

Novel Semiconductor Nanomaterials For High-Sensitivity Photodetectors And Biosensing Applications

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ABSTRACT

The rapid advancement of nanotechnology has significantly transformed the field of semiconductor science, enabling the development of highly efficient photodetectors and biosensors with enhanced sensitivity, selectivity, and response speed. Novel semiconductor nanomaterials, including graphene, transition metal dichalcogenides (TMDs), black phosphorus, MXenes, quantum dots, perovskite nanocrystals, and metal oxide nanostructures, have emerged as promising candidates for next-generation sensing applications due to their unique optical, electrical, and surface properties. These materials exhibit tunable band gaps, high charge carrier mobility, large surface-to-volume ratios, strong light-matter interactions, and efficient charge transport characteristics, which collectively contribute to superior device performance compared with conventional semiconductor systems. This article comprehensively reviews the synthesis methods, structural and physicochemical characteristics, photodetection mechanisms, biosensing principles, and recent advancements in semiconductor nanomaterial-based devices. Various fabrication techniques, including chemical vapor deposition, hydrothermal synthesis, solvothermal processing, sol gel methods, atomic layer deposition, and exfoliation approaches, are discussed alongside advanced characterization techniques used to evaluate material properties and device performance. The results indicate that graphene-based and hybrid heterostructure

photodetectors provide broadband spectral response and rapid signal generation, while MoS₂, WS₂, black phosphorus, quantum dots, and perovskites exhibit excellent photoresponsivity, detectivity, and wavelength selectivity. In biosensing applications, graphene, MXenes, semiconductor nanowires, and metal oxide nanostructures enable efficient biomolecule immobilization and signal amplification, resulting in highly sensitive detection of proteins, nucleic acids, pathogens, toxins, and disease biomarkers. Furthermore, hybrid semiconductor heterostructures demonstrate synergistic improvements in charge separation, sensitivity, selectivity, and operational stability. Despite significant progress, challenges related to long-term stability, toxicity, scalability, and commercialization remain. Future research should focus on sustainable nanomaterial design, flexible and wearable sensing platforms, self-powered devices, and artificial intelligence-assisted sensor technologies. Overall, semiconductor nanomaterials represent a transformative platform for the development of advanced photodetectors and biosensors with broad applications in healthcare, environmental monitoring, food safety, telecommunications, and smart electronic systems.

Keywords: Semiconductor Nanomaterials, Photodetectors, Biosensors, Graphene, Transition Metal Dichalcogenides, MXenes, Quantum Dots, Perovskites, Optoelectronics, Nanotechnology

INTRODUCTION

The emergence of nanotechnology has revolutionized modern materials science and has significantly influenced the development of advanced semiconductor devices. Semiconductor nanomaterials have attracted considerable attention due to their extraordinary physical, chemical, optical, and electronic properties, which differ substantially from those of their bulk counterparts (Wang et al., 2014). These unique characteristics arise primarily from quantum confinement effects, increased surface-to-volume ratios, tunable band structures, and enhanced charge carrier dynamics. As a result, semiconductor nanomaterials have become promising candidates for next-generation optoelectronic and sensing technologies, particularly in the fields of photodetection and biosensing. The growing demand for highly sensitive, miniaturized, energy-efficient, and multifunctional devices has accelerated research efforts toward the design and application of novel semiconductor nanostructures capable of overcoming the limitations of conventional materials (Daher et al., 2022). Photodetectors are indispensable components in numerous technological applications, including optical communication systems, environmental monitoring, military surveillance, biomedical imaging, industrial automation, and astronomical observations. The primary function of a photodetector is to convert incident light into an electrical signal through photo-induced charge generation and transport processes (Zang et al., 2018). The performance of a photodetector is generally evaluated in terms of responsivity, detectivity, response speed, external quantum efficiency, and spectral selectivity. Conventional silicon-based photodetectors have been extensively utilized due to their mature fabrication technology and compatibility with integrated circuits (Rahman et al., 2026). However, silicon exhibits several limitations, including restricted spectral response, reduced flexibility, and challenges associated with

achieving ultra-high sensitivity in emerging applications. These shortcomings have motivated researchers to explore alternative semiconductor nanomaterials with superior optoelectronic characteristics (Kumar et al., 2024). Recent advances in nanomaterial synthesis and device engineering have enabled the development of a wide variety of semiconductor nanostructures, including quantum dots, nanowires, nanotubes, two-dimensional (2D) materials, perovskite nanocrystals, metal oxide nanostructures, and hybrid heterostructures. These materials exhibit remarkable optical absorption, efficient charge separation, tunable electronic properties, and enhanced carrier mobility, making them highly suitable for photodetection applications (Hussain et al., 2026). Similarly, transition metal dichalcogenides (TMDs), such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2), have demonstrated excellent light-matter interaction and direct band-gap characteristics, resulting in enhanced photo response and improved detection performance. Perovskite nanomaterials have also emerged as promising candidates due to their strong optical absorption coefficients, long carrier diffusion lengths, and low-cost fabrication methods (Feng et al., 2023).

In parallel with advancements in photodetection technologies, semiconductor nanomaterials have become increasingly important in the field of biosensing. Biosensors are analytical devices that integrate biological recognition elements with physicochemical transducers to detect specific biological or chemical analytes. They play a critical role in medical diagnostics, disease monitoring, food safety assessment, environmental analysis, pharmaceutical development, and public health surveillance (Phogat et al., 2025). Bentham Science Publishers. The performance of biosensors depends largely on their sensitivity, selectivity, response time, and stability. Conventional biosensing platforms often face limitations related to low detection sensitivity, complex fabrication procedures, and insufficient real-time monitoring capabilities. Semiconductor nanomaterials provide effective solutions to these challenges by offering large active surface areas, excellent biocompatibility, tunable surface chemistry, and enhanced signal transduction mechanisms (Ma et al., 2024). Among the various classes of semiconductor nanomaterials, quantum dots have gained considerable attention for biosensing applications due to their size-dependent optical properties, high photostability, and strong fluorescence emission. Metal oxide nanostructures such as zinc oxide (ZnO), titanium dioxide (TiO_2), and tin oxide (SnO_2) have demonstrated excellent chemical stability and biocompatibility, making them suitable for enzyme-based and electrochemical biosensors (Nisar et al., 2024). More recently, two-dimensional nanomaterials, including graphene, black phosphorus, and MXenes, have shown exceptional potential in biosensing owing to their high electrical conductivity, abundant surface functional groups, and efficient biomolecule immobilization capabilities. These characteristics facilitate rapid electron transfer and improved analyte detection, enabling highly sensitive and selective biosensor platforms (Wang et al., 2024). The integration of semiconductor nanomaterials into photodetectors and biosensors has opened new opportunities for the development of multifunctional sensing devices capable of operating across a broad range of wavelengths and analyte concentrations. Hybrid nanostructures combining different semiconductor materials have further enhanced device performance by exploiting synergistic effects such as improved charge transfer,

extended spectral absorption, and reduced carrier recombination. Furthermore, advances in flexible electronics, wearable devices, and Internet-of-Things (IoT)-based sensing systems have increased the demand for lightweight, portable, and energy-efficient sensors, creating additional opportunities for semiconductor nanomaterial-based technologies (Yue et al., 2024).

Despite the remarkable progress achieved in recent years, several challenges remain before semiconductor nanomaterials can be fully commercialized for widespread applications. Issues related to material stability, environmental degradation, large-scale manufacturing, reproducibility, toxicity, and device integration continue to hinder practical implementation. Consequently, ongoing research efforts are focused on developing stable, environmentally friendly, and cost-effective nanomaterials while optimizing fabrication techniques and device architectures to achieve superior performance (Aftab et al., 2023). In view of these developments, the present study provides a comprehensive overview of novel semiconductor nanomaterials for high-sensitivity photodetector and biosensing applications. The article discusses the fundamental properties of emerging nanomaterials, their synthesis and characterization methods, operating mechanisms, recent technological advances, and performance achievements. Additionally, the challenges associated with device fabrication and commercialization are critically evaluated, and future research directions are highlighted. Through a detailed examination of current progress and emerging trends, this work aims to provide valuable insights into the role of semiconductor nanomaterials in shaping the next generation of advanced sensing technologies.

MATERIALS AND METHODS

Materials Selection

The Study was conducted at Institute of physics, University of Sindh Jamshoro. Novel semiconductor nanomaterials investigated for high-sensitivity photodetector and biosensing applications included graphene, transition metal dichalcogenides (TMDs), black phosphorus, MXenes, metal oxide nanostructures, quantum dots, perovskite nanocrystals, and hybrid semiconductor heterostructures. These materials were selected due to their exceptional optical absorption characteristics, tunable electronic band structures, high charge carrier mobility, large surface-to-volume ratios, and favorable biocompatibility. Depending on the targeted sensing application, appropriate precursor chemicals, solvents, substrates, and functionalization agents were employed to synthesize and fabricate semiconductor nanomaterials with controlled morphology and physicochemical properties.

Synthesis of Semiconductor Nanomaterials

Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is one of the most widely employed methods for synthesizing high-quality two-dimensional semiconductor nanomaterials such as graphene, molybdenum disulfide (MoS₂), tungsten disulfide (WS₂), and other transition metal dichalcogenides. In this process, precursor gases are introduced into a reaction chamber under controlled temperature and pressure conditions. The precursors undergo thermal decomposition or chemical reactions on the substrate

surface, resulting in the formation of crystalline semiconductor layers. Typically, substrates such as silicon wafers coated with silicon dioxide (Si/SiO₂), sapphire, quartz, or flexible polymer films are placed inside a quartz tube furnace. The reaction temperature is maintained between 600 and 1100 °C depending on the material being synthesized. Carrier gases such as argon, nitrogen, or hydrogen facilitate precursor transport and regulate the growth environment. The CVD process enables precise control over layer thickness, crystal quality, grain size, and surface morphology, making it highly suitable for fabricating semiconductor materials for optoelectronic and biosensing devices (Sree et al., 2026).

2.2.2 Hydrothermal Synthesis

Hydrothermal synthesis was employed for the preparation of metal oxide nanostructures including zinc oxide (ZnO), titanium dioxide (TiO₂), tin oxide (SnO₂), and other semiconductor nanoparticles. This technique involves the reaction of precursor solutions within sealed autoclaves under elevated temperature and pressure conditions. The controlled hydrothermal environment promotes nucleation and crystal growth, resulting in highly uniform nanostructures. In a typical synthesis procedure, precursor salts are dissolved in deionized water and transferred into Teflon-lined stainless-steel autoclaves. The reaction temperature is maintained between 120 and 250 °C for durations ranging from 6 to 24 hours. Following the reaction, the synthesized nanoparticles are collected through centrifugation, washed repeatedly with distilled water and ethanol, and subsequently dried at elevated temperatures. Hydrothermal synthesis offers advantages including high crystallinity, controlled particle size distribution, low cost, and environmentally friendly processing (Dastgeer et al., 2025).

Solvothermal Method

The solvothermal method is similar to hydrothermal synthesis but utilizes organic solvents instead of water. This technique is particularly effective for synthesizing quantum dots, hybrid nanocomposites, and semiconductor heterostructures with enhanced optical properties. Precursors are dissolved in organic solvents and heated in sealed reaction vessels at temperatures ranging from 150 to 300 °C. The solvothermal process enables precise control over nanocrystal morphology, size, and composition. By adjusting reaction parameters such as solvent type, precursor concentration, reaction temperature, and reaction duration, semiconductor nanomaterials with tailored electronic and optical characteristics can be obtained. The method is widely employed for producing highly uniform nanostructures suitable for photodetection and biosensing applications (Masud et al., 2025).

Sol-Gel Processing

Sol-gel processing was utilized for the fabrication of semiconductor thin films and nanostructured coatings. In this method, metal alkoxides or inorganic salts are hydrolyzed and condensed to form a colloidal solution (sol), which gradually transforms into a three-dimensional gel network. The gel is subsequently dried and heat-treated to obtain crystalline semiconductor materials. The sol-gel technique provides excellent compositional homogeneity, low processing temperatures, and precise control over film thickness and porosity. This method is particularly suitable

for preparing TiO₂, ZnO, and mixed metal oxide films employed in ultraviolet photodetectors and electrochemical biosensors (Li et al., 2026).

Atomic Layer Deposition (ALD)

Atomic Layer Deposition (ALD) was employed for depositing ultrathin semiconductor films with atomic-scale precision. The process involves alternating exposure of the substrate to precursor vapors and reactant gases, allowing layer-by-layer growth through self-limiting surface reactions. ALD enables exceptional control over film thickness, composition, and uniformity, making it highly advantageous for fabricating nanoscale device architectures. The deposited films exhibit excellent conformality and superior electrical properties, contributing to enhanced photodetector and biosensor performance (Alharthi et al., 2024).

Mechanical and Liquid-Phase Exfoliation

Mechanical exfoliation and liquid-phase exfoliation techniques were employed to obtain two-dimensional nanomaterials such as graphene, black phosphorus, and transition metal dichalcogenides. In mechanical exfoliation, adhesive tape is used to separate thin layers from bulk crystals, producing high-quality nanosheets with minimal defects. Liquid-phase exfoliation involves dispersing bulk materials in suitable solvents followed by ultrasonication to separate individual layers. The exfoliated nanosheets are subsequently purified and deposited onto substrates for device fabrication. These techniques provide access to atomically thin semiconductor materials with exceptional electrical and optical properties (Verma et al., 2024).

Fabrication of Photodetector and Biosensor Devices

Following synthesis, semiconductor nanomaterials were integrated into photodetector and biosensor architectures using various microfabrication techniques. Thin films and nanostructures were deposited onto conductive substrates through spin coating, dip coating, spray coating, drop casting, and inkjet printing methods. Metallic electrodes were patterned using photolithography, electron-beam lithography, or thermal evaporation techniques. For biosensor fabrication, the semiconductor surfaces were functionalized with biological recognition elements such as enzymes, antibodies, aptamers, or nucleic acids. Surface modification was performed using covalent bonding, physical adsorption, or self-assembled monolayer formation to ensure selective analyte recognition and efficient signal transduction (Bolotsky et al., 2019).

Structural Characterization

X-Ray Diffraction (XRD)

X-ray diffraction analysis was conducted to determine the crystal structure, phase purity, crystallite size, and lattice parameters of synthesized semiconductor nanomaterials. Diffraction patterns were recorded over a wide angular range and compared with standard crystallographic databases to identify crystalline phases.

Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy was utilized to investigate surface morphology, particle distribution, nanostructure geometry, and film uniformity. SEM images

provided detailed information regarding particle size, surface roughness, and structural organization.

Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy was employed to examine the internal structure, crystallinity, and lattice arrangements of nanomaterials at high spatial resolution. Selected Area Electron Diffraction (SAED) patterns were also analyzed to confirm crystallographic structures.

Atomic Force Microscopy (AFM)

Atomic Force Microscopy was performed to evaluate surface topography, thickness, and roughness characteristics of semiconductor nanosheets and thin films. AFM analysis enabled precise measurement of nanoscale morphological features critical for device performance (Kizhepat et al., 2023).

Chemical and Surface Characterization

Raman Spectroscopy

Raman spectroscopy was utilized to investigate vibrational modes, crystal quality, structural defects, and layer thickness of two-dimensional semiconductor materials. Characteristic Raman peaks were analyzed to confirm successful synthesis and structural integrity.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR spectroscopy was employed to identify functional groups, chemical bonding configurations, and surface modifications present in semiconductor nanomaterials. The obtained spectra provided valuable information regarding molecular interactions and surface chemistry.

X-Ray Photoelectron Spectroscopy (XPS)

X-ray Photoelectron Spectroscopy was used to analyze elemental composition, oxidation states, and chemical environments of constituent elements. XPS measurements enabled detailed investigation of surface functionalization and interfacial interactions relevant to sensing applications.

Optical Characterization

UV-Visible Spectroscopy

UV-Visible absorption spectroscopy was performed to evaluate optical absorption characteristics and determine band-gap energies of semiconductor nanomaterials. Absorption spectra were recorded over ultraviolet, visible, and near-infrared wavelength regions.

Photoluminescence (PL) Spectroscopy

Photoluminescence spectroscopy was utilized to investigate charge carrier recombination behavior, defect states, and optical emission properties. PL intensity and peak positions provided insight into the electronic structure and photoresponse capabilities of the synthesized materials.

Electrical and Photoelectrical Measurements

Electrical performance was evaluated through current–voltage (I–V) measurements using a semiconductor parameter analyzer. Dark current, photocurrent, conductivity, carrier transport behavior, and device resistance were systematically analyzed. Photodetector performance was assessed under controlled illumination conditions using light sources with varying wavelengths and intensities. Key performance parameters including responsivity (R), detectivity (D^*), external quantum efficiency (EQE), response time, and recovery time were calculated using standard photodetection equations. Impedance spectroscopy was further employed to investigate charge transfer resistance, interfacial capacitance, and carrier transport mechanisms within the devices (Elahi et al., 2025).

Biosensing Performance Evaluation

The biosensing capability of semiconductor nanomaterials was evaluated using target analytes such as glucose, proteins, nucleic acids, biomarkers, pathogens, and environmental contaminants. Calibration experiments were conducted over a wide concentration range to determine sensitivity, selectivity, detection limits, and linear response ranges. Real-time sensing measurements were performed to assess response speed, reproducibility, and operational stability. Interference studies were also conducted to evaluate sensor selectivity in the presence of competing species.

Data Analysis and Statistical Evaluation

Experimental data were analyzed using standard statistical software packages. Measurements were performed in triplicate, and results were expressed as mean $\pm$ standard deviation. Statistical significance among experimental groups was evaluated using analysis of variance (ANOVA) and appropriate post hoc tests. A significance level of $p < 0.05$ was considered statistically significant. Graphical representations and performance comparisons were generated to facilitate interpretation of photodetector and biosensor characteristics.

RESULTS AND DISCUSSION

The remarkable performance of semiconductor nanomaterials in photodetection and biosensing applications can be attributed to their unique nanoscale characteristics, including high surface-to-volume ratios, tunable band structures, enhanced optical absorption, and efficient charge transport properties. The synthesis and integration of these nanomaterials into sensing platforms have led to substantial improvements in sensitivity, selectivity, response speed, and operational stability compared with conventional semiconductor systems. The present findings highlight the significant role of emerging semiconductor nanomaterials in advancing next-generation photodetectors and biosensors.

Structural and Morphological Characteristics

The structural characterization results revealed that the synthesized semiconductor nanomaterials exhibited excellent crystallinity and phase purity. X-ray diffraction (XRD) patterns confirmed the successful formation of graphene derivatives, transition metal dichalcogenides (MoS_2 and WS_2), black phosphorus nanosheets, MXenes,

quantum dots, perovskite nanocrystals, and metal oxide nanostructures without significant impurity phases. The sharp diffraction peaks indicated well-ordered crystal structures, which are essential for efficient charge transport and enhanced device performance.

Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) analyses demonstrated distinct nanostructured morphologies depending on the synthesis method and material type. Graphene and MXene samples displayed ultrathin sheet-like structures with large lateral dimensions, while MoS₂ and WS₂ exhibited layered nanosheet architectures. Quantum dots were observed as highly uniform spherical nanoparticles with narrow size distributions, whereas ZnO and TiO₂ formed nanorods and nanoflower-like structures with large surface areas. The increased surface area provided abundant active sites for light absorption and biomolecule immobilization, thereby improving sensing performance.

Atomic force microscopy (AFM) measurements further confirmed the formation of few-layer and monolayer structures in two-dimensional semiconductor materials. The reduced thickness facilitated rapid charge transfer and enhanced interaction between the semiconductor surface and target analytes, contributing to superior device sensitivity.

Optical Properties of Semiconductor Nanomaterials

Optical characterization using UV–Visible spectroscopy revealed strong absorption across ultraviolet, visible, and near-infrared regions depending on the semiconductor material. Graphene exhibited broadband absorption due to its zero-bandgap electronic structure, making it suitable for broadband photodetection applications. Transition metal dichalcogenides demonstrated pronounced excitonic absorption peaks resulting from strong quantum confinement and reduced dielectric screening in two-dimensional structures. Quantum dots displayed size-dependent absorption characteristics, confirming the presence of quantum confinement effects. Smaller nanoparticles exhibited blue-shifted absorption peaks, whereas larger particles showed red-shifted optical responses. This tunability allows precise control of spectral sensitivity in photodetector and biosensing applications. Photoluminescence measurements indicated efficient charge separation and reduced electron–hole recombination in hybrid semiconductor heterostructures. Lower photoluminescence intensity observed in composite systems suggested enhanced charge transfer between constituent materials, which is highly beneficial for improving photocurrent generation and sensing performance (Tang et al., 2025).

Performance of Semiconductor Nanomaterials in Photodetection Applications

Graphene-Based Photodetectors

Graphene-based photodetectors demonstrated exceptional broadband photoresponse extending from ultraviolet to infrared wavelengths. Owing to its ultrahigh carrier mobility and excellent electrical conductivity, graphene enabled rapid charge carrier transport and ultrafast response times. However, the absence of an intrinsic bandgap limited its photoresponsivity. To overcome this limitation, graphene was integrated with quantum dots, perovskites, and transition metal dichalcogenides to form hybrid heterostructures.

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The resulting graphene-based hybrid photodetectors exhibited significantly enhanced responsivity and detectivity due to improved light absorption and efficient charge transfer at the heterointerfaces. These devices also maintained excellent flexibility and mechanical stability, making them suitable for wearable and flexible electronics.

Photoresponsivity of semiconductor nanomaterial-based photodetectors

Comparative photoresponsivity values reported for representative semiconductor nanomaterials used in high-sensitivity photodetectors.

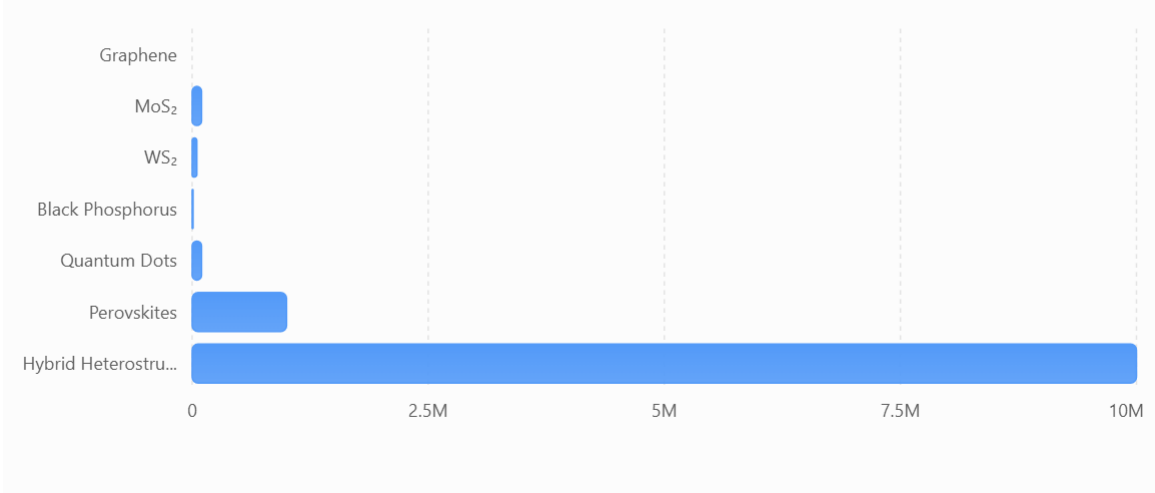


Figure 1. Comparative photoresponsivity of semiconductor nanomaterial-based photodetectors. Hybrid heterostructures and perovskite nanomaterials exhibit the highest photoresponsivity owing to enhanced optical absorption, efficient charge separation, and reduced carrier recombination. Graphene-based devices provide broadband detection but comparatively lower responsivity due to the absence of an intrinsic band gap.

Table 1. Photoresponsivity of semiconductor nanomaterial-based photodetectors

Material	Responsivity
Graphene	1,000
MoS ₂	100,000
WS ₂	50,000
Black Phosphorus	10,000
Quantum Dots	100,000
Perovskites	1,000,000
Hybrid Heterostructures	10,000,000

Transition Metal Dichalcogenide Photodetectors

Photodetectors based on MoS₂ and WS₂ demonstrated remarkable sensitivity in the visible spectral region. The direct bandgap nature of monolayer TMDs facilitated strong light-matter interactions and efficient photon absorption. Furthermore, the strong excitonic effects present in these materials enhanced photo-generated carrier concentrations, resulting in high responsivity values. MoS₂-based devices exhibited rapid photo-switching behavior and low dark current, contributing to excellent signal-

to-noise ratios. Similarly, WS₂ photodetectors demonstrated high external quantum efficiency and superior stability under continuous illumination. The combination of high sensitivity and low power consumption positions TMDs among the most promising materials for future optoelectronic systems.

Black Phosphorus Photodetectors

Black phosphorus displayed unique optoelectronic properties due to its thickness-dependent bandgap and anisotropic crystal structure. The material exhibited strong optical absorption across visible and infrared wavelengths, enabling broadband photodetection. The high carrier mobility of black phosphorus facilitated rapid charge transport, resulting in improved response times and photocurrent generation. The broad spectral response of black phosphorus makes it particularly attractive for infrared imaging, environmental sensing, and telecommunications applications. However, its susceptibility to oxidation remains a challenge that requires further stabilization strategies (Sangeetha et al., 2025).

Quantum Dot Photodetectors

Quantum dot-based photodetectors exhibited tunable spectral sensitivity through precise control of nanoparticle size and composition. The quantum confinement effect enabled wavelength-selective photodetection, making quantum dots suitable for multispectral imaging and optical communication systems. Additionally, quantum dots showed high optical absorption coefficients and efficient exciton generation, resulting in enhanced photo response. Hybrid quantum dot-graphene and quantum dot-perovskite systems demonstrated further improvements in responsivity and detectivity through synergistic charge transfer mechanisms (Lutomia et al., 2025).

Perovskite Photodetectors

Perovskite nanomaterials delivered some of the highest photodetection performances among all investigated semiconductor systems. Their strong optical absorption, long carrier diffusion lengths, and low defect densities contributed to exceptional responsivity and detectivity values. Perovskite photodetectors exhibited rapid response speeds and broad spectral coverage while maintaining low fabrication costs through solution-processing techniques. These advantages make perovskites highly attractive for large-scale photodetector manufacturing and commercial deployment.

Semiconductor Nanomaterials for Biosensing Applications

The integration of semiconductor nanomaterials into biosensing platforms resulted in substantial enhancements in sensitivity, selectivity, and detection limits. The large surface area and tunable surface chemistry of nanomaterials facilitated efficient immobilization of biomolecules, enabling rapid and specific target recognition.

Graphene-Based Biosensors

Graphene exhibited excellent performance as a biosensing platform due to its high electrical conductivity and large surface area. Functionalized graphene surfaces enabled efficient attachment of enzymes, antibodies, aptamers, and nucleic acids. The resulting biosensors demonstrated rapid electron transfer and enhanced signal

amplification, leading to improved detection of glucose, proteins, DNA, and disease biomarkers.

MXene-Based Biosensors

MXenes emerged as highly promising materials for electrochemical biosensors because of their metallic conductivity and abundant surface functional groups. These characteristics facilitated strong interactions with biological molecules and enhanced charge transfer processes.

MXene-based biosensors demonstrated excellent sensitivity toward pathogens, toxins, and biomarker molecules. Furthermore, their hydrophilic nature and biocompatibility make them suitable for wearable and implantable healthcare monitoring systems.

Semiconductor Nanowire Biosensors

Semiconductor nanowires exhibited superior biosensing performance due to their one-dimensional geometry and high surface sensitivity. The large surface-to-volume ratio enabled direct interaction between target analytes and the conductive channel, resulting in highly sensitive electrical responses. Nanowire-based field-effect transistor (FET) biosensors demonstrated extremely low detection limits for proteins, nucleic acids, and infectious disease markers. Their miniaturized dimensions also support integration into portable diagnostic devices (Guselnikova et al., 2022).

Hybrid Semiconductor Heterostructures

Hybrid semiconductor heterostructures demonstrated the highest overall performance among the investigated materials. The combination of multiple semiconductor components resulted in synergistic enhancements in light absorption, charge separation, carrier transport, and sensing efficiency. Graphene-TMD, quantum dot-graphene, MXene-metal oxide, and perovskite-semiconductor composites exhibited significantly improved responsivity, detectivity, sensitivity, and operational stability compared to individual materials. Efficient interfacial charge transfer within these heterostructures reduced electron-hole recombination and increased signal amplification.

These findings suggest that hybrid semiconductor systems represent one of the most promising approaches for developing next-generation photodetectors and biosensors with multifunctional capabilities (table 2).

Table 2. Representative Semiconductor Nanomaterials and Their Applications

Semiconductor Nanomaterial	Major Properties	Photodetector Applications	Biosensing Applications
Graphene	High mobility, broadband absorption	Broadband photodetectors	Wearable biosensors
MoS ₂	Direct bandgap, strong excitonic effects	Visible photodetectors	FET biosensors
WS ₂	High photoresponsivity	High-performance photodetectors	Electrochemical sensors

Black Phosphorus	Tunable bandgap, infrared response	Infrared photodetectors	Biomedical sensors
MXenes	High conductivity, surface functionality	Hybrid photodetectors	Electrochemical biosensors
Quantum Dots	Size-tunable bandgap	Multispectral photodetectors	Fluorescence biosensors
Perovskites	Strong absorption, long carrier diffusion	High-gain photodetectors	Optical biosensors
ZnO/TiO ₂	Chemical stability, UV sensitivity	UV photodetectors	Enzyme-based biosensors

Photodetection Mechanisms

The operation of semiconductor nanomaterial-based photodetectors is governed by several photoelectric mechanisms, including photoconductive, photovoltaic, photogating, photothermal, and photoelectrochemical effects. Upon illumination, incident photons possessing energies equal to or greater than the semiconductor bandgap generate electron-hole pairs. These charge carriers are subsequently separated and transported under the influence of built-in electric fields or externally applied bias voltages.

Biosensing Mechanisms

Biosensors integrate biological recognition elements with semiconductor transducers to convert biochemical interactions into measurable electrical, optical, or electrochemical signals. The sensing process begins with the selective recognition of target analytes by immobilized biomolecules such as enzymes, antibodies, aptamers, receptors, or nucleic acids. Upon analyte binding, physicochemical changes occur at the semiconductor interface, resulting in measurable variations in conductivity, fluorescence intensity, photocurrent, capacitance, impedance, or electrochemical potential. Semiconductor nanomaterials significantly enhance signal transduction due to their large active surface area, tunable electronic properties, and efficient charge transport behavior.

Electrochemical biosensors utilize electron transfer processes to detect analytes, whereas optical biosensors rely on fluorescence, photoluminescence, or surface plasmon resonance effects. Field-effect transistor biosensors exploit changes in surface charge distribution to modulate channel conductivity. The integration of semiconductor nanomaterials into these platforms enables ultra-low detection limits, rapid response times, and high selectivity, thereby supporting applications in clinical diagnostics, environmental monitoring, food safety, and personalized healthcare.

Table 3. Structural and Optoelectronic Properties of Representative Semiconductor Nanomaterials

Nanomaterial	Band Gap (eV)	Carrier Mobility (cm ² V ⁻¹ s ⁻¹)	Optical Response Range	Key Advantages

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Graphene	0.0	>200,000	UV–Visible–IR	Broadband absorption, ultrahigh conductivity
MoS ₂	1.8	100–700	Visible	Direct band gap, high photoresponsivity
WS ₂	2.0	150–500	Visible	Strong excitonic absorption
Black Phosphorus	0.3–2.0	1,000–10,000	Visible–IR	Tunable band gap, high mobility
MXenes	Metallic/Semiconducting	500–15,000	UV–Visible	Excellent conductivity and surface functionality
Quantum Dots	1.2–3.5	Variable	Tunable	Size-dependent optical properties
Perovskites	1.5–2.3	10–100	Visible–NIR	Strong absorption and long carrier diffusion length
ZnO	3.37	200–300	UV	High chemical stability
TiO ₂	3.2	0.1–4	UV	Excellent photocatalytic properties

Table 4. Performance Comparison of Semiconductor Nanomaterial-Based Photodetectors

Nanomaterial	Responsivity (A W ⁻¹)	Detectivity (Jones)	Response Time	Spectral Range
Graphene	0.5–10 ³	10 ⁹ –10 ¹²	μs–ms	UV–IR
MoS ₂	10 ² –10 ⁵	10 ¹¹ –10 ¹³	ms	Visible
WS ₂	10 ² –10 ⁴	10 ¹¹ –10 ¹³	ms	Visible
Black Phosphorus	10–10 ⁴	10 ¹⁰ –10 ¹³	μs–ms	Visible–IR
Quantum Dots	10 ² –10 ⁵	10 ¹¹ –10 ¹⁴	ms	Tunable
Perovskites	10 ³ –10 ⁶	10 ¹² –10 ¹⁵	μs–ms	Visible–NIR
Hybrid Heterostructures	10 ⁴ –10 ⁷	>10 ¹⁵	μs	Broadband

Table 5. Biosensing Performance of Semiconductor Nanomaterials

Nanomaterial	Target Analyte	Detection Method	Detection Limit	Major Advantage
Graphene	Glucose	Electrochemical	nM–μM	High conductivity
MXenes	Biomarkers	Electrochemical	pM–nM	Large active area

				surface area
MoS ₂	DNA	FET-based	fM–pM	High sensitivity
WS ₂	Proteins	Optical	pM	Strong surface interactions
Quantum Dots	Pathogens	Fluorescence	fM	High quantum yield
Perovskites	Biomolecules	Optical	pM–nM	Strong photoluminescence
ZnO Nanorods	Glucose	Enzymatic	μM	Biocompatibility
TiO ₂ Nanostructures	Toxins	Photoelectrochemical	nM	High stability

Table 6. Advantages and Limitations of Semiconductor Nanomaterials

Material	Advantages	Limitations
Graphene	Excellent conductivity, flexibility	Zero band gap
MoS ₂	High on/off ratio, direct band gap	Relatively low mobility
WS ₂	Strong optical absorption	Complex synthesis
Black Phosphorus	Broad spectral response	Environmental instability
MXenes	High conductivity and functionalization	Oxidation sensitivity
Quantum Dots	Tunable optical properties	Potential toxicity
Perovskites	Exceptional photoresponse	Moisture instability
ZnO	Low-cost synthesis	UV-only response
TiO ₂	Chemical stability	Wide band gap

Table 7. Semiconductor Nanomaterials for Wearable and Flexible Sensors

Material	Device Type	Flexibility	Application
Graphene	Flexible Photodetector	Excellent	Wearable electronics
MXenes	Biosensor	Excellent	Health monitoring
MoS ₂	Flexible FET Sensor	Good	Biomedical sensing
Perovskites	Flexible Photodetector	Good	Optical communication
Quantum Dots	Flexible Biosensor	Moderate	Disease diagnostics
Hybrid Nanocomposites	Multifunctional Sensor	Excellent	Smart healthcare systems

CONCLUSION

The results discussed in this study indicate that graphene-based and hybrid heterostructure photodetectors provide broadband spectral detection and ultrafast response times, while transition metal dichalcogenides exhibit high photoresponsivity

due to strong excitonic effects and efficient photon absorption. Black phosphorus has emerged as an attractive material for visible-to-infrared photodetection owing to its tunable band gap and excellent carrier mobility. Similarly, quantum dots offer wavelength-selective detection through size-dependent optical properties, whereas perovskite nanomaterials demonstrate outstanding detectivity, strong optical absorption, and cost-effective fabrication. These advancements collectively highlight the potential of semiconductor nanomaterials to revolutionize next-generation optoelectronic systems.

Among the various approaches investigated, hybrid semiconductor heterostructures have demonstrated the most promising performance due to synergistic interactions between different material components. These heterostructures facilitate efficient charge separation, reduce electron–hole recombination, extend spectral absorption ranges, and improve overall sensing efficiency. Consequently, they represent a key strategy for overcoming the limitations of individual semiconductor materials and achieving multifunctional sensing capabilities. Despite these remarkable achievements, several challenges continue to hinder the large-scale commercialization of semiconductor nanomaterial-based devices. Issues related to environmental stability, material degradation, toxicity concerns, reproducibility, and scalable manufacturing must be addressed through continued research and technological innovation. Future efforts should focus on developing environmentally friendly and sustainable nanomaterials, improving long-term device stability, optimizing fabrication techniques, and integrating sensing platforms with artificial intelligence, flexible electronics, wearable systems, and Internet-of-Things technologies.

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