International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Carbon-Based Nanomaterials in Next-Generation Semiconductor Technologies: From Fundamental Mechanisms to Sustainable Bioelectronics and Translational Life Science Applications

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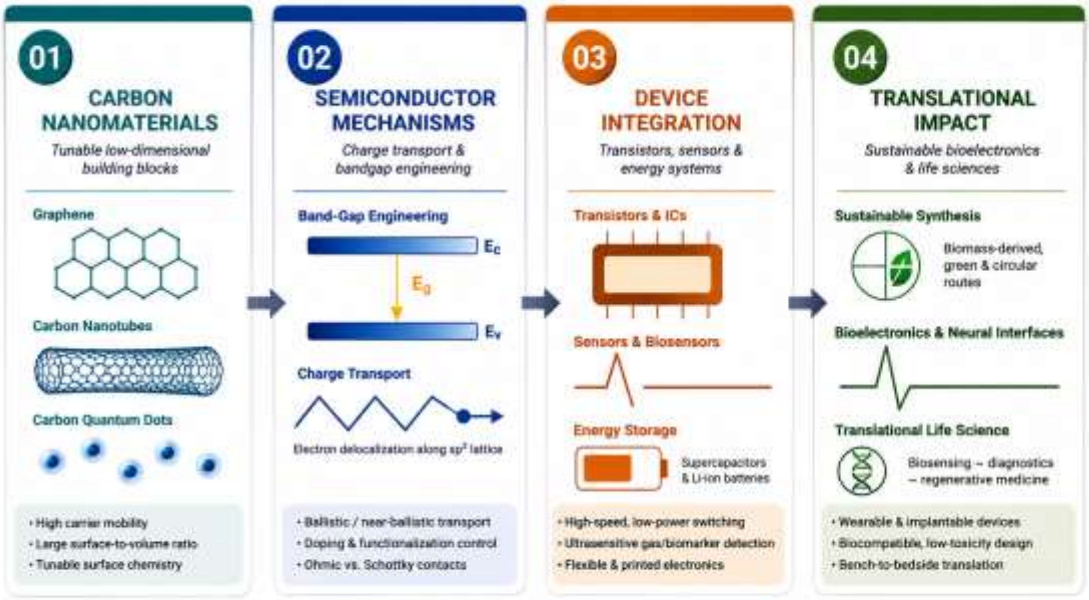
Abstract
Carbon-based nanomaterials have emerged as key functional materials for next-generation semiconductor technologies owing to their exceptional electrical conductivity, high carrier mobility, mechanical robustness, thermal stability, and tuneable electronic characteristics. Materials such as graphene, carbon nanotubes, fullerenes, graphene derivatives, and carbon quantum dots are increasingly being explored to overcome the performance limitations of conventional semiconductor systems and to enable miniaturized, energy-efficient, and multifunctional electronic devices. This review examines the fundamental mechanisms governing the integration of carbon-based nanomaterials into semiconductor architectures, with particular emphasis on charge transport, bandgap engineering, interface modulation, heterostructure design, and advanced fabrication strategies. Recent developments in transistors, sensors, optoelectronic devices, energy storage systems, printed electronics, and flexible platforms are critically discussed. The review further highlights emerging opportunities in sustainable bioelectronics through the use of biomass-derived carbon nanomaterials, green synthesis approaches, wearable biosensors, biomedical diagnostics, and environmentally responsible electronic systems, demonstrating their growing relevance to translational life science applications. Current challenges, including scalable synthesis, structural reproducibility, contact resistance, CMOS compatibility, manufacturing cost, and environmental safety, are also evaluated. By integrating advances in materials science, semiconductor engineering, sustainable bioelectronics, and life sciences, this review provides a multidisciplinary framework for the development of intelligent, high-performance, and environmentally sustainable electronic technologies.

Keywords: Carbon-based nanomaterials, next-generation semiconductor technologies, sustainable bioelectronics, graphene, carbon nanotubes, translational life science applications.



Graphical Abstract. Carbon nanomaterials as enabling platforms for semiconductor technologies: from low-dimensional carbon nanostructures and charge-transport mechanisms to device integration and translational applications.

1. Introduction

The recent rapid evolution of semiconductor technology has formed the basis of modern electronic devices and has rendered advancements in energy systems, computing, communication, and sensing possible. The electronics world had been dominated by traditional semiconductor materials such as silicon (Si) and germanium (Ge) due to their stable electrical characteristics and established fabrication manufacturing processes over many years (Kolahdouz et al., 2022). Traditional materials are incapable of meeting the needs of higher speed, lower power consumption and smaller device scaling as they approach both the physical and quantum limits set by Moore's law (Sengupta & Hussain, 2023). To counter these limitations, the scientific community has shifted its focus to new low-dimensional materials. Carbon-based nanomaterials, including graphene, carbon nanotubes (CNTs), fullerenes, and carbon quantum dots, have been of great interest due to their remarkable electrical, mechanical, thermal and optical properties (Kolahdouz et al., 2022). These materials can be used in next-generation semiconductor applications because of their special properties, such as high carrier mobility, ballistic electron transport, enormous surface area and tunable electronic architectures (Nandan et al., 2023). Due to its outstanding electron mobility and conductivity, graphene, which is a single sheet of carbon atoms arranged in a hexagonal structure, is of particular interest in the form of a two-dimensional (2D) sheet (Roy et al., 2024). Carbon nanotubes are 1D (one-dimensional) tube structures constructed of rolled graphene sheets, which have high current-carrying capacity and near-ballistic transport (Tao et al., 2024). These properties place carbon nanomaterials at a vantage to either supplement or displace silicon in nanoscale electronics such as optoelectronic systems, sensors and field-effect transistors (FETs) (Zhu et al., 2024). Band structure and interface characteristics governing charge transport in semiconductor technology are significant factors in device performance. The customizable bandgap achieved through chemical functionalization, doping and structural manipulation enables carbon nanomaterials to tune their electrical behavior, and their reduced dimensionality gives them better electrostatic control in transistors. Carbon nanomaterials are capable of forming effective heterojunctions with conventional semiconductors, thereby improving device performance in solar cells, biosensors and photodetectors (Kolahdouz et al., 2022; Sengupta & Hussain, 2023; Nandan et al., 2023; Roy et al., 2024). Recent progress in hybrid nanostructures and two-dimensional semiconductor systems has accelerated the incorporation of carbon nanomaterials into state-of-the-art electronic devices. These materials allow the creation of ultra-thin, flexible and energy-efficient components that form the core of modern technologies such as wearable electronics, Internet of Things (IoT) devices and quantum computing platforms (Kolahdouz et al., 2022; Sengupta & Hussain, 2023; Tao et al., 2024). Various concerns have hindered the extensive application of carbon-based nanomaterials in semiconductor technology, although the potential is extraordinary. These concerns include scalability issues, reproducibility issues, controlled synthesis, and compatibility with existing silicon-based manufacturing methods. Practical device applications are also greatly hindered by issues such as the absence of an intrinsic band gap in graphene and uncertainty regarding CNT properties (Kolahdouz et al., 2022; Nandan et al., 2023; Zhu et al., 2024). Thus, next-generation electronic devices can only be developed through a proper understanding of the role of carbon-based nanomaterials in semiconductor technology. Besides shedding light on various current problems and possible development paths, this review is also an objective study of the nature, mechanism, production technology and application of carbon nanomaterials in semiconductor systems.

2. Overview of Carbon-Based Nanomaterials

A broad and quickly developing family of sophisticated materials, carbon-based nanomaterials (CBNs) are mostly made up of carbon atoms organized at the nanoscale. Because of their distinct electrical structure, high surface-to-volume ratio, and adjustable physicochemical characteristics, CBNs have become important materials in a variety of fields, from biomedicine and environmental cleanup to nanoelectronics and energy storage. The predominance of sp^2-hybridized carbon frameworks, which support delocalized π-electron systems and permit outstanding electrical, thermal, and mechanical properties, is largely responsible for these materials' exceptional performance (Tundwal et al., 2024; Jiang et al., 2023). Furthermore, by allowing control over surface chemistry and structural flaws, new developments in synthesis and functionalization have increased their usefulness (Kogan, 2022).

2.1. Classification of Carbon-Based Nanomaterials

Based on their dimensionality, carbon-based nanomaterials are typically divided into three categories: zero-dimensional (0D), one-dimensional (1D), and two-dimensional (2D) nanostructures. Their physicochemical behavior and possible applications are largely determined by this classification.

2.1.1. Graphene

A single sheet of sp^2-hybridized carbon atoms organized in a hexagonal lattice makes up graphene, the archetypal two-dimensional (2D) nanomaterial. It is the basic component of other carbon nanostructures, such as fullerenes and carbon nanotubes (CNTs) (Kogan, 2022). Graphene has exceptional mechanical strength, high electrical conductivity, remarkable thermal conductivity (2000-5000 W m^{-1} K^{-1}), and very high carrier mobility (Li et al., 2021; Balandin, 2011). It is ideal for use in sensors, supercapacitors, and catalytic systems due to its huge specific surface area and chemical stability (Kogan, 2022; Sun et al., 2025).

2.1.2. Carbon Nanotubes (CNTs)

Graphene sheets are rolled into one-dimensional (1D) cylindrical nanostructures called carbon nanotubes.

Depending on the number of concentric layers they have, they are divided into single-walled (SWCNTs) and multi-walled (MWCNTs) nanotubes. CNTs have outstanding electrical and thermal conductivity, a high aspect ratio, and remarkable tensile strength (Balandin, 2011; Xing et al., 2024). Crucially, their diameter and chirality determine their electrical characteristics, allowing them to function as either semiconducting or metallic materials (Li et al., 2021). Because of these qualities, CNTs are very appealing for use in energy storage devices, nanocomposite reinforcement, and nanoelectronics (Li et al., 2021; Balandin, 2011; Xing et al., 2024).

2.1.3. Fullerenes

The zero-dimensional (0D) nanostructures known as fullerenes are made up of carbon atoms organized in closed-cage forms such as C_{60} and C_{70}. These molecules have spherical or ellipsoidal shapes composed of pentagonal and hexagonal rings. Applications in organic photovoltaics, drug delivery systems, and antioxidant therapies benefit from fullerenes' special electron-accepting qualities and high chemical reactivity (Si et al., 2024). Their adaptability in electronic and biomedical applications is further increased by their capacity to undergo functionalization.

2.1.4. Carbon Quantum Dots (CQDs)

Carbon quantum dots (CQDs), which are quasi-spherical nanoparticles usually less than 10 nm in size, exhibit intense photoluminescence because of quantum confinement and surface defect states. Their excellent water solubility, low toxicity, and tunable optical properties make them suitable for optoelectronic, bioimaging, and sensing applications (Zhou et al., 2025; Xiao et al., 2023). Recent advances have focused on green synthesis methods and surface passivation techniques to improve their quantum yield and stability (Narayan & Bezborah, 2024).

2.1.5. Graphene Oxide (GO) and Reduced Graphene Oxide (rGO)

Graphene oxide (GO) is an oxidized derivative of graphene containing oxygen-based functional groups such as hydroxyl, epoxy, and carboxyl groups. These functionalities significantly enhance its chemical reactivity and dispersibility in aqueous media. Reduced graphene oxide (rGO), obtained through thermal or chemical reduction of GO, partially restores the sp^2 carbon network and improves electrical conductivity while retaining some structural defects (Kogan, 2022). Because of their tunable surface chemistry, GO and rGO have been widely investigated for environmental remediation, catalysis, and energy storage applications (Li et al., 2023).

2.2. Structural Features of Carbon-Based Nanomaterials

The remarkable physicochemical properties of carbon-based nanomaterials (CBNs) are fundamentally governed by their structural characteristics. Their dimensionality, hybridization state, crystal arrangement, defect density, and surface functionalization collectively determine their electrical, mechanical, thermal, and optical behavior. A thorough understanding of these structural features is essential for tailoring CBNs for semiconductor and nanoelectronic applications (Tundwal et al., 2024; Kogan, 2022).

2.2.1. Dimensionality

Carbon-based nanomaterials are classified according to their dimensionality into zero-dimensional (0D), one-dimensional (1D), and two-dimensional (2D) structures. Carbon quantum dots and fullerenes belong to the 0D category, carbon nanotubes represent 1D nanostructures, while graphene and graphene derivatives are typical 2D materials. The dimensionality strongly influences electron confinement, charge transport, surface area, and optical characteristics. As dimensionality decreases, quantum confinement effects become increasingly significant, enabling tunable electronic and optical properties suitable for nanoscale semiconductor devices (Kogan, 2022; Li et al., 2021; Zhou et al., 2025).

2.2.2. Carbon Hybridization

The electronic behavior of carbon nanomaterials is largely determined by the hybridization state of carbon atoms. Most carbon nanomaterials are dominated by sp^2 hybridization, in which each carbon atom forms three σ bonds while the remaining p orbital contributes to a delocalized π-electron network. This conjugated structure is responsible for their excellent electrical conductivity and high carrier mobility. In contrast, sp^3 hybridization, observed in diamond and partially oxidized graphene structures, results in insulating characteristics due to the absence of delocalized π electrons. Controlled conversion between sp^2 and sp^3 configurations through functionalization or defect engineering enables tuning of the electronic properties for specific semiconductor applications (Tundwal et al., 2024; Li et al., 2021; Narayan & Bezborah, 2024).

2.2.3. Crystal Structure

Graphene possesses a highly ordered two-dimensional hexagonal honeycomb lattice composed entirely of sp^2-bonded carbon atoms. Carbon nanotubes inherit this lattice by rolling graphene sheets into seamless cylinders whose chirality determines whether the nanotube behaves as a metallic or semiconducting material. Fullerenes consist of closed carbon cages containing pentagonal and hexagonal rings, whereas graphene oxide and reduced graphene oxide possess disrupted graphitic lattices because of oxygen-containing functional groups and structural defects. These crystal structures directly influence charge transport, phonon scattering, and mechanical stability (Li et al., 2021; Balandin, 2011; Li et al., 2023).

2.2.4. Surface Functionalization

Surface functionalization is one of the most effective strategies for modifying the physicochemical properties of carbon nanomaterials. Chemical attachment of functional groups such as hydroxyl, carboxyl, amino, or epoxy groups improves dispersibility, chemical stability, and compatibility with polymers and semiconductor materials. Functionalization also provides active sites for catalytic reactions, biosensing, and biomolecule immobilization while allowing precise control over electronic characteristics through surface engineering (Nandan et al., 2023; Xiao et al., 2023; Narayan & Bezborah, 2024).

2.2.5. Structural Defects

Structural defects, including vacancies, Stone-Wales defects, grain boundaries, and substitutional dopants, significantly influence the electronic and mechanical properties of carbon nanomaterials. Although defects generally reduce carrier mobility and electrical conductivity, they often enhance catalytic activity, chemical reactivity, and sensing performance by creating additional active sites. Defect engineering has therefore become an important strategy for optimizing carbon nanomaterials for transistors, sensors, energy storage devices, and optoelectronic systems (Tundwal et al., 2024; Li et al., 2021; Narayan & Bezborah, 2024).

2.3. Key Properties of Carbon-Based Nanomaterials

2.3.1. Electrical Conductivity

Delocalized π-electrons in sp^2-hybridized carbon networks are the main cause of the remarkable electrical conductivity of carbon-based nanomaterials. The extended conjugation of π-electrons in materials like graphene and carbon nanotubes (CNTs) allows for quick charge transport with little dispersion, leading to exceptionally high carrier mobility. Under ideal circumstances, graphene in particular exhibits near-ballistic electron transport and very high carrier mobility (Li et al., 2021). Similarly, depending on their diameter and chirality, CNTs can behave as metals or semiconductors, which makes them extremely adaptable for use in nanoelectronic applications (Balandin, 2011). Additionally, these nanomaterials' electrical characteristics can be adjusted by doping, defect engineering, and surface functionalization, greatly expanding their use in energy storage devices, flexible electronics, and sensors (Jiang et al., 2023; Kogan, 2022). However, interfacial resistance, contaminants, and structural flaws in composite systems can lower total conductivity, reinforcing the significance of regulated synthesis and processing methods.

2.3.2. Thermal Conductivity

The exceptionally high thermal conductivity of carbon nanomaterials, especially graphene and carbon nanotubes (CNTs), is attributed to effective phonon transport over the sp^2-bonded carbon lattice. One of the most thermally conductive materials known is graphene, which has thermal conductivity values between 2000 and 5000 $W\ m^{-1}\ K^{-1}$ (Balandin, 2011). Similarly, because of their strong covalent bonding and one-dimensional structure, CNTs exhibit efficient heat conduction along their axial direction (Balandin, 2011). Carbon nanoparticles are ideal for thermal management applications, including heat sinks, thermal interface materials, and cooling systems in electronic devices, due to their exceptional thermal transfer capabilities. However, in real-world applications, interfacial resistance in composites, grain boundaries, and imperfections frequently affect thermal conductivity (Li et al., 2023). Thus, maximizing thermal performance in composite materials requires optimizing dispersion and alignment.

2.3.3. Mechanical Strength

The strong covalent interaction between carbon atoms in sp^2-hybridized structures gives carbon-based nanomaterials their exceptional mechanical characteristics. With a Young's modulus of about 1 TPa and a tensile strength of about 130 GPa, graphene is regarded as one of the strongest materials ever discovered. Similarly, because of their high aspect ratio and cylindrical form, CNTs have remarkable tensile strength and flexibility (Xing et al., 2024). Because of these characteristics, carbon nanoparticles are well suited for strengthening ceramics, metal matrix composites, and polymers, resulting in improved mechanical performance, durability, and resistance to wear and fracture. They can also be used in flexible electronics and structural materials due to their lightweight nature and flexibility. However, problems including uneven dispersion, poor interfacial bonding, and agglomeration in composite matrices can restrict their efficacy, requiring sophisticated functionalization and processing techniques (Balandin, 2011).

2.3.4. Optical Characteristics

Surface flaws, electronic transitions, and quantum confinement phenomena give carbon-based nanomaterials their distinct optical characteristics. In particular, carbon quantum dots (CQDs) exhibit high photoluminescence with tunable emission wavelengths that are controllable by surface functional groups, particle size, and synthesis techniques (Zhou et al., 2025). Because of these characteristics, CQDs are very appealing for use in light-emitting devices, bioimaging, and sensing. Under some circumstances, graphene and its derivatives, such as graphene oxide (GO) and reduced graphene oxide (rGO), can show intriguing optical behavior, such as broadband absorption, nonlinear optical response, and fluorescence. Photodetectors, solar cells, and optical sensors all make extensive use of these characteristics (Narayan & Bezborah, 2024). Furthermore, these materials' optical performance is further improved by surface modification and heteroatom doping, increasing their potential for use in sophisticated optoelectronic systems (Kogan, 2022; Narayan & Bezborah, 2024).

3. Semiconductor Technology Foundations

Modern electrical and optoelectronic devices, including transistors, solar cells, sensors, LEDs, and integrated circuits, depend heavily on semiconductor technology. Because of their regulated electrical conductivity, conventional semiconductors like silicon (Si) and germanium (Ge) have been employed extensively. However, the creation of sophisticated semiconductor materials has been stimulated by the increasing need for small, flexible, and high-performing electronic devices. Because of their superior electrical, thermal, and optical properties, carbon-based nanomaterials such as graphene, carbon nanotubes (CNTs), carbon quantum dots (CQDs), fullerene, and graphitic carbon nitride (g-C3N4) have drawn a lot of attention (Kolahdouz et al., 2022; Sengupta & Hussain, 2023; Nandan et al., 2023; Kogan, 2022).

3.1. Fundamental Concepts: Band Gap, Charge Carriers, and Mobility

The band structure of semiconductors mostly dictates their electrical activity. The band gap is the energy difference between the conduction and valence bands. Carbon-based nanomaterials can be used in semiconductor applications because of their variable band gaps. For instance, semiconducting carbon nanotubes (CNTs) have variable band gaps based on their structure, whereas graphene has a nearly negligible band gap and extremely high electrical conductivity (Kolahdouz et al., 2022). Electrons and holes are the charge carriers that facilitate electrical conduction. The delocalized π-electrons in the carbon network of graphene and carbon nanotubes (CNTs) provide exceptional charge transfer. Additionally, these materials exhibit extremely high carrier mobility, which enhances switching speed and lowers energy loss in electrical systems (Li et al., 2021). Graphene and carbon nanotubes (CNTs) are attractive materials for nanoelectronics, sensors, and photovoltaic applications due to their high carrier mobility (Balandin, 2011).

3.2. Semiconductor Types: Intrinsic and Extrinsic

There are two types of semiconductors: intrinsic and extrinsic. Pure materials devoid of impurities, such as pure silicon and germanium, are known as intrinsic semiconductors. Thermally produced electron-hole pairs are the primary source of their conductivity (Sengupta & Hussain, 2023). In order to increase conductivity, impurities are added through doping to create extrinsic semiconductors. Excess electrons are found in n-type semiconductors, while excess holes are found in p-type semiconductors (Sengupta & Hussain, 2023). To change their electrical characteristics, carbon nanomaterials can also be doped with elements like phosphorus, boron, and nitrogen. For electronic and energy applications, nitrogen-doped graphene and boron-doped carbon nanotubes exhibit increased conductivity and better semiconductor performance (Sengupta & Hussain, 2023; Nandan et al., 2023; Kogan, 2022; Li et al., 2021).

3.3. Fundamentals of PN Junction

P-type and n-type semiconductors are joined to create a PN junction. An internal electric field and a depletion region are created at the junction as electrons and holes diffuse over the interface. PN junctions are essential parts of solar cells, LEDs, diodes, and transistors. By improving charge transfer, lowering recombination losses, and raising conductivity, carbon-based nanomaterials enhance PN junction performance. Heterojunctions based on graphene and carbon nanotubes are being researched extensively for high-efficiency solar and nanoelectronic devices (Roy et al., 2024).

Conventional semiconductor materials have drawbacks such as heat generation, energy loss, scaling limitations, and mechanical rigidity. Therefore, next-generation electronics require advanced semiconductor materials (Kolahdouz et al., 2022; Sengupta & Hussain, 2023). Carbon-based nanomaterials offer several advantages, including:

- Excellent electrical conductivity
- Outstanding thermal conductivity
- High carrier mobility

- Mechanical flexibility
- Tunable electronic properties
- Capability for nanoscale device fabrication (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024; Kogan, 2022)

For flexible electronics, high-speed transistors, sensors, solar cells, and optoelectronic devices, graphene, carbon nanotubes, and related carbon nanomaterials are ideal due to these unique properties (Kolahdouz et al., 2022; Nandan et al., 2023; Li et al., 2021).

4. Carbon Nanomaterial Integration in Semiconductor Technology

Carbon-based nanomaterials like graphene and carbon nanotubes (CNTs) are frequently utilized in semiconductor technology because of their superior electrical conductivity, high carrier mobility, and nanoscale dimensions. These materials facilitate downsizing in contemporary electronics, enhance device performance, and lower power consumption (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

4.1. Mechanism of Charge Transport

Ballistic Transport in CNTs

Carbon nanotubes exhibit ballistic electron transport, in which electrons move with comparatively little resistance and dispersion. Because of their one-dimensional structure and strong sp^2 carbon bonding, which allow for rapid charge transport, CNTs are ideal for high-speed transistors and nanoelectronic devices. CNT-based field-effect transistors (CNTFETs) show low power loss and high current density when compared to conventional silicon devices (Kim & Kuljanishvili, 2025).

High Carrier Mobility of Graphene

Graphene has very high carrier mobility because of its two-dimensional honeycomb lattice structure. Graphene increases device efficiency and accelerates data transmission by allowing electrons to move through it rapidly with minimal resistance. These characteristics make graphene highly suitable for high-frequency electronic devices, sensors, and next-generation communication systems (Kolahdouz et al., 2022; Li et al., 2021).

4.2. Band Structure Engineering

Bandgap Tuning (Functionalization and Doping)

Enhancing the semiconductor behavior of graphene and carbon nanotubes requires bandgap engineering. The bandgap in graphene can be opened and tuned through chemical functionalization and doping with elements like nitrogen or boron. Similarly, the diameter and chirality of CNTs affect their electrical characteristics. For semiconductor applications, these changes enhance electronic conductivity and switching performance (Manawi et al., 2018).

4.3. Interface Engineering

Semiconductor-Carbon Junctions

When combined with semiconductor materials like silicon, graphene and carbon nanotubes create effective junctions. These interfaces increase the efficiency of electronic devices, lower contact resistance, and facilitate charge transfer. Proper interface engineering is essential for achieving stable and high-performance semiconductor devices (Kolahdouz et al., 2022).

Ohmic vs. Schottky Contacts

Carbon nanomaterials can form either Ohmic or Schottky contacts with semiconductors. Ohmic contacts provide low-resistance pathways for efficient current flow in transistors and integrated circuits, whereas

Schottky contacts create a potential barrier that is advantageous in diodes, photodetectors, and sensors. The nature of the contact is primarily determined by the work-function alignment and interface characteristics (Manawi et al., 2018).

4.4. Emerging Heterostructures Based on Carbon Nanomaterials

Recent advances in semiconductor technology have focused on van der Waals (vdW) heterostructures, in which graphene and other carbon-based nanomaterials are integrated with two-dimensional semiconductors such as molybdenum disulfide (MoS2), tungsten disulfide (WS2), and hexagonal boron nitride (h-BN). Unlike conventional semiconductor junctions, these heterostructures are formed without lattice matching constraints, enabling atomically sharp interfaces and minimizing defect-induced carrier scattering (Yahyazadeh et al., 2024). The resulting devices exhibit enhanced charge transport, efficient carrier separation, tunable band alignment, and improved electrostatic control, making them highly suitable for field-effect transistors (FETs), photodetectors, light-emitting devices, and flexible electronics. The exceptional interface quality and reduced power consumption of vdW heterostructures have established them as promising candidates for next-generation nanoelectronic and optoelectronic applications (Sun et al., 2025).

5. Applications of Carbon Nanomaterials in Semiconductor Technology

Carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs) are widely utilized in semiconductor technology as they have excellent electrical conductivity, large surface area, mechanical flexibility, and thermal stability. Their unique electrical, optical, thermal, and mechanical properties make them suitable for applications in transistors, sensors, energy storage devices, and optoelectronic systems (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

5.1. Transistors

Carbon Nanotube Field-Effect Transistors (CNTFETs)

Because of their near-ballistic electron transport and high carrier mobility, carbon nanotubes are widely utilized in field-effect transistors. Compared to conventional silicon-based transistors, CNTFETs offer higher current-carrying capacity, lower power consumption, and faster switching speeds. CNTs also facilitate further semiconductor device miniaturization because of their nanoscale dimensions. Hence, CNTFETs are highly recommendable for high-performance integrated circuits and nanoelectronics (Zhu et al., 2024; Kim & Kuljanishvili, 2025; Manawi et al., 2018).

Graphene Transistors

Since graphene has high electron mobility, graphene transistors provide enhanced thermal management and ultrafast signal transmission. Additionally, graphene is mechanically flexible, making it suitable for flexible and wearable electronics. Researchers are concentrating on bandgap engineering techniques to overcome graphene's lack of an intrinsic bandgap, which remains a challenge for digital switching applications (Kolahdouz et al., 2022; Li et al., 2021; Manawi et al., 2018).

Advantages over Silicon

Carbon nanomaterials exhibit superior electrical conductivity, higher carrier mobility, lower heat generation, and greater mechanical flexibility than silicon. They also enable low-power operation and nanoscale device fabrication, both of which are essential for next-generation semiconductor technologies (Kolahdouz et al., 2022; Tao et al., 2024; Zhu et al., 2024).

5.2. Sensors

Gas Sensors

Carbon nanomaterials possess high electrical sensitivity and an exceptionally large surface-to-volume ratio, making them ideal for gas sensing applications. Gas sensors based on graphene and carbon nanotubes can detect hazardous gases such as CO, NH3, and NO2 at extremely low concentrations. Adsorption of gas molecules onto the carbon surface alters the electrical conductivity, enabling rapid and highly sensitive detection (Nandan et al., 2023; Narayan & Bezborah, 2024; Sun et al., 2025).

Biosensors

CNTs and graphene are extensively employed in biosensors for medical diagnostics and environmental monitoring. Their excellent conductivity, large surface area, biocompatibility, and strong interaction with biomolecules significantly enhance sensing performance. Carbon nanomaterial-based biosensors can detect glucose, proteins, DNA, pathogens, and various disease biomarkers with high sensitivity and selectivity (Roy et al., 2024; Sun et al., 2025).

High Sensitivity Due to Large Surface Area

The exceptionally high surface area of graphene and carbon nanotubes provides abundant active sites for interaction with gas molecules and biomolecules. Consequently, sensor sensitivity is significantly improved while detection limits are reduced (Nandan et al., 2023; Narayan & Bezborah, 2024).

5.3. Energy Storage and Conversion Devices

Solar Cells

Carbon nanomaterials improve solar-cell performance by enhancing light absorption and charge transport. Graphene is commonly employed as a transparent conductive electrode, whereas CNTs improve electron transport and reduce charge recombination losses. Their incorporation facilitates the development of lightweight, flexible, and highly efficient photovoltaic devices (Kolahdouz et al., 2022; Tao et al., 2024; Gendron & Bubak, 2023).

Supercapacitors

Graphene and carbon nanotubes are extensively used in supercapacitors because of their high electrical conductivity and exceptionally large surface area. These materials exhibit high power density, rapid charge-discharge capability, and excellent cycling stability, making them promising candidates for advanced energy storage systems (Almaraz-Vega et al., 2026).

Lithium-Ion Batteries

Carbon nanotubes are utilized as electrode materials in lithium-ion batteries to improve electrical conductivity, energy density, and battery lifespan. Graphene further enhances structural stability and facilitates rapid ion diffusion during charge-discharge processes, resulting in improved battery performance (Saranraj et al., 2026).

5.4. Optoelectronic Devices

Light-Emitting Diodes (LEDs)

Graphene and carbon nanotubes are employed in light-emitting diodes because of their excellent transparency and electrical conductivity. These materials improve charge injection efficiency, reduce energy losses, and enhance the overall performance and flexibility of LED devices (Miao & Fan, 2023).

Photodetectors

Carbon nanomaterials are widely investigated for photodetector applications because of their broad optical absorption spectrum and rapid photoresponse. Graphene-based photodetectors provide high sensitivity together with ultrafast signal processing over a wide wavelength range (Narayan & Bezborah, 2024; Miao & Fan, 2023).

Flexible Electronics

Graphene and CNTs are highly suitable for flexible electronics, including wearable sensors, foldable displays, and smart electronic devices, because of their excellent mechanical flexibility and lightweight nature. These materials maintain stable electrical performance even under repeated bending and stretching conditions, making them promising candidates for next-generation portable electronic systems (Kolahdouz et al., 2022; Tao et al., 2024; Miao & Fan, 2023).

5.5. Printed Electronics and Internet of Things (IoT) Devices

Recent advances in printed electronics have created new opportunities for the application of carbon-based nanomaterials in flexible and wearable semiconductor devices. Graphene- and CNT-based conductive inks enable the fabrication of lightweight, transparent, and mechanically flexible electronic circuits using low-cost printing techniques. These materials are increasingly employed in flexible displays, smart packaging, wearable health-monitoring systems, radio-frequency identification (RFID) tags, and Internet of Things (IoT) devices. Their excellent electrical conductivity, chemical stability, and mechanical durability ensure reliable device performance under repeated bending and stretching. Consequently, carbon nanomaterials are expected to play a significant role in the commercialization of next-generation printed and flexible electronic technologies (Nandan et al., 2023; Tao et al., 2024; Yahyazadeh et al., 2024; Kim et al., 2018).

5.6. Biomedical, Bioelectronic, and Translational Life Science Applications of Carbon-Based Nanomaterials

Beyond their well-established role in semiconductor and optoelectronic devices, carbon-based nanomaterials (CBNs) such as graphene, carbon nanotubes (CNTs), graphene oxide (GO), and carbon quantum dots (CQDs) have become central to the emerging field of nanobioelectronics, where electronic and biological systems are directly interfaced (Parvin et al., 2024). The same properties that make CBNs attractive for transistors and sensors, namely high carrier mobility, tunable surface chemistry, mechanical flexibility, and an exceptionally large surface-to-volume ratio, also make them well suited for biomolecular recognition, bioelectrical signal transduction, and cellular interfacing, thereby linking semiconductor engineering directly to translational life science research (Shin et al., 2024). This section extends the preceding discussion of electronic applications to the biomedical and life-science domain, covering molecular biosensing, bioelectronic neural interfaces, nanomedicine, and tissue engineering, before addressing the biocompatibility considerations required for clinical translation.

5.6.1. Carbon Nanomaterial-Based Biosensors for Molecular Diagnostics

Field-effect transistor (FET) biosensors built from CNTs and graphene exploit the same charge-transport mechanisms described in Section 4 to achieve label-free, real-time detection of biomolecules. Functionalizing the nanomaterial channel with antibodies, aptamers, or enzymes allows binding events to be transduced directly into a measurable change in channel conductance, enabling detection of cancer biomarkers, infectious-disease antigens, and neurodegenerative-disease markers at clinically relevant concentrations (Sengupta & Hussain, 2025). Recent architectural innovations, including floating-gate CNT-FETs and dual-microfluidic field-effect biosensor platforms coupled with carboxylated graphene quantum dots, have further improved sensitivity and multiplexing capability, although scalability, batch-to-batch reproducibility, and long-term operational stability remain barriers to widespread clinical deployment (Sengupta & Hussain, 2025).

5.6.2. Bioelectronic Neural Interfaces and Brain-Machine Interfaces

Carbon nanomaterials are increasingly used as electrode materials in implantable neural interfaces, where they must simultaneously satisfy electrical, electrochemical, mechanical, and biological compatibility requirements. Graphene and CNT-based electrodes offer low electrochemical impedance, high charge-injection capacity, and mechanical compliance that better matches soft neural tissue than rigid metal electrodes, reducing the foreign-body response associated with chronic implants (Gou et al., 2024). For example, nanoporous reduced graphene oxide thin-film microelectrodes have achieved high-fidelity local field potential recordings and selective, low-threshold nerve stimulation in rodent models, demonstrating the feasibility of flexible, wafer-scale graphene electrode arrays for bidirectional brain and peripheral-nerve interfacing (Viana et al., 2024). Hybrid graphene-CNT films have similarly been shown to increase electrode-neuron contact area and reduce impedance while retaining mechanical flexibility under bending and deformation (Gou et al., 2024). These developments position carbon-based semiconducting nanomaterials as strong candidates for next-generation brain-computer interfaces, neuroprosthetics, and closed-loop neuromodulation devices.

5.6.3. Drug Delivery, Gene Delivery, and Nanomedicine

The large specific surface area and tunable surface chemistry of graphene, GO, and CNTs enable high drug-loading capacity and stimuli-responsive release, making these materials attractive nanocarriers for targeted therapeutics. Surface functionalization with hydrophilic groups, targeting ligands, or stimuli-responsive polymers allows graphene-based carriers to release therapeutic payloads selectively in response to pH, temperature, light, or redox gradients characteristic of diseased tissue, improving therapeutic efficacy while reducing off-target toxicity (Khakpour et al., 2023). CNT-polymer nanocomposites have similarly been explored as nanocarriers for chemotherapeutic agents and can be combined with photothermal or photodynamic therapy to enhance tumor-selective cell killing, while carbon quantum dots offer the additional advantage of intrinsic photoluminescence for simultaneous drug tracking and bioimaging (Parvin et al., 2024).

5.6.4. Tissue Engineering and Regenerative Medicine

Carbon-based nanomaterials are also incorporated into scaffolds for tissue engineering because of their capacity to support cell adhesion, proliferation, and differentiation while imparting electrical conductivity that can guide electroactive tissue regeneration. Graphene oxide and CNTs incorporated into polymer scaffolds have been shown to enhance mesenchymal stem cell adhesion and to promote osteogenic and adipogenic differentiation, with GO's oxygen-containing functional groups improving protein adsorption and focal adhesion formation relative to unmodified substrates (Shin et al., 2024). Composite carbon-nanomaterial scaffolds have been applied to the regeneration of skin, cartilage, nerve, muscle, and bone tissue, underscoring the versatility of CBNs as multifunctional biomaterials that bridge electronic device engineering and regenerative medicine (Parveen et al., 2025).

5.6.5. Biocompatibility, Cytotoxicity, and Biosafety Considerations

Translating carbon-based nanomaterials from semiconductor devices and biosensors into implantable or in vivo biomedical applications requires careful evaluation of their biological safety, complementing the environmental toxicity considerations discussed in Section 9. The cytotoxic and genotoxic potential of CNTs is influenced by particle dimension, aspect ratio, surface functionalization, and dose, and is mediated predominantly through the generation of reactive oxygen species (ROS), which can trigger oxidative stress, mitochondrial dysfunction, and DNA damage in exposed cells (Fatkhutdinova et al., 2024). Comparative studies using human bronchial epithelial and lung cell lines indicate that multi-walled

CNTs can directly translocate into the cell nucleus and interact with genetic material, while single-walled CNTs appear to induce DNA damage through additional, less well-characterized pathways beyond oxidative stress alone (Fatkhutdinova et al., 2024). Appropriate surface functionalization, dose control, and purification of residual metal catalysts have been shown to substantially reduce these adverse effects, and rigorous in vitro and in vivo biocompatibility testing is now considered an essential prerequisite for the clinical translation of carbon nanomaterial-based biosensors, neural interfaces, and drug-delivery systems (Gou et al., 2024).

5.6.6. Translational Outlook

Collectively, these developments demonstrate that the electronic properties exploited in carbon-nanomaterial semiconductor devices, namely high carrier mobility, tunable bandgap, and large functionalizable surface area, translate directly into functional advantages for biosensing, neural interfacing, targeted drug delivery, and tissue engineering. Continued progress in scalable, reproducible synthesis, standardized biocompatibility assessment, and integration with flexible, low-power electronic architectures will be essential to move carbon-based nanobioelectronic devices from laboratory demonstration toward routine clinical and life-science application, fulfilling the translational potential highlighted in the title of this review.

6. Methods of Synthesis and Fabrication of Carbon-Based Nanomaterials

The structural, electrical, and mechanical properties of carbon-based nanomaterials are largely determined by their synthesis and fabrication methods. Various top-down and bottom-up approaches are employed to produce graphene, carbon nanotubes (CNTs), and other carbon nanomaterials for semiconductor applications. In addition, functionalization techniques are widely used to improve device performance, stability, and compatibility with semiconductor materials (Nandan et al., 2023; Tao et al., 2024; Manawi et al., 2018).

6.1. Top-Down Methods

Mechanical Exfoliation

One of the simplest methods for producing graphene from graphite is mechanical exfoliation. In this technique, thin graphene layers are peeled from bulk graphite using adhesive tape or mechanical forces. The process produces high-quality graphene with excellent electrical properties and minimal structural defects. However, because of its low production yield and labor-intensive nature, mechanical exfoliation is unsuitable for large-scale industrial manufacturing and is mainly employed in laboratory research (Sumdani et al., 2021).

Lithography

Lithography techniques are extensively used to pattern carbon nanomaterials into nanoscale semiconductor devices. Methods such as photolithography and electron-beam lithography enable graphene and CNTs to be fabricated into precise device geometries required for transistors, sensors, and integrated circuits. Although lithography provides excellent dimensional control, the process is relatively expensive and may introduce structural defects during fabrication (Kim & Kuljanishvili, 2025).

6.2. Bottom-Up Methods

Chemical Vapor Deposition (CVD)

Chemical Vapor Deposition (CVD) is one of the most widely used techniques for synthesizing high-quality graphene and carbon nanotubes. During this process, hydrocarbon gases such as methane decompose at elevated temperatures in the presence of catalytic metal substrates, resulting in the formation of carbon nanostructures. CVD offers excellent control over film thickness, crystallinity, purity, and uniformity, making it highly suitable for large-scale semiconductor manufacturing. CVD-grown graphene is widely applied in sensors, flexible electronics, transparent electrodes, and optoelectronic devices (Nandan et al., 2023; Tao et al., 2024; Manawi et al., 2018).

Arc Discharge

Arc discharge is one of the earliest methods developed for synthesizing carbon nanotubes. In this technique, a high-current electric arc is generated between two graphite electrodes in an inert atmosphere, producing extremely high temperatures that vaporize carbon atoms. These carbon atoms subsequently condense to form CNTs with excellent crystallinity and electrical properties. Although the technique produces high-quality nanotubes, purification is often required to remove amorphous carbon and metallic catalyst residues, limiting its large-scale industrial application (Yahyazadeh et al., 2024).

Laser Ablation

Laser ablation is another bottom-up synthesis technique in which a high-power laser beam vaporizes a graphite target containing metal catalysts under controlled conditions. The vaporized carbon species condense into high-purity carbon nanotubes with relatively uniform diameters. Laser ablation produces CNTs with excellent structural quality; however, the high equipment cost and limited production rate restrict its commercial scalability compared with Chemical Vapor Deposition (Yahyazadeh et al., 2024).

6.3. Functionalization Techniques

Chemical Functionalization

Chemical functionalization modifies the surface chemistry of graphene and carbon nanotubes by introducing functional groups such as hydroxyl, carboxyl, and amine groups. Functionalization improves dispersibility, solubility, and compatibility with semiconductor matrices. It also enables tuning of the electrical and optical properties of carbon nanomaterials for applications including transistors, sensors, photovoltaic devices, and energy storage systems (Xiao et al., 2023; Narayan & Bezborah, 2024).

Surface Engineering

Surface engineering techniques enhance interface bonding, stability, and charge-transfer characteristics of carbon nanomaterials. Methods such as plasma treatment, thin-film coating, and heteroatom doping reduce structural defects while improving carrier transport and device reliability. Surface-engineered graphene and carbon nanotubes have demonstrated excellent performance in biosensors, photovoltaic devices, flexible electronics, and high-performance semiconductor systems (Sun et al., 2025).

Table 1. Comparison of Methods of Synthesis and Fabrication

Method	Product Quality	Cost	Scalability	Major Advantage	Limitation
Mechanical Exfoliation	Very High	Low	Poor	Defect-free graphene	Low yield
CVD	High	Medium	Excellent	Large-area films	High temperature
Arc Discharge	Very High	High	Moderate	High-quality CNTs	Purification required
Laser Ablation	Very High	Very High	Low	Uniform CNTs	Expensive
Lithography	Device fabrication	High	Excellent	Precise patterning	Costly

7. Advantages of Carbon-Based Nanomaterials in Semiconductor Technology

The exceptional electrical, mechanical, thermal, and optical properties of carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs) make them highly suitable for advanced semiconductor technologies. Compared with conventional semiconductor materials such as silicon, carbon nanomaterials offer superior charge transport, excellent thermal management, outstanding mechanical flexibility, and nanoscale dimensions. Consequently, they are widely employed in nanoelectronics, sensors, energy storage systems, flexible electronics, and optoelectronic devices (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

7.1. High Electron Mobility

One of the most significant advantages of carbon nanomaterials is their exceptionally high electron mobility. Because of its delocalized π-electrons and two-dimensional honeycomb lattice structure, graphene exhibits ultrafast electron transport. Similarly, carbon nanotubes demonstrate near-ballistic electron transport with extremely low scattering losses. High carrier mobility enhances electrical conductivity, increases switching speed, and improves the performance of transistors and integrated circuits. These characteristics make graphene and CNTs promising alternatives to silicon for future nanoelectronic devices (Li et al., 2021; Kim & Kuljanishvili, 2025).

7.2. Mechanical Flexibility and Optical Transparency

Graphene and carbon nanotubes possess excellent mechanical flexibility and optical transparency, making them ideal materials for flexible and wearable electronics. Graphene exhibits approximately 97% optical transparency while maintaining outstanding electrical conductivity. These unique properties enable their application in transparent electrodes, flexible displays, wearable sensors, and foldable electronic devices. Unlike brittle silicon, carbon nanomaterials maintain their electrical performance even after repeated bending and stretching (Nandan et al., 2023; Narayan & Bezborah, 2024).

7.3. Low Power Consumption

Carbon nanomaterials enable low-power electronic operation because of their high electrical conductivity and low resistance. Compared with conventional silicon devices, CNT-based transistors operate at lower voltages and generate less heat during operation. Efficient charge transport significantly reduces power dissipation, making these materials highly attractive for portable electronics, high-density integrated circuits, and energy-efficient semiconductor systems (Zhu et al., 2024; Kim & Kuljanishvili, 2025).

7.4. Potential for Device Miniaturization

The atomic-scale thickness of graphene and the nanoscale dimensions of carbon nanotubes enable the fabrication of ultra-compact semiconductor devices. As silicon technology approaches its physical scaling limits, carbon nanomaterials provide an effective pathway for continued miniaturization. Their high current-carrying capacity, superior thermal stability, and excellent electrical properties support the development of next-generation processors, nanoscale transistors, and advanced integrated circuits (Kolahdouz et al., 2022; Sengupta & Hussain, 2023; Tao et al., 2024).

7.5. Excellent Thermal Conductivity

Carbon-based nanomaterials exhibit exceptionally high thermal conductivity, making them highly effective for heat dissipation in semiconductor devices. Graphene possesses thermal conductivity values exceeding those of most conventional materials, while carbon nanotubes efficiently conduct heat along their axial direction. Efficient thermal management minimizes overheating, improves device reliability, enhances operating speed, and extends the lifetime of electronic components. These advantages make carbon nanomaterials particularly attractive for high-performance processors, power electronics, and densely integrated semiconductor systems (Balandin, 2011; Xing et al., 2024; Li et al., 2023).

Table 2. Comparison of Carbon Nanomaterials and Conventional Silicon

Property	Silicon	Graphene/CNTs
Electron Mobility	Moderate	Very High
Thermal Conductivity	Moderate	Excellent
Mechanical Flexibility	Poor	Excellent
Optical Transparency	No	Yes
Power Consumption	Higher	Lower
Miniaturization	Limited	Excellent

8. Challenges and Limitations

Despite the remarkable electrical, thermal, and mechanical properties of carbon-based nanomaterials such as graphene and carbon nanotubes (CNTs), several challenges continue to hinder their widespread commercialization in semiconductor technology. Issues related to large-scale synthesis, structural uniformity, device reliability, interface engineering, manufacturing cost, and compatibility with existing silicon-based technologies remain significant barriers to industrial adoption (Kolahdouz et al., 2022; Nandan et al., 2023; Roy et al., 2024).

8.1. Challenges in Large-Scale Production

One of the major limitations of carbon nanomaterials is the difficulty in producing high-quality materials on a large scale with consistent structural properties. Although techniques such as Chemical Vapor Deposition (CVD) enable the synthesis of high-quality graphene and CNTs, maintaining uniformity in thickness, chirality, defect density, and purity over large areas remains challenging. Variations in these structural parameters directly influence the electrical performance and reproducibility of semiconductor devices. Furthermore, industrial-scale production requires sophisticated equipment, high processing temperatures, and complex fabrication procedures, which significantly increase manufacturing costs (Roy et al., 2024; Tao et al., 2024; Manawi et al., 2018).

8.2. Reproducibility and Stability

The long-term stability and reproducibility of carbon nanomaterial-based semiconductor devices remain major concerns. Environmental factors such as moisture, oxygen exposure, temperature fluctuations, and chemical contamination can alter the electrical characteristics of graphene and CNTs over time. In addition, slight variations during synthesis often result in inconsistent device performance. Since reproducibility is essential for large-scale semiconductor manufacturing, improved synthesis control, standardized fabrication protocols, and effective encapsulation strategies are required to ensure reliable device operation (Kolahdouz et al., 2022; Roy et al., 2024; Zhu et al., 2024).

8.3. Graphene's Bandgap Limitation

Although graphene possesses exceptionally high carrier mobility, its intrinsic zero bandgap limits its application in digital electronics and logic transistors. Semiconductor switching devices require a finite bandgap to achieve a high ON/OFF current ratio. To overcome this limitation, researchers have explored various bandgap engineering approaches, including chemical functionalization, heteroatom doping, graphene nanoribbons, bilayer graphene, and strain engineering. However, achieving a stable and controllable bandgap without significantly degrading carrier mobility remains one of the greatest challenges in graphene-based semiconductor technology (Kolahdouz et al., 2022; Nandan et al., 2023; Zhou et al., 2025).

8.4. Contact Resistance

High contact resistance between carbon nanomaterials and metal electrodes is another significant challenge in semiconductor device fabrication. Poor electrical contact limits carrier injection, increases power dissipation, and reduces the overall efficiency of transistors and integrated circuits. Considerable research is focused on optimizing electrode materials, interface engineering, and fabrication techniques to reduce contact resistance and improve device reliability. Developing low-resistance and stable electrical contacts remains essential for the commercialization of graphene- and CNT-based semiconductor devices (Kolahdouz et al., 2022; Nandan et al., 2023; Zhu et al., 2024).

8.5. Integration with Existing Silicon Technology

Integrating graphene and carbon nanotubes with conventional silicon-based Complementary Metal-Oxide-Semiconductor (CMOS) technology presents another significant challenge. Differences in fabrication temperatures, material compatibility, interface characteristics, and processing techniques complicate device integration. Maintaining the superior electrical properties of carbon nanomaterials while ensuring compatibility with existing semiconductor manufacturing infrastructure remains an active area of research. Successful integration with CMOS technology is expected to accelerate the industrial adoption of carbon nanomaterial-based electronic devices (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

8.6. Cost Considerations

The synthesis, purification, characterization, and device fabrication of high-quality carbon nanomaterials remain expensive compared with conventional silicon processing. Advanced synthesis methods, specialized characterization equipment, and complex fabrication procedures contribute significantly to production costs. Consequently, developing scalable, energy-efficient, and cost-effective manufacturing techniques is essential for the commercial viability of carbon nanomaterials in semiconductor applications (Roy et al., 2024; Tao et al., 2024; Manawi et al., 2018).

Table 3. Challenges and Solutions

Challenge	Impact on Semiconductor Devices	Possible Solution
Large-scale production	Non-uniform material quality	Improved CVD and scalable synthesis
Bandgap limitation	Poor switching behavior	Bandgap engineering, doping, nanoribbons
Contact resistance	Reduced current injection	Interface engineering, optimized metal contacts
CMOS integration	Manufacturing incompatibility	Hybrid fabrication processes
High cost	Limited commercialization	Low-cost, scalable synthesis methods

9. Environmental and Health Considerations

Although carbon-based nanomaterials offer numerous technological advantages for semiconductor applications, their potential environmental and biological impacts must also be carefully considered. As the production and utilization of graphene, carbon nanotubes (CNTs), and other carbon nanomaterials continue to increase, concerns regarding toxicity, environmental accumulation, occupational exposure, and sustainable manufacturing have become increasingly important. Therefore, comprehensive environmental risk assessment and the development of safe, sustainable fabrication strategies are essential for the responsible commercialization of carbon nanomaterials (Roy et al., 2024; Gendron & Bubak, 2023; Almaraz-Vega et al., 2026).

9.1. Toxicity Concerns

The toxicity of carbon nanomaterials depends on several factors, including particle size, morphology, concentration, surface chemistry, and exposure route. Studies have reported that prolonged exposure to high concentrations of carbon nanotubes may cause respiratory inflammation, oxidative stress, and cellular damage. Furthermore, owing to their nanoscale dimensions, some carbon nanomaterials can penetrate biological membranes and interact with cellular components, potentially affecting normal biological functions. Consequently, comprehensive toxicological investigations, standardized safety protocols, and appropriate occupational exposure guidelines are essential to ensure their safe handling in research laboratories and industrial environments (Roy et al., 2024; Gendron & Bubak, 2023).

9.2. Environmental Impact

Improper disposal of carbon nanomaterials may lead to contamination of soil and aquatic ecosystems. In addition, synthesis and processing techniques may generate hazardous by-products and chemical wastes that require appropriate treatment before disposal. The long-term environmental fate, transport mechanisms, biodegradation, and ecological effects of carbon nanomaterials remain under active investigation. Therefore, life-cycle assessment (LCA), environmental monitoring, and environmentally responsible manufacturing practices are necessary to minimize potential ecological risks associated with large-scale production (Roy et al., 2024; Gendron & Bubak, 2023).

9.3. Sustainable Synthesis Approaches

Green and sustainable synthesis methods have emerged as promising alternatives to conventional fabrication techniques for carbon nanomaterials. These approaches employ renewable resources, biomass-derived carbon precursors, environmentally benign solvents, and low-energy processing methods to reduce environmental impact. Waste-derived carbon materials, solvent-free synthesis, and energy-efficient production technologies have demonstrated significant potential for improving the sustainability of carbon nanomaterial manufacturing. Such environmentally friendly approaches are expected to support future large-scale industrial applications while minimizing carbon emissions and hazardous waste generation (Roy et al., 2024; Almaraz-Vega et al., 2026).

9.4. Recycling and End-of-Life Management

As the commercial utilization of carbon nanomaterials continues to expand, effective recycling and end-of-life management have become increasingly important. Developing efficient recycling technologies can minimize environmental pollution, recover valuable carbon-based materials, and reduce dependence on virgin raw materials. Furthermore, adopting circular economy principles and sustainable waste management strategies can significantly improve resource efficiency and reduce the environmental footprint of semiconductor manufacturing. Continued research on recyclable nanomaterials and environmentally responsible disposal methods will be essential for the long-term sustainability of carbon-based semiconductor technologies (Saranraj et al., 2026).

10. Future Perspectives

Carbon-based nanomaterials are expected to play a transformative role in future semiconductor and nanoelectronic technologies owing to their exceptional electrical, thermal, optical, and mechanical properties. Continuous advancements in material synthesis, interface engineering, and device fabrication are expected to overcome many of the current limitations associated with graphene and carbon nanotubes (CNTs). Future research will primarily focus on enhancing scalability, improving device reliability, reducing manufacturing costs, and integrating carbon nanomaterials into emerging technologies such as artificial intelligence (AI), quantum computing, flexible electronics, and next-generation communication systems (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

10.1. AI-Integrated Semiconductor Devices

The rapid development of Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) has created an increasing demand for semiconductor devices that are faster, smaller, and more energy-efficient. Graphene- and CNT-based transistors exhibit exceptional carrier mobility, low power consumption, and high switching speeds, making them promising candidates for AI accelerators, neuromorphic computing, and intelligent sensing platforms. Their excellent electrical characteristics are expected to support the development of high-performance computing architectures for future AI-driven applications (Nandan et al., 2023; Zhu et al., 2024).

10.2. Flexible and Wearable Electronics

The outstanding flexibility, transparency, lightweight nature, and excellent electrical conductivity of graphene and carbon nanotubes make them ideal materials for wearable electronics, smart sensors, foldable displays, and biomedical monitoring devices. Their ability to maintain electrical performance under repeated bending and stretching enables the fabrication of next-generation flexible electronic systems with enhanced durability and energy efficiency. Continued progress in printable electronics and stretchable conductive materials is expected to accelerate their commercialization in consumer electronics and healthcare applications (Roy et al., 2024; Miao & Fan, 2023).

10.3. Quantum Computing Applications

The unique quantum transport properties of graphene nanoribbons and carbon nanotubes have attracted considerable attention for quantum computing and quantum communication technologies. Their nanoscale dimensions, tunable electronic structures, and spin-dependent transport characteristics make them suitable for quantum dots, spintronic devices, and quantum information processing. Continued research on carbon-based quantum materials may contribute significantly to the realization of scalable quantum computing platforms (Nandan et al., 2023; Tao et al., 2024).

10.4. Carbon-Metal Oxide Hybrid Nanocomposites

Hybrid nanocomposites consisting of carbon nanomaterials and metal oxides have demonstrated significant improvements in electrical conductivity, electrochemical performance, charge storage capacity, and catalytic activity. These hybrid materials effectively combine the superior conductivity of graphene and CNTs with the functional properties of metal oxides, resulting in enhanced performance in transistors, sensors, batteries, supercapacitors, photocatalysts, and optoelectronic devices. Further optimization of hybrid interfaces is expected to enable high-performance multifunctional semiconductor systems (Tundwal et al., 2024; Sun et al., 2025).

10.5. Flexible and Printed Electronics

Future research is expected to accelerate the commercialization of flexible and printed electronics using graphene- and CNT-based conductive materials. Advances in printable conductive inks, stretchable electronic circuits, transparent conductive films, and roll-to-roll manufacturing technologies will enable the low-cost production of wearable healthcare devices, smart packaging, flexible displays, electronic textiles, and next-generation Internet of Things (IoT) systems. These developments are anticipated to significantly expand the industrial adoption of carbon-based nanomaterials in future semiconductor technologies (Miao & Fan, 2023; Kim et al., 2018).

10.6. Outlook

Although several scientific and technological challenges remain, continuous progress in material synthesis, bandgap engineering, interface optimization, and sustainable manufacturing is expected to facilitate the widespread commercialization of carbon-based nanomaterials. Their integration with artificial intelligence, quantum computing, flexible electronics, and advanced semiconductor manufacturing processes is likely to redefine the future of nanoelectronics. Consequently, carbon-based nanomaterials are expected to become key building blocks for high-performance, energy-efficient, and environmentally sustainable semiconductor devices in the coming decades (Kolahdouz et al., 2022; Nandan et al., 2023; Tao et al., 2024).

11. Conclusion

Carbon-based nanomaterials, particularly graphene and carbon nanotubes (CNTs), have emerged as promising materials for next-generation semiconductor technologies owing to their exceptional electrical conductivity, high carrier mobility, excellent thermal conductivity, superior mechanical strength, optical transparency, and nanoscale dimensions. These unique properties have enabled their application in a wide range of semiconductor devices, including field-effect transistors, sensors, energy storage systems, photovoltaic devices, optoelectronic components, and flexible electronic systems. Their ability to overcome several limitations of conventional silicon-based materials makes them strong candidates for future nanoelectronic and semiconductor applications.

This review has discussed the fundamental properties of carbon-based nanomaterials, their synthesis and fabrication methods, integration mechanisms within semiconductor devices, and their diverse applications in modern electronics. In addition, the major advantages of these materials, including high electron mobility, low power consumption, excellent thermal management, and miniaturization capability, have been highlighted. The review has also examined the key challenges associated with their commercialization, including large-scale synthesis, reproducibility, contact resistance, bandgap engineering, compatibility with CMOS technology, manufacturing cost, and environmental and health concerns.

Although considerable progress has been achieved over the past decade, several scientific and technological challenges must still be addressed before carbon nanomaterials can be fully integrated into commercial semiconductor manufacturing. Future research should focus on scalable and cost-effective synthesis techniques, precise bandgap engineering, interface optimization, environmentally sustainable manufacturing processes, and seamless integration with existing silicon-based technologies. Continued advances in material science, nanofabrication, and device engineering are expected to significantly improve the performance, reliability, and commercial viability of carbon-based semiconductor devices.

Furthermore, the convergence of carbon nanomaterials with emerging technologies such as artificial intelligence (AI), Internet of Things (IoT), quantum computing, flexible electronics, wearable devices, and advanced energy systems is expected to create new opportunities for innovation. The development of hybrid nanocomposites, printed electronics, and sustainable semiconductor manufacturing processes will further expand their industrial applications and accelerate their commercialization.

In conclusion, carbon-based nanomaterials possess enormous potential to transform the future of semiconductor technology. With continued interdisciplinary research and advancements in synthesis, interface engineering, and large-scale manufacturing, these materials are expected to play a pivotal role in the development of high-performance, energy-efficient, flexible, and environmentally sustainable electronic devices. Their successful integration into future semiconductor platforms will contribute significantly to the advancement of nanoelectronics and next-generation intelligent technologies.

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