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Development of 2D Materials for Next-Generation Semiconductors

GAJENDRA KUMAR MAHAWAR

ASSOCIATE PROFESSOR IN PHYSICS

GOVT. COLLEGE RAJGARH (ALWAR)

Abstract

The development of two-dimensional (2D) materials for next-generation semiconductors represents a promising frontier in materials science and electronics. 2D materials, such as graphene, transition metal dichalcogenides (TMDs), and black phosphorus, exhibit unique electrical, optical, and mechanical properties that distinguish them from traditional bulk materials. These properties, including high carrier mobility, tunable bandgaps, and exceptional mechanical strength, make 2D materials ideal candidates for a range of semiconductor applications, including high-speed transistors, optoelectronic devices, and flexible electronics. Notably, TMDs like MoS2 and WS2 offer a direct bandgap in their monolayer form, making them suitable for optoelectronic devices such as photodetectors, light-emitting diodes (LEDs), and solar cells. The ability to tune the electronic properties of 2D materials through doping, strain engineering, and layer number modulation further enhances their potential. Despite these advantages, challenges in the large-scale synthesis, integration with conventional semiconductor technologies, and environmental stability remain obstacles for widespread adoption. This research explores the synthesis methods, electronic properties, and potential applications of 2D materials, as well as the ongoing challenges and future directions in their development.

Keywords: 2D Materials, Two-dimensional, semiconductor, Technology

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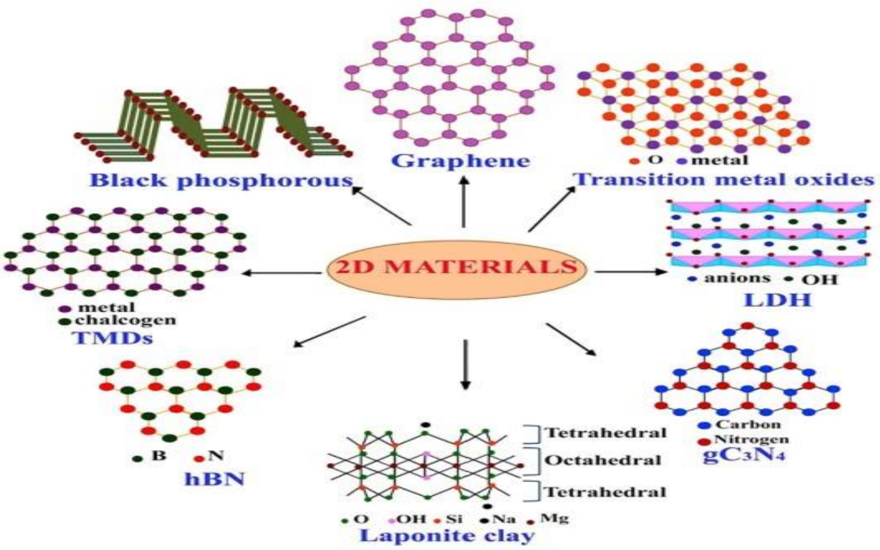
Introduction

The development of next-generation semiconductors is a critical area of research in modern electronics, with the demand for faster, smaller, and more energy-efficient devices increasing rapidly. Traditional silicon-based semiconductors, while highly successful for decades, are reaching their physical and performance limits as Moore's Law slows down. To meet the evolving demands of the electronics industry, researchers are exploring novel materials that can overcome these limitations. Among the most promising candidates are two-dimensional (2D) materials, which exhibit unique properties due to their atomic-scale thickness. These materials, which are only a few atoms thick, offer exceptional electrical, optical, and mechanical characteristics that are ideal for use in next-generation semiconductor devices. Notably, 2D materials like graphene, transition metal dichalcogenides (TMDs), and black phosphorus have garnered significant attention for their ability to revolutionize semiconductor technologies, offering improved carrier mobility, flexibility, and tunable electronic properties.



Two-dimensional materials have potential because they can fit into present semiconductor manufacturing procedures and they give rise to new opportunities to boost device functionality. Researchers find that 2D materials display adaptable properties which they can tune by altering layer counts, introducing dopant levels and structural defects thus granting these materials wide application diversity. 2D materials allow transistors to have quicker switching rates and reduced energy usage while these improvements remain essential for next-generation high-power computing equipment. The custom optical effects of these materials allow photonics and optoelectronics applications to develop new opportunities for their usage. Numerous promising advantages of 2D materials are hindered by the large-scale production challenges alongside integration issues with existing semiconductor technologies and requisite stable real-world device performance. Recent improvements in material synthesis and device fabrication along with progress in characterization techniques extend the capabilities of new materials for future semiconductor technologies.

Overview of semiconductor industry and current trends

The semiconductor industry supported major technological innovation standards across electronics and telecommunications for multiple decades along with numerous additional industries. Devices from computers and smartphones through automobiles to home appliances depend on semiconductors as critical components. Since the transistor was introduced in the late 1940s the semiconductor industry experienced substantial development as device miniaturization allowed for advanced technologies that improved efficiency and computational capability. Silicon became the primary choice for semiconductor manufacturing because it provides both plentiful material supply and economic practicality while its chemical properties are thoroughly researched. Silicon technology approaches certain boundaries while consumer needs push for even smaller device components that deliver better performance with reduced power usage.

Semiconductor industry leaders now pursue approaches to overcome silicon's boundaries while seeking functional alternatives to silicon-based technological frameworks. Researchers are working towards discovering innovative materials which deliver better performance results while solving silicon-related technological challenges. Research focuses on gallium nitride (GaN) and silicon carbide (SiC) because they support higher voltages and elevated temperature operations for power electronics and electric vehicles. Researchers and technologists now consider two-dimensional (2D) materials to be excellent candidates for advanced semiconductors because their distinct electrical, optical, and mechanical features provide exceptional performance improvements. Advanced manufacturing methods like extreme ultraviolet lithography now attract strong industry attention because this technology supports future transistor miniaturization while enabling integrated circuit improvements. With ever-increasing demand for computing power primarily from AI and high-performance computing sectors and 5G communications driving growth the semiconductor industry now develops advanced materials manufacturing methods and new device architectures to keep pace. The semiconductor industry's recent developments forecast an era of advanced semiconductors equipped to satisfy the increasing needs for computation and connectivity.

Importance of advancing materials for next-generation semiconductors

The development of next-generation semiconductor materials forms a critical foundation to fulfill the growing need for electronic devices that operate with greater speed while using less energy. Modern electronic devices need to expand beyond what silicon-based semiconductors provide because these materials strive for higher performance while remaining foundational yet at their capacity for speed and complexity reduction. Advancing the mission of miniaturization and performance improvement requires searching for new materials with enhanced electrical and thermal capabilities together with better mechanical attributes. Research on gallium nitride (GaN), silicon carbide (SiC), and two-dimensional (2D) materials aims to solve silicon's efficiency problems by delivering better power efficiency with quicker switching performance plus stronger thermal features. Next-generation applications in high-performance computing power electronics 5G communications and AI require advanced materials because standard semiconductor technology fails to meet those demands. Graphene together with transition metal dichalcogenides (TMDs) as examples of 2D materials demonstrate exceptional characteristics by offering both high carrier mobility and adjustable bandgaps which qualify them as optimal materials for development of future transistors as well as sensor and optoelectronic technologies. These materials power energy-saving devices which support worldwide efforts for sustainable electronics. The electronic materials industry must develop new research into advanced materials which semiconductor manufacturing will utilize to break silicon limits and create faster and more sustainable powerful devices. Creating new materials will power upcoming technological advancements including quantum computing expansion as well as broader Internet of Things (IoT) developments.

Purpose and scope of the study

The study aims to investigate how advanced materials especially 2D materials can create superior semiconductors to overcome silicon-based technology limitations. The investigation analyzes how modern materials like graphene and black phosphorus aim to improve semiconductor systems while enabling new research for superior computing performance including AI and 5G processes as market demand requires devices which operate faster and consume less power. Our research analyzes both electrical and thermal properties together with optical capabilities of selected materials as well as their prospective uses in semiconductor electronics including transistors and sensors alongside optoelectronic devices. The structure looks at production techniques for these materials alongside the obstacles faced during integration into semiconductor manufacturing and compares their performance metrics to established silicon-based materials. This research will analyze both current progress with these materials along with case studies showing realistic applications examining their production capabilities together with performance longevity and ecological outcomes. The study evaluates advanced materials to reveal their potential to drive semiconductor technology evolution and analyze solutions to current industry challenges. The resulting insights from this study will show how ongoing development in materials science remains critical for semiconductor advances that drive progress in modern electronics alongside other technology areas.

Literature Review

Zhou, X., et al (2016). Innovative progress in Group IV–VI semiconductors has generated fresh organizational leadership within the 2D material field which scientific communities now call the "fresh blood" of the 2D family. Semiconductors derived from combinations of Group IV elements such as silicon or germanium with Group VI elements sulfur selenium and tellurium demonstrate distinctive properties suitable across various electronic optoelectronic and energy harvesting applications. The transition to a single-layer or minimal-layer form unlocks outstanding properties in these materials through high carrier mobility alongside adjustable bandgaps and powerful light-matter interactions. The advanced capabilities of multiple-layer elements position them perfectly for research and development of new electronic devices such as transistors and solar cells while enabling better performance in photodetection applications.

Liu, C., Chen, H., et al (2020). The rapid emergence of two-dimensional materials stands at the forefront of next-generation computing technology because they display exceptional electronic properties that combine with their optical attributes and precise mechanical characteristics. Graphene and transition metal dichalcogenides (TMDs) demonstrate superior carrier mobility and adjustable bandgaps plus flexibility which positions them perfectly for use in modern electronic and optoelectronic technologies. Two-dimensional materials belong in cutting-edge computing because they are capable of creating transistors that combine ultra-small dimensions with low power consumption and high functionality to tackle conventional silicon technology limitations near Moore's Law boundaries. Graphene's high electron mobility holds promise for faster processor development but TMDs provide tunable bandgaps for better field-effect transistor switching capability.

Wang, S., et al (2022). 2D semiconductors represent an important development during the silicon age in electronics evolution because they embody potential future alternatives or supporting components alongside existing silicon-based technologies. The fundamental role of silicon in today's electronics industry encounters boundary limits as miniaturization capacity drops back alongside power efficiency and speed because we reach Moore's Law physical constraints. Graphene alongside transition metal dichalcogenides (TMDs) and black phosphorus stands among the new 2D semiconductors now capturing industrial attention because of their revolutionary properties. The unique capabilities of ultra-thin 2D materials with high surface areas and adjustable electronic traits establish them as ideal components for next-generation efficient and fast devices. 2D semiconductors enable cutting-edge transistors and photodetectors together with quantum computing applications by exhibiting direct bandgaps as well as strong electron mobility and mechanical flexibility. The compatibility of 2D semiconductors with existing silicon technology produces devices which successfully merge the strengths of both materials.

Cao, W., Jiang, J., et al (2018). Next-generation electronic devices might revolutionize electricity manipulation thanks to the distinctive qualities of 2D layered materials which offer asymmetric electron mobility along with mechanical adaptability and adjustable bandgaps. Several novel materials such as graphene combined with transition metal dichalcogenides (TMDs) and black phosphorus show potential to transform electronic devices that range from sensors and transistors to quantum computing and flexible display technologies. Atomic level device miniaturization keeps performance intact and enables ultra-compact electronic devices at low power which silicon materials find difficult to produce. Bringing 2D materials to commercial electronic products encounters multiple difficulties.

Cheng, Z., Cao, R., et al (2021). Integrated optoelectronics is being changed by the leading-edge properties of 2D materials which enables advanced functionality in communication technologies as well as sensing and imaging applications. Graphene and transition metal dichalcogenides (TMDs) together with black phosphorus show distinctive optoelectronic behaviours including strong light-matter interaction and customizable bandgaps which endows them with high flexibility while establishing them as essential materials for making photodetectors light-emitting diodes (LED) modulators and photonic circuits. Optoelectronic devices become both more efficient and energy-saving through 2D material integration which drives progress in communication technology data transfer systems. These materials can be modified at the atomic level so engineers can produce multi-functional devices which show reduced size and weight alongside better efficiency when compared to standard materials. Production of large quantities of high-quality 2D materials presents an unresolved challenge that hinders their full integration into current semiconductor manufacturing techniques. Scientists refine both chemical vapor deposition (CVD) along with exfoliation approaches as they look for new methods to direct defects, material interfaces and doping features.

Buscema, M., et al (2015). Researchers find that photocurrent generation through two-dimensional van der Waals semiconductors stands as a remarkably promising research field because 2D materials boost optoelectronic device efficiency. Transition metal dichalcogenides (TMDs) and black phosphorus represent excellent photocurrent generation materials because they enable strong light-matter interactions and have controllable bandgaps. These semiconductors generate electron-hole pairs through light exposure which enables collectors to utilize photovoltaic effects separated into photocurrent. Van der Waals forces in these materials enable researchers to stack distinct 2D layers crafting heterostructures with high photocurrent response. Users can achieve multiple benefits from this design approach which helps manipulate optical features while controlling electronic behavior and maximizing energy conversion parameters. The excellent photoresponsivity features of 2D semiconductors stem from their high surface-to-volume ratio together with their flexibility and mechanical sturdiness that creates new possibilities for flexible and wearable optoelectronic devices.

Geng, D., & Yang, H. Y. (2018). The development of new 2D materials past graphene and transition metal dichalcogenides now enables improved electronic application possibilities together with advances in optical electronics and enhanced energy storage solutions. As researchers seek advanced 2D material options scientists show more interest in black phosphorus and phosphorene and Group IV–VI semiconductors because they provide distinctive electronic and optical characteristics that either match or exceed those found in traditional 2D materials. Chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and liquid-phase exfoliation represent innovative growth methods that advance the quality and scalability of these modern 2D materials alongside enhanced material controllability. Group III–V semiconductors alongside new 2D oxides together with organic-inorganic hybrid materials expand the potential uses of 2D materials through their unique versatile and functional attributes. Two-dimensional topological insulators together with semiconductors possessing substantial spin-orbit interaction create paths towards spintronics and quantum computation improvements.

Types of 2D Materials for Semiconductor Applications

2D materials have garnered significant interest for semiconductor applications due to their unique properties, which can be tailored for various uses in electronics, optoelectronics, and energy storage. Several types of 2D materials, each with distinct characteristics, hold promise for enhancing the performance of next-generation semiconductor devices. Some of the key types include:

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1. **Graphene**:

Graphene is one of the most well-known 2D materials, consisting of a single layer of carbon atoms arranged in a honeycomb lattice. It exhibits exceptional electrical conductivity, high carrier mobility, and thermal properties. However, graphene lacks a bandgap, which makes it unsuitable for conventional transistor applications. Researchers are exploring ways to induce a bandgap in graphene through methods like strain engineering, edge modification, and doping, which could potentially make it useful in high-speed transistors and flexible electronics.

2. **Transition Metal Dichalcogenides (TMDs)**:

TMDs, such as **MoS2**, **WS2**, **MoSe2**, and **WSe2**, are composed of a layer of transition metal atoms sandwiched between two layers of chalcogen atoms (e.g., sulfur, selenium, or tellurium). These materials exhibit a direct bandgap in their monolayer form, making them ideal for optoelectronic devices like photodetectors, light-emitting diodes (LEDs), and lasers. TMDs also offer high carrier mobility, making them suitable for high-performance transistors and flexible electronics. The ability to tune the bandgap by changing the number of layers or applying external stimuli adds to their versatility in semiconductor applications.

3. **Black Phosphorus (Phosphorene)**:

Black phosphorus, also known as phosphorene when in its monolayer form, has an anisotropic crystal structure, which results in excellent electronic properties that can be tuned by adjusting the number of layers. It has a tunable direct bandgap, making it a promising candidate for use in field-effect transistors (FETs), photodetectors, and other optoelectronic devices. However, black phosphorus is highly sensitive to environmental factors like oxygen and moisture, which can degrade its performance. Researchers are working on improving its stability and scalability for practical applications.

4. **Hexagonal Boron Nitride (h-BN)**:

Hexagonal boron nitride is a wide-bandgap semiconductor with excellent insulating properties, often referred to as "white graphene." It is highly stable, chemically inert, and has high thermal conductivity, making it suitable for use as a dielectric material in semiconductor devices. It is often used as a substrate for growing other 2D materials like graphene or TMDs, providing a stable platform for device fabrication. Its insulating properties also make it an ideal candidate for use in heterostructures and devices that require high isolation.

5. **MXenes**:

MXenes are a family of 2D transition metal carbides, nitrides, and carbonitrides. These materials exhibit excellent electrical conductivity, mechanical strength, and tunable surface chemistry, making them suitable for applications in energy storage, sensors, and flexible electronics. MXenes have been explored for use in supercapacitors and batteries due to their high surface area and conductivity. Their ability to be easily functionalized also makes them attractive for a wide range of applications in semiconductor technologies.

6. **Topological Insulators (TI)**:

Topological insulators are materials that have insulating bulk properties but conductive surface states. These materials, such as **Bi2Se3** and **Bi2Te3**, have garnered interest in semiconductor applications due to their unique electronic properties that are protected by time-reversal symmetry. These properties make them ideal candidates for quantum computing, spintronics, and low-power electronics, where the manipulation of surface states can lead to new types of devices with enhanced efficiency.

Each of these 2D materials offers distinct advantages for semiconductor applications, with their ability to be tuned and integrated into existing semiconductor processes allowing for new devices with improved performance in terms of speed, flexibility, power consumption, and miniaturization. However, challenges in large-scale fabrication, stability, and integration with existing semiconductor technologies remain areas of active research.

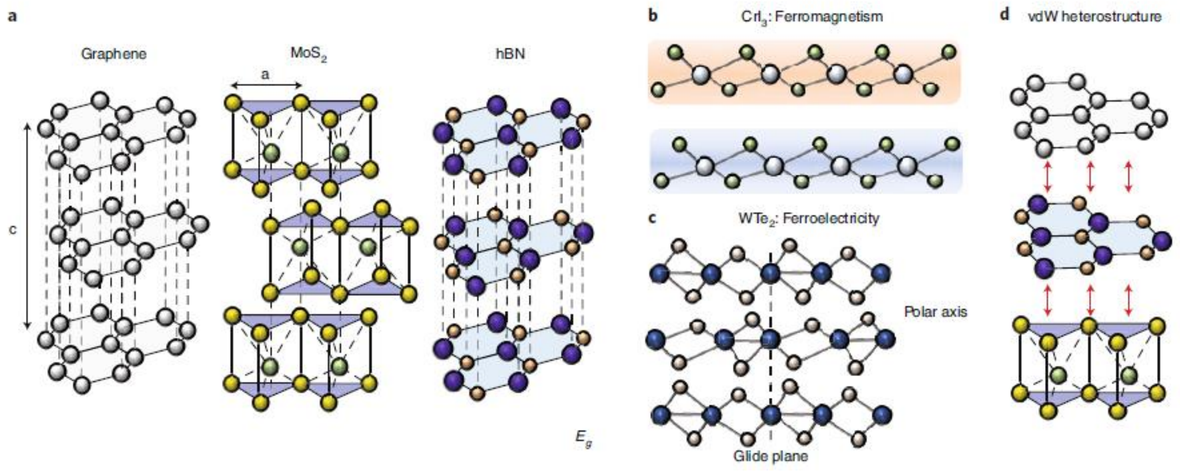
Electrical and Optical Properties of 2D Materials

Because of their essential electrical and optical properties next-generation semiconductor technology stands to gain significantly from 2D materials. 2D materials showcase remarkable electrical conductivity together with exceptional carrier mobility through materials including graphene as well as transition metal dichalcogenides (TMDs). Extraordinary electron mobility defines graphene as the best material for high-speed transistors and various high-performance electronic devices. A natural bandgap is missing in graphene which creates difficulties for its application in standard transistors because it fails to easily transition between conductive and non-conductive states. The monolayer form of TMDs MoS2 and WS2 features a direct bandgap enabling their use to function effectively at optoelectronic purposes including photodetection, photoluminescence and solar energy conversion. By adjusting their layered structure TMDs modify their direct bandgap which allows these materials to serve multiple application domains. 2D materials achieve superior semiconductor device performance through electronic property modulation by means of doping and external field application.

2D materials stand out in optoelectronic applications because their optical properties pair powerfully with their inherent electrical characteristics. MoS2 displays strong visible spectrum light absorption behavior which enables 2D materials to function well as photodetectors and in light-emitting devices. The light emission characteristics of these materials show tunability through layer adjustment which enables innovation in light-emitting output devices and photonics technology development. The union of optical characteristics and material flexibility with substrate integration capabilities establishes 2D materials as essential components for future semiconductor technology and sensor development as well as display systems. Respective obstacles exist when researchers attempt to control closely situated defects while also expanding large-scale growth and establishing material compatibility with traditional semiconductor production methods.

2D materials for next-generation computing technologies

2D materials stand out as highly innovative for future computing applications because of their distinctive properties. Two-dimensional materials stand apart from traditional three-dimensional substances because their one-to-few atom thickness grants them exceptional electrical optical and mechanical characteristics. As the most recognizable 2D material Graphene demonstrates strong electrical flow alongside outstanding carrier movement which creates perfect conditions for applications in quick response transistors and electronic displays with flexible panels. Graphene contains no natural bandgap and therefore fails to function effectively in digital logic devices. Monolayer Transition metal dichalcogenides (TMDs) such as MoS2 and WS2 display direct bandgaps which support efficient photodetectors LED devices and transistors for optoelectronic low-power applications. The two-dimensional material black phosphorus named phosphorene demonstrates potential for use in field-effect transistors (FETs) and photodetectors thanks to its adjustable bandgap property. Scientists who control layer quantity in 2D materials achieve better electronic performance and this versatility creates opportunities for quantum computing and AI development. Despite their potential impact on technology 2D materials continue to face obstacles such as efficient scalable production methods environmental robustness and compatibility with traditional semiconductor manufacturing techniques. The current research endeavors eliminate the barriers halting 2D materials adoption so future computing systems can benefit from increased speed and greater efficiency while reducing energy consumption.



The image illustrates the crystal structures and key properties of various 2D materials and their heterostructures. In panel (a), it compares the atomic structures of graphene, MoS2, and hBN, highlighting their distinct lattice arrangements and band gaps (Eg) that make them suitable for

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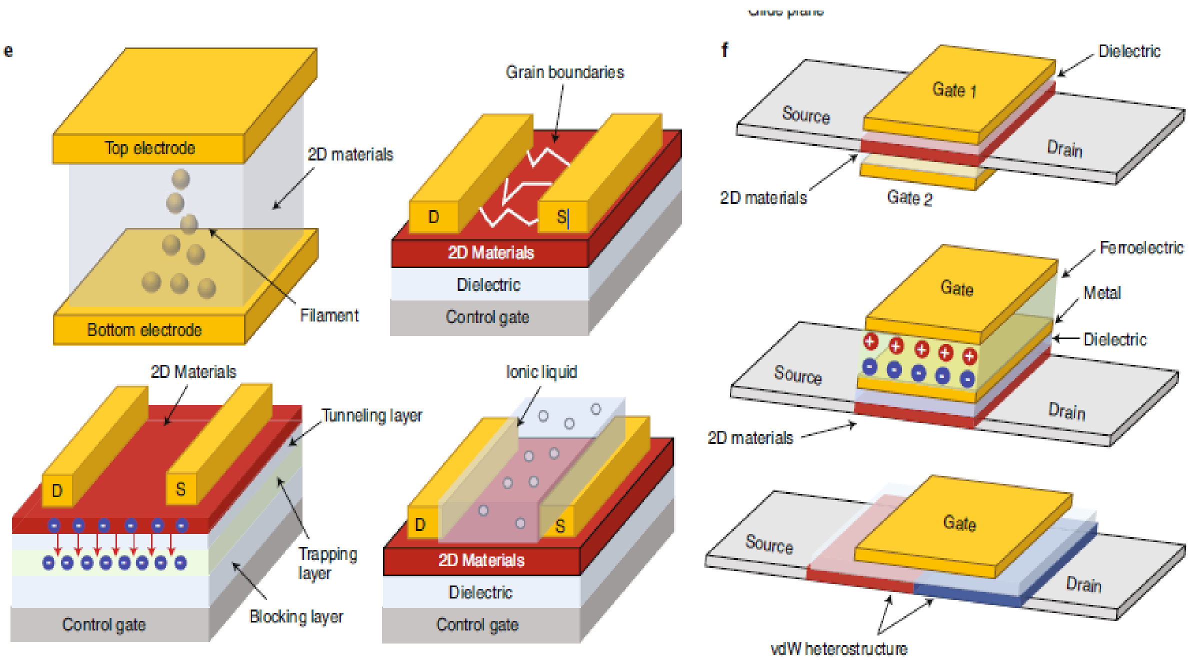
different semiconductor applications. Panel (b) demonstrates ferromagnetism in CrI3, showcasing magnetic ordering within a 2D material. Panel (c) features WTe2, known for ferroelectricity, where the crystal structure has a polar axis and glide plane, enabling specific electronic properties. Finally, panel (d) highlights the formation of van der Waals (vdW) heterostructures, where 2D materials are stacked to combine complementary properties for enhanced performance in devices.



The diagram features multiple device structures where 2D materials serve semiconductor roles. The configuration from panel (e) demonstrates top and bottom electrodes which construct either a filament or tunneling layer and serve as components in memristor-type devices and electronic switching frameworks. This system comprises dielectric and control gates with an electric-conducting trap layer linked to iodine-analogs to provide various methods for modifying electronic characteristics. The shown field-effect transistor structure on panel (f) uses dual gate architecture with ferroelectric material integration for better functionality and van der Waals heterostructures to optimize performance demonstrating 2D material potential in complex semiconductor components.

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Methodology

The methodology for this study on the development of 2D materials for next-generation semiconductors involves a comprehensive review of secondary data gathered from existing literature, case studies, and experimental research. A systematic literature review is conducted to explore the current advancements, synthesis methods, properties, and applications of various 2D materials, including graphene, transition metal dichalcogenides (TMDs), and black phosphorus, in semiconductor devices. The review focuses on analyzing the key properties of these materials, such as their electrical conductivity, bandgap tunability, and photoluminescence, which are crucial for semiconductor applications. Additionally, the challenges and limitations, such as scalability, integration with existing semiconductor technologies, and environmental stability, are examined through a synthesis of published research. Case studies of successful applications of 2D materials in real-world semiconductor devices, such as high-speed transistors, photodetectors, and energy-efficient devices, are analyzed to evaluate their potential and performance in practical settings. The study also includes an analysis of the latest developments in fabrication techniques like chemical vapor deposition (CVD), liquid-phase exfoliation, and molecular beam epitaxy (MBE), which are critical for producing high-quality 2D materials. The collected data is analyzed to identify trends, challenges, and breakthroughs in the field. This approach provides a holistic understanding of the current state of research, offering insights into the future directions for the integration of 2D materials in next-generation semiconductor technologies.

Results and Discussion

Key Properties, Applications, Challenges, and Recent Developments of 2D Materials for Semiconductor Technologies

2D Material	Key Properties	Applications	Challenges	Recent Developments/Case Studies
Graphene	High electrical conductivity, flexibility, high mobility, no bandgap	High-speed transistors, flexible electronics, sensors	Lack of bandgap for switching, integration with existing tech	Research on graphene-based FETs and optoelectronics, but still facing integration issues
MoS_2 (Transition Metal Dichalcogenides)	Direct bandgap in monolayer, high mobility, tunable electronic properties	Photodetectors, LEDs, solar cells, field-effect transistors (FETs)	Scalability, environmental stability, high-quality monolayer production	Demonstrated in high-efficiency photodetectors and low-power FETs
WS_2 (Transition Metal Dichalcogenides)	Direct bandgap, high mobility, photoluminescence	Optoelectronics, photodetectors, and high-speed electronics	Synthesis of high-quality monolayers, stability under ambient conditions	Used in visible and infrared photodetectors with high performance
Black Phosphorus (Phosphorene)	Tunable bandgap, high mobility, anisotropic properties	FETs, photodetectors, flexible electronics	Air and moisture sensitivity, degradation under ambient conditions	Research on enhancing stability and scalability for flexible electronics
Hexagonal Boron Nitride (h-BN)	Wide bandgap, excellent insulation, high thermal conductivity	Dielectric materials, substrates for 2D heterostructures, insulators	Synthesis of high-quality layers, integration challenges with other 2D materials	Used as a substrate for graphene and other 2D materials in heterostructures
MXenes	High electrical conductivity, mechanical strength, tunable surface chemistry	Energy storage devices, sensors, flexible electronics	Scalability of production, environmental stability, integration with semiconductor	Emerging use in supercapacitors and energy-efficient devices

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Topological Insulators (e.g., Bi2Se3)	Conductive surface states, insulating bulk, robustness against perturbations	Quantum computing, spintronics, low-power electronics	Fabrication challenges, integration into large-scale devices	Research on spintronic devices and topological quantum computing systems

This table show information about essential 2D materials alongside their properties together with their applications challenges and current research progress. Due to highly conductive graphene having excellent flexibility it serves high-speed transistors and flexible electronics but faces limitations in traditional switching devices because it doesn't possess a bandgap. Since both MoS2 and WS2 transition metal dichalcogenides display direct bandgaps when formed as monolayers they become functional components for devices like photodetectors and LEDs but engineers still need to overcome hurdles related to environmental stability alongside scalability. The tunable bandgap and directional properties of black phosphorus make this material desirable for FETs and photodetectors while its air and moisture sensitivity poses operational challenges. Despite acting as a substrate material because of its broad bandgap and desirable thermal properties hexagonal boron nitride faces integration difficulties with other two-dimensional materials. Energy storage and sensor developments study phases include MXenes even as Bi2Se3 shows growing applications in quantum computing and spintronics operations.

Synthesis methods, electrical properties, optical properties, and potential device applications

2D Material	Synthesis Method	Electrical Properties	Optical Properties	Potential Device Applications
Graphene	Mechanical exfoliation, Chemical vapor deposition (CVD)	High electron mobility, no bandgap	Transparent, excellent light absorption, tunable optical response	High-speed transistors, flexible electronics, sensors, photodetectors
MoS2	CVD, Liquid-phase exfoliation, Mechanical exfoliation	Direct bandgap (1.8 eV for monolayer), high mobility	Strong photoluminescence, tunable absorption with layer number	Photodetectors, LEDs, low-power FETs, flexible electronics
WS2	CVD, Liquid-phase exfoliation, Mechanical exfoliation	Direct bandgap (1.8 eV for monolayer), high mobility	Photoluminescence, tunable optical response based on layer thickness	Optoelectronics, photodetectors, FETs
Black Phosphorus	Chemical vapor deposition (CVD), Liquid-phase exfoliation	Tunable direct bandgap (0.3 eV to 2.0 eV depending on layer count), anisotropic mobility	Strong photoluminescence, absorption in the visible to infrared range	FETs, photodetectors, flexible electronics
Hexagonal Boron Nitride (h-BN)	CVD, Mechanical exfoliation	Wide bandgap (5.9 eV), insulating, high thermal conductivity	Transparent to visible light, low absorption, high dielectric strength	Substrate for 2D heterostructures, insulating layer, dielectric material
MXenes	Selective etching of metal carbides/nitrides	High conductivity, tunable electrical properties based on surface functionalization	High absorption in the UV-visible range	Energy storage, sensors, flexible electronics, photodetectors
Bi2Se3 (Topological Insulator)	Molecular beam epitaxy (MBE), CVD	Conductive surface states, insulating bulk	Limited optical transparency, indirect bandgap	Quantum computing, spintronics, low-power electronics

The table presents properties alongside synthesis methods for different 2D materials as well as their potential use cases. Researchers produce graphene by mechanical exfoliation and CVD yet it demonstrates maximum electron mobility while missing a bandgap that positions it as optimal for fast-switching transistors and flexible electronic components. A monolayer of MoS2 has a direct bandgap of 1.8 eV which enables effective use in photodetectors LEDs low-power FETs plus demonstrates strong photoluminescence. WS2 functions as another TMD which shows both direct bandgap properties and tunable optical behavior so it can be used effectively in optoelectronic devices alongside FETs. Black phosphorus features a tunable bandgap appropriate for FETs along with photodetectors but environmental stability suffers in the presence of air and moisture. Teams use Hexagonal boron nitride (h-BN), which provides electrical insulation through a wide bandgap property as a dielectric layer or substrate base when working with two-dimensional heterostructures. The selective etching production process creates MXenes which demonstrate high conductivity and find application in both energy storage systems and sensing technology. Researchers use Bi2Se3 topological insulators for both quantum computing and spintronic applications because of their conductive surface states.

Conclusion

Research into 2D materials for semiconductors presents new frontiers within materials science by delivering exceptional properties that better silicon-based devices need for improved performance. Current advancements in material technology allow the development of high-speed transistors while supporting flexible electronics, optoelectronic systems and modern quantum computing platforms. Next-generation technologies require tunable bandgaps and high carrier mobility from semiconductor materials and versatile device integration capacities to break silicon's physical boundaries and drive technological miniaturization. Existing challenges such as manufacturing at a large scale and ensuring material stability when exposed to real-world conditions along with perfect integration within current semiconductor manufacturing processes still need resolution. The field advances towards overcoming current barriers through better synthesis methods and enhanced material characterizations along with specialized device design. Modern case study findings prove that 2D materials offer substantial performance benefits in high-efficiency photodetectors as well as low-power transistor systems and energy storage solutions to establish practical usage possibilities across multiple electronic and optoelectronic domains. Advances in research that enables successful 2D material integration with semiconductors promise profound electronic industry transformation through devices that operate at higher speeds with better efficiency and sustainability to satisfy evolving computing and energy needs.

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