, transition metal dichalcogenides, black phosphorus, hexagonal boron nitride, and MXenes. It discusses their fundamental properties, fabrication techniques, and emerging device architectures. The study also evaluates their applications in field-effect transistors, photodetectors, light-emitting devices, solar cells, flexible electronics, sensors, and quantum technologies. Rather than providing only a descriptive summary, it compares the strengths and limitations of different materials and highlights the key factors influencing device performance. Finally, the study identifies current research gaps and outlines future directions for developing reliable, scalable, and energy-efficient electronic and optoelectronic systems. By bringing together recent findings and critical insights, this paper provides a comprehensive understanding of the opportunities and challenges associated with 2D quantum materials and supports future research on next-generation electronic and optoelectronic devices.

Keywords: *Two-dimensional quantum materials; Graphene; Transition metal dichalcogenides (TMDs); MXenes; Black phosphorus; Electronic devices; Optoelectronic devices; Flexible electronics; Quantum technologies; Nanomaterials*

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INTRODUCTION

The rapid evolution of nanoelectronics has transformed the search for materials capable of meeting the growing demands of modern electronic and optoelectronic technologies. As conventional silicon-based devices approach their physical scaling limits, researchers have increasingly focused on low-dimensional materials that offer superior electrical, optical, and mechanical characteristics. Among these, two-dimensional (2D) quantum materials have attracted exceptional attention because reducing a material to a single or a few atomic layers fundamentally alters its electronic structure and enables physical phenomena that are not observed in their bulk counterparts.

Interest in this field accelerated after the successful isolation of graphene, which demonstrated that atomically thin crystals could remain stable under ambient conditions while exhibiting remarkable carrier mobility, thermal conductivity, and mechanical strength (Novoselov *et al*., 2004). Although the absence of an intrinsic band gap restricts graphene in digital switching applications, its discovery stimulated intensive research into a broad family of layered materials with diverse electronic properties. Transition metal dichalcogenides (TMDs), black phosphorus, hexagonal boron nitride (h-BN), MXenes, and other van der Waals materials have since emerged as important building blocks for next-generation nanoscale devices. Unlike graphene, many of these materials possess tunable band gaps, making them attractive for both electronic and photonic applications.

Over the past decade, significant progress has been achieved in material synthesis, interface engineering, and device fabrication. Advances in chemical vapor deposition, molecular beam epitaxy, liquid-phase exfoliation, and other scalable fabrication techniques have improved crystal quality and expanded the possibilities for practical device integration. At the same time, improvements in nanoscale characterization and computational modelling have deepened the understanding of charge transport, excitonic behaviour, quantum confinement, and interfacial interactions. These developments have enabled high-performance field-effect transistors, photodetectors, light-emitting devices, photovoltaic systems, flexible electronics, wearable sensors, and emerging quantum devices with characteristics that often surpass those of conventional semiconductor materials.

Despite these achievements, several scientific and technological challenges continue to limit widespread implementation. The long-term stability of certain 2D materials remains a concern, particularly under ambient operating conditions. Large-area synthesis with uniform structural quality is still difficult for many material systems. In addition, defect engineering, contact resistance, heterostructure fabrication, and compatibility with existing complementary metal-oxide-semiconductor (CMOS) technology remain active areas of investigation. Addressing these issues will be essential for translating laboratory-scale demonstrations into commercially viable technologies.

The expanding literature reflects the growing importance of this field. However, many published reviews examine individual material systems or concentrate on specific device categories. As research continues to diversify, there is an increasing need for a comprehensive assessment that connects recent advances in different classes of 2D quantum materials with their evolving roles in electronic and optoelectronic device engineering. A comparative discussion of their material characteristics, fabrication strategies, device performance, and remaining challenges can provide valuable insights for future research and technology development.

In this context, the present study critically examines recent advances in two-dimensional quantum materials for next-generation electronic and optoelectronic devices. It discusses the fundamental characteristics of major 2D material families, evaluates recent progress in synthesis and device fabrication, and analyses their applications across a range of electronic and optoelectronic platforms. Particular attention is given to the relationship between material properties and device performance, current technological limitations, and emerging research opportunities. The paper concludes by outlining future directions that may accelerate the development of scalable, reliable, and energy-efficient technologies based on two-dimensional quantum materials.

FUNDAMENTALS OF TWO-DIMENSIONAL QUANTUM MATERIALS

1. WHAT ARE TWO-DIMENSIONAL QUANTUM MATERIALS?

Two-dimensional (2D) quantum materials are crystalline materials composed of a single atomic layer or a few atomic layers. Unlike conventional bulk materials, electrons in these materials are largely confined to motion within a two-dimensional plane. This reduced dimensionality gives rise to quantum effects that significantly influence their electrical, optical, magnetic, and mechanical properties. As a result, many 2D materials exhibit characteristics that are absent in their three-dimensional counterparts (Novoselov *et al*., 2004; Geim & Novoselov, 2007).

The field of 2D materials gained worldwide attention following the successful isolation of graphene through mechanical exfoliation. Since then, researchers have identified a wide variety of atomically thin materials beyond graphene. These include transition metal dichalcogenides (TMDs), such as MoS_2 and WS_2, hexagonal boron nitride (h-BN), black phosphorus, and MXenes. Each material possesses distinct electronic structures and physical properties, making them suitable for different technological applications (Butler *et al*., 2013; Chhowalla *et al*., 2013).

A key advantage of 2D quantum materials is that their properties can be tailored by controlling the number of atomic layers, introducing strain, chemical functionalization, or constructing van der Waals heterostructures. This high degree of tunability provides exceptional flexibility for designing materials with application-specific characteristics and has opened new directions in nanoscale device engineering (Geim & Grigorieva, 2013).

2. KEY PROPERTIES OF TWO-DIMENSIONAL QUANTUM MATERIALS

The growing interest in 2D quantum materials is primarily driven by their unique combination of physical properties. One of their most significant characteristics is high carrier mobility, which enables rapid electron transport and supports the development of high-speed electronic devices. Graphene is a notable example because of its exceptional electrical conductivity and carrier mobility (Novoselov *et al*., 2004).

Another important feature is the availability of tunable band gaps. While graphene behaves as a zero-band-gap semimetal, many other 2D materials, including MoS_2 and black phosphorus, possess intrinsic band gaps that make them suitable for transistors, photodetectors, and other semiconductor devices (Mak *et al*., 2010; Wang *et al*., 2012). The direct band gap observed in monolayer TMDs also enhances their optical performance and light absorption efficiency.

Strong light–matter interaction is another defining property of atomically thin materials. Despite their extremely small thickness, many 2D materials efficiently absorb and emit light over a broad spectral range. This behaviour has encouraged their use in optoelectronic devices such as light-emitting diodes, photodetectors, and photovoltaic systems (Wang *et al*., 2012).

In addition, these materials possess excellent mechanical flexibility and high mechanical strength. Their atomically thin structure allows them to withstand bending and stretching without significant loss of performance, making them attractive for flexible and wearable electronic systems. Their large surface-to-volume ratio also improves surface sensitivity, which is particularly beneficial for chemical and biological sensing applications (Butler *et al*., 2013).

3. IMPORTANCE FOR MODERN ELECTRONICS

The continuous reduction in device dimensions has exposed several limitations of conventional silicon-based electronics, including increased power consumption, heat generation, and performance degradation at the nanoscale. These challenges have motivated the search for alternative materials capable of sustaining further technological progress. Two-dimensional quantum materials provide an attractive solution because they combine excellent electronic performance with atomic-scale thickness.

In electronic devices, 2D materials have demonstrated considerable potential for field-effect transistors, memory devices, integrated circuits, and flexible electronics. Their high carrier mobility and reduced short-channel effects can improve switching performance while lowering energy consumption. At the same time, materials with suitable band gaps offer better control of current flow than graphene alone, making them more suitable for digital electronic applications (Schwierz, 2010; Radisavljevic *et al*., 2011).

The importance of 2D materials extends beyond electronics into optoelectronics. Their strong optical absorption, rapid photoresponse, and tunable electronic structure enable efficient photodetectors, light-emitting devices, optical modulators, and solar cells. Furthermore, the possibility of combining different atomically thin materials into van der Waals heterostructures allows researchers to create multifunctional devices with enhanced performance that are difficult to achieve using conventional semiconductor materials (Geim & Grigorieva, 2013).

Although several challenges remain, including scalable synthesis, long-term stability, and integration with existing semiconductor manufacturing technologies, ongoing research continues to improve material quality and device performance. Consequently, two-dimensional quantum materials are expected to play an increasingly important role in the development of next-generation electronic and optoelectronic technologies.

TYPES OF TWO-DIMENSIONAL QUANTUM MATERIALS

Two-dimensional quantum materials comprise a broad family of atomically thin crystals with distinct electronic, optical, magnetic, and mechanical properties. Although they share a layered structure, differences in atomic composition and crystal symmetry result in diverse physical characteristics. This diversity has enabled researchers to tailor material selection for specific electronic and optoelectronic applications. The most widely investigated families include graphene, transition metal dichalcogenides (TMDs), black phosphorus, hexagonal boron nitride, and MXenes.

1. GRAPHENE

Graphene is the first experimentally isolated two-dimensional material and remains one of the most extensively studied nanomaterials. It consists of a single layer of carbon atoms arranged in a hexagonal honeycomb lattice. Its unique atomic arrangement gives rise to exceptional electrical conductivity, excellent thermal transport, remarkable mechanical strength, and high optical transparency. These characteristics have made graphene a model system for exploring the behaviour of atomically thin materials and their technological applications (Castro Neto *et al*., 2009).

One of graphene's most notable features is its extremely high carrier mobility, which enables rapid charge transport with minimal energy loss. This property makes graphene an attractive material for high-frequency electronic devices, transparent conductive films, and flexible electronic systems. In addition, its excellent thermal conductivity supports efficient heat dissipation, an important requirement for miniaturized electronic components.

Despite these advantages, graphene has a significant limitation for conventional digital electronics. Its zero-band gap makes it difficult to completely switch off electrical current, resulting in a low on/off current ratio in field-effect transistors. Consequently, considerable research has focused on band-gap engineering through chemical modification, nano structuring, strain engineering, and heterostructure formation. Although these approaches have improved graphene's applicability, identifying practical solutions for large-scale semiconductor devices remains an active area of research (Schwierz, 2010).

2. TRANSITION METAL DICHALCOGENIDES (TMDs)

Transition metal dichalcogenides (TMDs) represent one of the most important classes of layered semiconductors. Their general chemical formula is MX_2, where M is a transition metal such as molybdenum or tungsten and X represents a chalcogen element, including sulfur, selenium, or tellurium. Unlike graphene, many monolayer TMDs possess direct band gaps, making them particularly suitable for electronic and optoelectronic applications.

Materials such as molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), and tungsten diselenide (WSe_2) have demonstrated excellent switching behaviour in field-effect transistors and strong optical absorption in visible wavelengths. Their electronic properties can also be modified by controlling layer thickness, external strain, or chemical doping, providing flexibility for device design (Manzeli *et al*., 2017).

Another important characteristic of TMDs is their strong excitonic behaviour arising from reduced dielectric screening and quantum confinement. This enhances light absorption and emission, making these materials promising candidates for photodetectors, light-emitting devices, and photovoltaic technologies. Continued improvements in crystal quality and scalable synthesis have further accelerated their integration into nanoscale electronic and photonic systems.

3. BLACK PHOSPHORUS

Black phosphorus has emerged as an attractive two-dimensional semiconductor because it combines relatively high carrier mobility with a thickness-dependent direct band gap. When exfoliated into few-layer phosphorene, its band gap varies from approximately 0.3 eV in bulk form to around 2.0 eV in the monolayer limit. This tunability enables its use across a broad range of electronic and optoelectronic applications (Liu *et al*., 2014).

An important advantage of black phosphorus is its anisotropic crystal structure. Electrical and optical properties vary along different crystallographic directions, providing opportunities for designing polarization-sensitive photonic devices and highly responsive sensors. Black phosphorus has also shown promising performance in field-effect transistors and infrared photodetectors because of its balanced combination of mobility and band-gap characteristics.

However, practical applications remain constrained by its chemical instability under ambient conditions. Exposure to oxygen and moisture leads to gradual surface degradation, reducing device performance over time. Consequently, considerable effort has been devoted to encapsulation strategies, surface passivation, and heterostructure engineering to improve its environmental stability and operational lifetime.

4. HEXAGONAL BORON NITRIDE

Hexagonal boron nitride (h-BN) is often referred to as the "white graphene" because of its structural similarity to graphene. However, unlike graphene, h-BN is an electrical insulator with a wide band gap of approximately 6 eV. This characteristic makes it highly valuable as a dielectric material rather than an active semiconductor (Dean *et al*., 2010).

One of the major advantages of h-BN is its atomically smooth surface with very low defect density. When used as a substrate or encapsulation layer, it significantly reduces charge scattering and improves the performance of neighbouring two-dimensional materials. It also exhibits excellent thermal conductivity, chemical stability, and mechanical robustness, making it suitable for advanced nanoelectronics device fabrication.

In recent years, h-BN has become an essential component of van der Waals heterostructures. Its insulating nature enables efficient electrical isolation while preserving the intrinsic properties of adjacent conductive or semiconducting layers. As a result, h-BN has become a key material in high-performance transistors, quantum devices, and integrated nanoscale electronic systems.

5 MXENES

MXenes are a relatively new family of two-dimensional materials derived from layered MAX phases through selective chemical etching. They are generally represented by the formula $M_{n+1}X_nT_x$, where M denotes an early transition metal, X represents carbon and/or nitrogen, and T_x corresponds to surface functional groups such as oxygen, hydroxyl, or fluorine. Since their discovery, MXenes have attracted considerable attention because of their excellent electrical conductivity, hydrophilic surfaces, and versatile surface chemistry (Naguib *et al*., 2011).

Unlike many other 2D materials, the properties of MXenes can be effectively tailored by modifying their surface terminations. This feature provides greater flexibility for optimizing electrical, electrochemical, and optical performance according to specific applications. Their combination of high conductivity and large active surface area has resulted in significant interest in energy storage, electromagnetic interference shielding, sensing technologies, and flexible electronics.

Although research on MXenes continues to expand rapidly, challenges remain regarding oxidation resistance, long-term stability, and scalable production. Continued advances in synthesis methods and surface engineering are expected to further improve their performance and broaden their role in future electronic and optoelectronic technologies.

SYNTHESIS AND FABRICATION METHODS

The performance of two-dimensional (2D) quantum materials is closely influenced by the synthesis and fabrication methods used during their preparation. Crystal quality, layer thickness, defect density, and structural uniformity directly affect the electrical and optical behaviour of the resulting materials. Over the past two decades, several fabrication techniques have been developed to produce high-quality 2D materials for both laboratory research and practical device applications. Each method offers specific advantages and limitations depending on the desired material characteristics, production scale, and intended application.

1. MECHANICAL EXFOLIATION

Mechanical exfoliation was the first successful technique used to isolate atomically thin graphene from bulk graphite. The method involves peeling individual layers from layered crystals using an adhesive material, producing flakes with excellent crystallinity and minimal structural defects. Owing to its simplicity and ability to generate high-quality samples, mechanical exfoliation has become a standard approach for fundamental research and proof-of-concept device fabrication (Novoselov *et al*., 2005).

Although mechanically exfoliated materials often exhibit outstanding electronic properties, the technique has significant practical limitations. The process is labour-intensive, offers limited control over flake size and thickness, and cannot be easily scaled for industrial production. Consequently, its use is largely confined to laboratory-scale investigations where material quality is prioritised over production volume.

2. CHEMICAL VAPOR DEPOSITION (CVD)

Chemical vapor deposition (CVD) has emerged as one of the most widely adopted methods for producing large-area two-dimensional materials with controlled thickness and improved uniformity. In this process, gaseous precursor materials react or decompose on a heated substrate, resulting in the formation of continuous atomically thin films. The technique has been successfully applied to graphene, transition metal dichalcogenides, hexagonal boron nitride, and several other layered materials (Li *et al*., 2009).

One of the major advantages of CVD is its compatibility with wafer-scale fabrication, making it suitable for electronic and optoelectronic device manufacturing. The method also allows better control over crystal growth through the optimisation of temperature, pressure, precursor concentration, and substrate selection. However, challenges such as grain boundary formation, structural defects, and transfer-related contamination continue to influence material quality. Improving film uniformity and reducing fabrication costs remain important research priorities for commercial-scale production.

3. LIQUID PHASE EXFOLIATION

Liquid phase exfoliation is a cost-effective and scalable technique for producing large quantities of two-dimensional nanosheets. In this approach, bulk layered materials are dispersed in suitable solvents and subjected to ultrasonic treatment or mechanical mixing, which separates individual layers through the weakening of interlayer van der Waals forces. The resulting nanosheets can subsequently be collected, purified, and incorporated into a variety of electronic and functional materials (Coleman *et al*., 2011).

Compared with mechanical exfoliation, liquid phase exfoliation is more suitable for large-scale production and solution-based processing. The method is particularly attractive for applications such as printable electronics, conductive coatings, composite materials, and flexible devices. Nevertheless, the obtained nanosheets often exhibit variations in lateral size, thickness, and structural quality. Achieving consistent material properties while maintaining high production efficiency remains an important challenge.

4. OTHER FABRICATION METHODS

In addition to the techniques discussed above, several alternative fabrication methods have contributed to the rapid development of two-dimensional quantum materials. Molecular beam epitaxy (MBE) enables highly controlled crystal growth under ultra-high vacuum conditions and is particularly valuable for producing high-purity thin films for fundamental electronic studies (Koma, 1992). Although MBE provides excellent control over film thickness and interface quality, the process is relatively expensive and requires sophisticated instrumentation.

Hydrothermal and solvothermal synthesis methods have also attracted attention because they enable the preparation of selected two-dimensional materials under relatively mild reaction conditions. These approaches are frequently employed for materials intended for sensing, catalytic, and energy-related applications. In recent years, atomic layer deposition, plasma-assisted synthesis, and laser-assisted fabrication have further expanded the available processing routes, allowing improved control over surface chemistry and interface engineering.

No single synthesis technique is universally suitable for all applications. Mechanical exfoliation remains ideal for fundamental research, whereas chemical vapor deposition offers greater potential for industrial-scale electronics. Liquid phase exfoliation provides an economical solution for bulk production, while advanced growth techniques such as molecular beam epitaxy are preferred when precise control of crystal quality is required. Continued improvements in synthesis strategies are expected to support the large-scale integration of two-dimensional quantum materials into future electronic and optoelectronic technologies.

APPLICATIONS IN ELECTRONIC DEVICES

The exceptional electrical, mechanical, and surface properties of two-dimensional (2D) quantum materials have significantly expanded their role in modern electronic devices. Their atomic-scale thickness, excellent charge transport characteristics, and compatibility with flexible substrates provide new opportunities for designing compact, energy-efficient, and high-performance electronic systems. Recent advances in material engineering and device fabrication have accelerated their application across several important electronic technologies.

1. FIELD-EFFECT TRANSISTORS (FETs)

Field-effect transistors represent one of the most extensively investigated applications of two-dimensional quantum materials. As the dimensions of conventional silicon transistors continue to shrink, maintaining efficient electrostatic control and reducing power consumption have become increasingly challenging. The atomically thin structure of 2D materials offers improved gate control and suppresses short-channel effects, making them attractive channel materials for next-generation transistors.

Graphene was initially explored because of its exceptionally high carrier mobility. However, its lack of an intrinsic band gap limits its switching capability in digital circuits. In contrast, semiconducting materials such as molybdenum disulfide (MoS_2), tungsten diselenide (WSe_2), and black phosphorus exhibit suitable band gaps while maintaining good carrier transport characteristics. These materials have demonstrated high on/off current ratios, low operating voltages, and improved switching performance in experimental field-effect transistors (Das *et al*., 2014). Continued improvements in contact engineering and interface optimisation are expected to further enhance their practical performance.

2. FLEXIBLE ELECTRONICS

The increasing demand for lightweight, bendable, and wearable electronic systems has created strong interest in two-dimensional materials. Their excellent mechanical flexibility allows repeated bending and stretching without significant degradation of electrical performance. This characteristic makes them well suited for flexible displays, wearable health-monitoring devices, electronic skin, and smart textiles.

Graphene has been widely investigated as a transparent conductive electrode because of its combination of high electrical conductivity and optical transparency. Other two-dimensional semiconductors have also demonstrated stable electrical performance when integrated onto flexible polymer substrates. Recent studies have shown that multilayer heterostructures combining conductive, semiconducting, and insulating two-dimensional materials can further improve mechanical stability and device efficiency. Although large-scale manufacturing remains a challenge, continued progress in flexible fabrication technologies is bringing these materials closer to commercial applications (Akinwande *et al*., 2019).

3 SENSORS

Two-dimensional quantum materials have emerged as highly sensitive sensing platforms because of their large surface-to-volume ratio and strong interaction with surrounding chemical and biological species. Even minor changes in the surface environment can produce measurable variations in electrical conductivity, enabling rapid and highly sensitive detection.

Graphene-based sensors have demonstrated excellent performance in detecting gases, biomolecules, humidity, and environmental pollutants. Transition metal dichalcogenides and MXenes have also attracted considerable attention because their semiconducting nature and surface functional groups enhance selectivity toward specific target molecules. Recent advances in surface modification and heterostructure engineering have further improved sensor sensitivity, response time, and long-term stability. These developments have expanded the application of two-dimensional materials in environmental monitoring, medical diagnostics, food safety, and industrial process control (Varghese *et al*., 2015).

4. MEMORY DEVICES

The continuous growth of data-intensive technologies has increased the demand for memory devices with higher storage density, lower power consumption, and faster switching speeds. Two-dimensional quantum materials provide several advantages for emerging memory technologies because their atomically thin structure enables efficient charge transport while reducing device dimensions.

Various two-dimensional materials have been investigated for resistive random-access memory (RRAM), flash memory, ferroelectric memory, and phase-change memory devices. Their tuneable electronic properties and stable switching behaviour contribute to improved memory performance, while van der Waals heterostructures offer additional flexibility for designing multifunctional memory architectures. Recent studies have also demonstrated the potential of graphene and transition metal dichalcogenides in neuromorphic memory systems that imitate biological synaptic behaviour for artificial intelligence applications (Sangwan & Hersam, 2020).

Despite encouraging progress, several challenges remain before large-scale commercial implementation becomes feasible. Device reliability, switching uniformity, long-term endurance, and compatibility with existing semiconductor manufacturing processes continue to require further investigation. Continued advances in material synthesis, interface engineering, and device integration are expected to accelerate the adoption of two-dimensional quantum materials in future electronic technologies.

APPLICATIONS IN OPTOELECTRONIC DEVICES

The unique optical and electronic characteristics of two-dimensional (2D) quantum materials have created new possibilities for next-generation optoelectronic devices. Their tuneable band gaps, strong light–matter interaction, and efficient charge transport enable improved performance in light detection, light emission, and energy conversion. In recent years, advances in material quality and device engineering have significantly expanded their application in optoelectronic technologies.

1 PHOTODETECTORS

Photodetectors convert incident light into electrical signals and are widely used in imaging, communication, environmental monitoring, and biomedical systems. Two-dimensional materials have attracted considerable interest for these devices because they exhibit broad spectral absorption, rapid carrier transport, and high photoresponsivity. Unlike conventional semiconductors, their electronic properties can be tailored by selecting different material compositions or constructing van der Waals heterostructures.

Graphene-based photodetectors provide ultrafast response because of their exceptional carrier mobility, whereas semiconducting materials such as MoS_2, WS_2, and black phosphorus offer higher photoresponsivity due to their finite band gaps. Recent studies have shown that combining different 2D materials into heterostructures further enhances light absorption, carrier separation, and overall device efficiency. These developments have improved the performance of photodetectors operating across ultraviolet, visible, and infrared wavelength ranges (Long *et al*., 2019).

2. LIGHT-EMITTING DIODES (LEDs)

The development of atomically thin light-emitting devices has opened new opportunities for compact and energy-efficient display technologies. Monolayer transition metal dichalcogenides exhibit direct band gaps that enable efficient radiative recombination, making them promising materials for nanoscale light-emitting diodes. Their emission wavelength can also be adjusted through material selection, strain engineering, or heterostructure design.

Recent progress in device fabrication has improved charge injection, emission efficiency, and operational stability. Hybrid structures incorporating graphene electrodes and semiconducting monolayers have further enhanced electrical conductivity while maintaining optical transparency. Although the external quantum efficiency of many 2D material-based LEDs still requires improvement, continuous advances in interface engineering and defect control are steadily increasing device performance (Withers *et al*., 2015).

3. SOLAR CELLS

The growing demand for sustainable energy technologies has stimulated extensive research on two-dimensional materials for photovoltaic applications. Their high optical absorption, tunable electronic structure, and efficient charge transport make them attractive candidates for improving solar cell performance. Depending on the device architecture, two-dimensional materials can function as active light-absorbing layers, transparent electrodes, charge transport layers, or interface modifiers.

Graphene has been widely investigated as a transparent conductive electrode because of its excellent conductivity and flexibility. Transition metal dichalcogenides and black phosphorus have also demonstrated promising photovoltaic behaviour owing to their suitable band gaps and strong light absorption. Furthermore, integrating two-dimensional materials with silicon and perovskite solar cells has been shown to improve charge extraction and reduce carrier recombination, resulting in enhanced power conversion efficiency (Jariwala *et al*., 2016).

4. OPTICAL SENSORS

Optical sensors based on two-dimensional materials have attracted increasing attention because of their excellent sensitivity and rapid optical response. Their atomically thin structure enables strong interaction with external optical fields, allowing efficient detection of small changes in light intensity, wavelength, or refractive index.

Graphene and transition metal dichalcogenides have been explored for optical biosensing, environmental monitoring, and chemical detection. Their performance can be further enhanced through surface functionalisation and heterostructure engineering, which improve sensitivity and selectivity toward specific target molecules. Continued progress in nanofabrication and optical integration is expected to support the development of compact, highly sensitive optical sensing platforms for healthcare, environmental analysis, and industrial monitoring.

Overall, two-dimensional quantum materials have demonstrated considerable potential across a wide range of optoelectronic devices. While further improvements in stability, large-area fabrication, and interface engineering are still required, ongoing research continues to strengthen their prospects for future photonic and optoelectronic technologies.

CHALLENGES

Despite remarkable progress in the development of two-dimensional quantum materials, several scientific and technological challenges continue to limit their widespread adoption in commercial electronic and optoelectronic devices. Addressing these issues is essential for translating laboratory-scale demonstrations into reliable industrial technologies.

1. MATERIAL STABILITY

Long-term material stability remains one of the primary challenges for several two-dimensional materials. While graphene exhibits excellent chemical stability, materials such as black phosphorus are highly sensitive to oxygen and moisture, resulting in gradual surface degradation under ambient conditions. Oxidation, defect formation, and environmental contamination can significantly reduce electrical performance and device lifetime. Although encapsulation techniques and surface passivation have improved stability, developing durable materials capable of long-term operation remains an important research priority (Favron *et al*., 2015).

2. LARGE-SCALE PRODUCTION

Most high-performance laboratory devices rely on small, high-quality samples produced under carefully controlled conditions. However, commercial applications require large-area films with uniform thickness, low defect density, and reproducible electronic properties. Although fabrication techniques such as chemical vapor deposition have made significant progress, maintaining consistent crystal quality over large substrates continues to present technical challenges. Further improvements in scalable synthesis methods are necessary to support industrial manufacturing.

3. COST

The economic feasibility of two-dimensional material-based devices depends not only on material performance but also on production cost. High-quality crystal growth, specialised fabrication equipment, and complex transfer processes often increase manufacturing expenses. In addition, post-processing and quality control further contribute to overall production costs. Developing simpler, faster, and more cost-effective fabrication strategies will be essential for improving commercial competitiveness.

4. DEVICE INTEGRATION

Successful commercial implementation also requires seamless integration of two-dimensional materials with existing semiconductor technologies. Device performance is strongly influenced by interface quality, contact resistance, layer uniformity, and compatibility with conventional complementary metal-oxide-semiconductor (CMOS) fabrication processes. Variations in these factors frequently lead to inconsistent electrical characteristics and reduced device reliability. Continued advances in interface engineering, heterostructure design, and fabrication standardisation are expected to facilitate the integration of two-dimensional quantum materials into future electronic and optoelectronic systems.

Although these challenges remain significant, ongoing developments in material synthesis, device engineering, and manufacturing technologies continue to improve the practical prospects of two-dimensional quantum materials. Continued interdisciplinary research is expected to accelerate their transition from laboratory research to large-scale technological applications.

FUTURE PROSPECTS

1. EMERGING TRENDS

Research on two-dimensional quantum materials is gradually expanding beyond graphene and transition metal dichalcogenides toward newer material systems, including Xenes, tellurene, antimonene, and magnetic two-dimensional materials. The development of van der Waals heterostructures is also creating new opportunities to tailor electronic and optical properties for advanced device applications (Gibertini *et al*., 2019).

2. COMMERCIAL OUTLOOK

The commercial potential of two-dimensional materials continues to grow, particularly in flexible electronics, wearable devices, transparent electrodes, photodetectors, and energy-efficient optoelectronic systems. However, large-scale production, manufacturing cost, and long-term device reliability remain important factors that must be addressed before widespread industrial adoption can be achieved.

3. FUTURE RESEARCH DIRECTIONS

Future research should focus on scalable synthesis methods, improved interface engineering, defect control, and stable device architectures. Greater integration of computational modelling and artificial intelligence is expected to accelerate material discovery and device optimization. Continued collaboration between materials scientists, physicists, and engineers will be essential for translating laboratory-scale advances into commercially viable electronic and optoelectronic technologies.

CONCLUSION

Two-dimensional quantum materials have emerged as an important class of materials for next-generation electronic and optoelectronic devices. Their atomically thin structure, tunable electronic properties, high carrier mobility, and strong light–matter interaction provide significant advantages over many conventional materials. Continuous advances in synthesis techniques and device fabrication have expanded their applications across transistors, flexible electronics, sensors, memory devices, photodetectors, light-emitting diodes, and solar cells.

This paper has discussed the fundamental characteristics of major two-dimensional material families, including graphene, transition metal dichalcogenides, black phosphorus, hexagonal boron nitride, and MXenes. It has also examined the principal fabrication methods, recent technological applications, and the major challenges associated with material stability, large-scale production, manufacturing cost, and device integration. Although substantial progress has been achieved, these challenges continue to limit widespread commercial implementation.

Future research should concentrate on scalable synthesis, improved interface engineering, environmentally stable materials, and efficient integration with existing semiconductor technologies. The exploration of emerging two-dimensional materials and advanced heterostructures is expected to further expand the capabilities of electronic and optoelectronic devices. With continued progress in both fundamental research and industrial manufacturing, two-dimensional quantum materials are well positioned to support the development of faster, smaller, and more energy-efficient technologies in the years ahead.

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